

# Study of the petroleum potential of an onshore region of the Lusitanian Basin: Arruda Sub-basin, Abadia Valley, Montejunto Anticline

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**Abstract:** Hydrocarbon reservoirs are, normally, associated to large geologically complex areas. Its identification and characterization is difficult, costly and time consuming. At early stages of exploration and characterization studies of regional scope the interpretation of the available data, normally seismic reflection data, allows the development of a geological model for a specific sedimentary basin, or prospect. All the available data: composed by exploration wells, outcrops, geophysical data, or even studies of other areas with similar geological background, may provide, through analogy, valuable information to understand the geological evolution and identify areas likely of accumulating hydrocarbons. The Lusitanian basin is a highly geologically complex region, but is also one of the Portuguese basins with more information and which has triggered more interest over the years. There are records of exploration in this basin since 1844, with the exploitation of asphaltic sands. This study intends to contribute to a revision of a specific onshore region within the Lusitanian Basin, serving as a departure point to future studies, or the reformulation and evolution of this one, with the integration of new data or the formulation of new hypothesis, and thus contribute to better understand the petroleum potential in the Abadia Valley, Montejunto Anticline region including the area where the exploration well Benfeito-1 was drilled.

**Keywords:** Reservoir Characterization, Seismic Interpretation, Information Integration, Potential Hydrocarbon Evaluation, Benfeito-1, 3D Seismic Data, Montejunto, Lusitanian Basin, Portugal.

## 1. Objective

Using, as starting point, the existing data of a recent 3D seismic reflection data (acquired by Mohave, 2010) from the Montejunto area, and two 2D seismic lines acquired by Petrogal in 1980 in the same area. It is the purpose of this work to map spatially the seismic reflections that correspond to the top and base of the main geological formations as interpreted from detailed information through the available data of exploration wells drilled in this region, such as, Benfeito-1, Lapaduços-2, Freixial-1, and Aldeia Grande-2.

Other objective of the work developed under the scope of this thesis is acquiring training, competences and methods regarding seismic interpretation from an exploratory point of view.

Thus, we intend to accomplish the review and analysis of the region under study with the evaluation of the main geological formations, by using well data, and by its integration with the seismic reflection data, contributing in this way to the enlightenment of the geological model proposed for this region and, namely, the identification of:

- Source rocks, with adequate characteristics for hydrocarbon generation and its time framing;
- Geological formations with lithological and petrophysical characteristics, which may constitute reservoir rocks;
- Traps allowing hydrocarbon imprisonment and accumulation, its locations, geological period of formation and retention capacity.

## 2. Brief review on the hydrocarbon exploration in Portugal

The exploration of hydrocarbon in the Lusitanian basin, and in Portugal, has begun in the middle of the 19<sup>th</sup> century, with exploration records dating from 1844 (exploration of asphaltic sands, in São Pedro de Moel).

So far, several exploration wells have already been drilled, (175 wells), and good indications of the existence of hydrocarbon have been found in some of them. The following wells can be highlighted (Fig.1): Lula-1 (1985), with 4.040 m depth, Benfeito-1 (1982) with 3.343 m, Aljubarrota-2 (1998), with 3.343 m, and tests of gas production, and still the Fracares-1 (1999) well, with hints of oil and gas.

Several concessions for the exploration of the Portuguese basins potential demonstrate the increasing interest over the recent years (Fig. 2).

Nome	Identificação	Operador	Ano	TB (m)	WATER DE FTH (KB Equivalent)	Evidências	Localização
14A-1	14A-1	SHELL	1975	2882,00	43,00	Óleo recuperado em testes	Offshore
DOURADA-1C	Do-1C	SUN OIL COMP	1974	3688,00	84,10	Evidências de óleo	
MOREIA-1	Mo-1	SUN OIL COMP	1974	2144,00	44,80	Óleo recuperado em testes	
ABADIA-14	Ab-14	CPP	1954	147,00	132,21	Óleo recuperado em testes	Onshore
ABADIA-18	Ab-18	CPP	1954	190,04	154,30	Gás recuperado em testes	
BENFEITO-1	Bf-1	PETROGAL E.P.	1982	3343,00	249,00	Óleo recuperado em testes	
MONTALEGRE-1	Mt-1	CPP	1949	1749,55	193,10	Evidências de óleo	
MONTE REAL OESTE-9	MWR-9	CPP-COFEFA	1962	1388,00	5,00	Óleo recuperado em testes	
SÃO PEDRO DE MUEL-2	SPM-2	CPP	1963	1507,35	80,80	Evidências de óleo	
TORRES VEDRAS-4	TV-4	CPP	1951	2340,20	65,00	Óleo recuperado em testes	
VERMOIL-1	Vm-1	CPP	1958	2309,00	227,60	Evidências de óleo	
VERRIDE-1	Ve-1	CPP	1952	1494,00	39,80	Evidências de óleo	
BARREIRO-1	Br-1	CPP-MOBIL	1956	3611,00	6,80	Evidências de óleo	
BARREIRO-2	Br-2	CPP-MOBIL	1959	2425,00	21,70	Evidências de óleo	

Figure 1 - Main wells in the Lusitanian Basin, with signs of oil and gas (UPEP,2015).

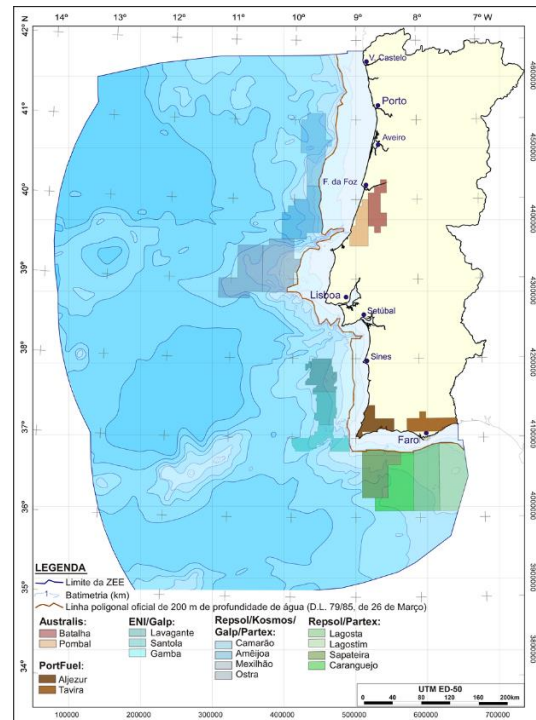


Figure 2 - Actual concessions for petroleum exploration and production: Repsol\*/Kosmos/Galp/Partex: 4 deep offshore concessions; ENI\*/Galp: 3 deep offshore concessions; Repsol\*/Partex: 4 deep offshore concessions; PortFuel: 2 onshore concessions; Australis: 2 onshore concessions. (\*operator) (ENMC, 2016).

## 3. Lusitanian Basin

The Lusitanian Basin is a sedimentary basin which developed in the Western Iberia margin during the Mesozoic. It is located south of the Porto Basin and it is the Portuguese sedimentary basin best studied so far. With an area of approximately 22.000 km<sup>2</sup> it stretches from onshore to offshore with a length of 250-300 Km in the NNW-SSE direction (maximum subsidence axis) and 100-150 km wide, with 2/3 of the continental area continental emerged and the remaining area submersed in the continental platform (Kullberg, 2006; Fig. 3).



Figure 3 - Geological Map of Portugal, scale 1:1.000.000, with the Lusitanian Basin represented by the red line.

### 3.1 Geological setting and Tectonic-Stratigraphic Evolution of the Lusitanian Basin

The Mezo-Cenozoic Portuguese basins were created by *rifting* processes that led to the opening of the North Atlantic Ocean, within the Pangea continent fragmentation. The Basin evolution was, generically, a result of an extensive process that occurred during the Mesozoic, for around 150 Ma, followed by compression in the Cenozoic (basin inversion). There is still no consensus among the authors that have studied the tectonic-stratigraphic evolution of the basin, namely regarding the number of rifting episodes and its boundaries.

Ribeiro *et al.* (1996) redefined the sectors proposed by Rocha & Soares (1984 and 1990), namely the central sector and its south boundary, with the outcome of the sectors indicated below and in Fig. 4. (Dias, 2005):

- North Sector, located North of the Nazaré fault;
- Central Sector, located between the Nazaré fault and Tagus Valley fault;

- South Sector, located between the Tagus estuary and the Arrábida fault.

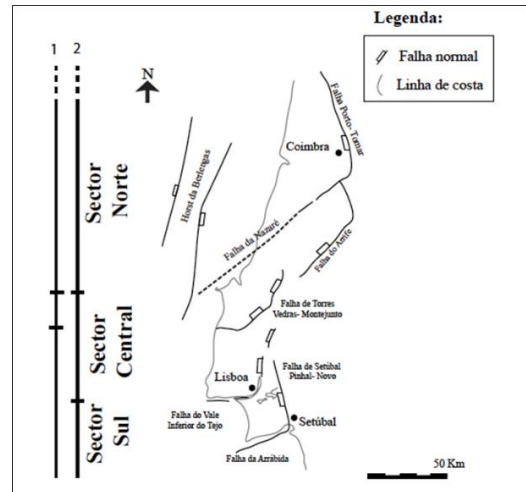


Figure 4 - 1 – Rocha & Soares (1984); 2 – Ribeiro *et al* (1996) – Sectors division: Lusitanian Basin boundaries location and faults controlling its evolution during Jurassic. (adapted from Kullberg, 2000).

### 3.2 Diapirism in the Lusitanian Basin

The diapirism in the Lusitanian Basin is also object of some controversy among the scientific community, namely on the tectonic style and its conditioning of the substrate geometry where the units of the Late Jurassic are found; on the mechanisms, responsible for the movement of the evaporitic level (Dagorda formation) and the periods where the diapirism occurred; in short concepts associated with the salt tectonics (Kullberg *et al.*, 2006).

There is the possibility that the movements of the salt layer (halokinesis) have originated the formation of traps in the basin. So, it is very important to take in consideration these phenomena and its possible relevance to the basin structural style. Within this specific base, and due to its characteristics, diapirism in extensive regime is probably the best way to explain the formation of the diverse existing diapirs which can be interpreted in seismic reflection data (Dias, 2005).

For the region under study, the Arruda sub-basin, and specifically the Montejuento Anticline structure, the salt diapirism

phenomena was originated at the Dagorda formation. Leinfelder & Wilson (1989), consider that this structure, which separates the Sub-basins of Arruda and Bombarral, would have had its first pulse during the Oxfordian and Lower Kimeridgian.

### 3.3 Petroleum Systems

A Petroleum System can be defined as a dynamic physical-chemical system that evolves in space and geological time, and is capable of generating and accumulate hydrocarbons (Demaison & Huizinga, 1991 and 1994). In early appraisal stage, one must look to define and find evidences of a generator subsystem, responsible for the production and release of hydrocarbons from the source rock over a determined geological period and another subsystem responsible for its migration and imprisonment. These will be the minimum conditions for the possibility of formation and preservation of petroleum. However, the existence of these conditions does not guarantee its existence, thus it is of extreme importance the confirmation through physical evidence (i.e. by executing exploration wells) and complementary studies to the maximum extent possible.

#### 3.3.1 Evidences of an active petroleum system in the sedimentary Lusitanian Basin.

There are several surface manifestations of hydrocarbon associated to geological outcrops and indications of oil/gas recovered in exploration wells that suggest the existence of active petroleum systems in the Lusitanian Basin. These numerous surface indications may also hint to a lesser reservoir retention or that the basin tectonic evolution, after the migration, may have led to the dispersion of some part of the hydrocarbon from the reservoirs.

The exploration well Benfeito-1, used on this study, produced, on tests, 795 liters of oil (5 bbl.), of high grade API (41-44°). Identically, offshore exploration wells 14A-1 and

Moreia-1 (Fig. 5), produced, in tests, respectively, 290 and 525 liters of oil, among other encouraging indications from other wells. These, with many other records and studies, point to the possible existence of petroleum systems in the Lusitanian Basin.



Figure 5 - Location of some wells with more significant indications in the Lusitanian Basin, onshore (Benfeito-1) and offshore (14A-1 and Moreia-1) (UPEP 2015).

#### 3.3.2 Identification of the Petroleum Systems

Three Petroleum Systems can be appointed in the Lusitanian Basin. We can characterize the first (Pre-salt System) as a Paleo-Mesozoic Petroleum System, with Paleozoic source rocks, Late Triassic (or more recent) reservoir rocks and Early Jurassic (or more recent) seal rocks; and the second and third systems as Meso-Cenozoic Petroleum Systems, with Jurassic source rocks, and Jurassic/Cretaceous and/or Cenozoic reservoir and seal rocks.

In the next table (Fig. 6) it is possible to identify the various elements of a Petroleum System for the Lusitanian Basin and the proposed critical moments. It also contains information on the different geologic formations.

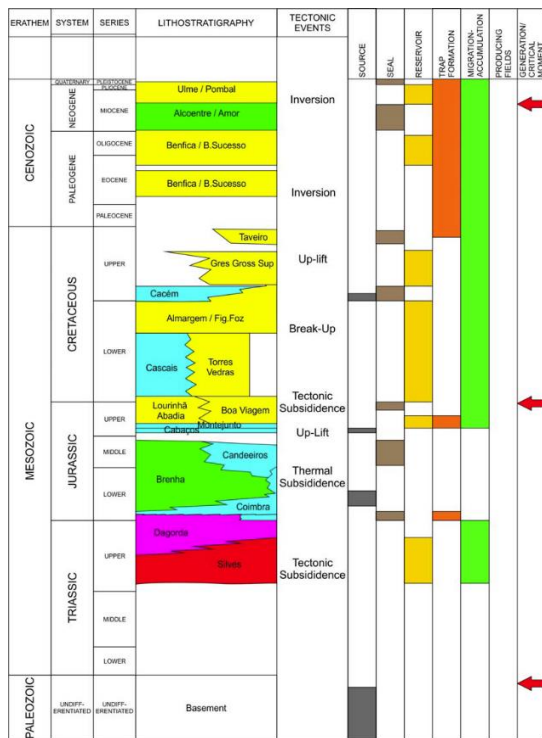


Figure 6 - Litho-Stratigraphy and Petroleum Systems in Portugal with critical moments indication and different source, reservoir and seal rocks, trap formation period, and possible migration (adaptation based on Azerêdo et al., 2003).

In the Lusitanian Basin, sediments were deposited essentially between the Triassic and the end of Cretaceous, although most the sedimentary record represents Jurassic deposits. Thus, three main litho-stratigraphic units are recognized, including organic rich rocks with high potential for hydrocarbon generation (Dagorda formation- Early Jurassic; Coimbra e Brenha formations- Early Jurassic; Cabaços formation – Late Jurassic). Source rocks associated to the Paleozoic (Vale da Ursa and Sazes formation) are also considered.

Rocks from the Silves formation (Late Triassic), with moderate to good porosity (that may, in certain areas reach 20%) are considered as reservoir rocks. The evaporites sequence of the Hettangian (Dagorda formation), which cover these continental sediments may represent an excellent seal rock.

The marine carbonates from the Coimbra formation (Sinemurian – Early Jurassic), deposited above the evaporitic sequence and including vacuolar porosities and

reasonable fracture zones, with fairly good permeability, are also considered as possible reservoir rocks. The coarse sediments of the Figueira da Foz and Torres Vedras formations, extending over almost of the Lusitanian Basin, with porosities up to 35%, have also reservoir rock potential.

The targeted traps in the Lusitanian Basin have been, mainly, of structural nature. The *rifting* phase of Late Jurassic and the Late Cretaceous-Eocene (Meso-Cenozoic) inversion followed by the Miocene-Betic (Cenozoic) inversion, caused a structural complexity and created a tectonic “puzzle”, involving phenomena of localized subsidence and later uprising due to salt tectonic movements. These phenomena may have induced fractures in the existing seals, destructing of the existing potential reservoir with the release of hydrocarbons. However, it may also have allowed the interconnection of different source rocks and different migration paths with diverse reservoir rocks, and thus there is the necessity of a better comprehension of these complex models for the understanding of these phenomena.

The possibility of the existence of older traps, previous to the migration of hydrocarbons, which have not been fractured or affected by the inversions, should also be analyzed.

The salt movements may have had an important role in the creation of structures with potential for hydrocarbon accumulation, facilitating its capture in the siliciclastic formations around the diapirs or in the folds induced by salt domes combined with sealing shale layers.

The Brenha formation constitutes a potential rock for *shale gas*, possibly being simultaneously the source rock and reservoir and, hypothetically, be exploited by non-conventional methods.

Mohave also approached the hypothesis of a pre-salt system and identified significant structural traps in the Silves formation. Although these traps are mainly considered as structural, they also possess an important stratigraphic component (UPEP 2015).

## 4. Study area

The study region appraised under the scope of this work includes the Montejuento Anticline and Abadia Valley areas, where the exploratory well Benfeito-1 was drilled. In the south, the Lusitanian Basin is sub-divided in three sub-basins by the intersection of the Torres Vedras fault, the Montejuento Anticline and the Sobral fault (Fig. 7). The Bombarral sub-basin is located north of this intersection, in a “Y” shape, the Arruda sub-basin is located SE and the Turcifal sub-basin on the SW. The junction zone is characterized by a saline structure, the Matacães diapir.

This area is characterized by a high structural complexity and the Montejuento Anticline structure is not considered a simple anticline, but an uplift, with a “pop-up” structure in the central region and asymmetric surrounding zones with a complex fault system.

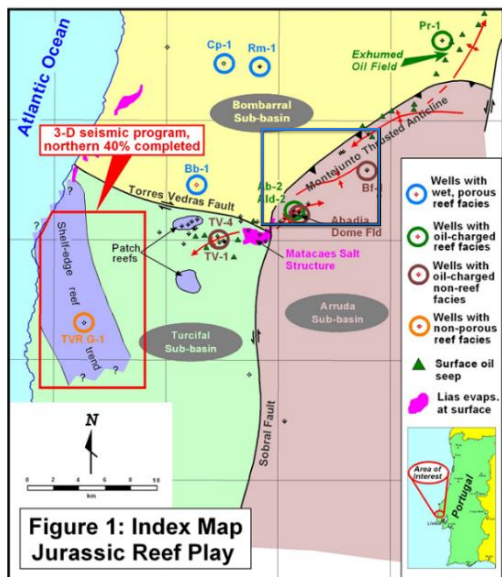


Figure 1 - Location of the interest region, identification of the Bombarral, Turcifal e Arruda sub-basins, main structures and research wells (Uphoff, 2010). Region of interest corresponds to blue square.

### 4.2 Data

This study uses the 3D seismic reflection data acquired by the Mohave Oil & Gas Corporation, in 2010, and the seismic lines AR05-80 e AR09-80, acquired by Petrogal in 1980 and 1981.

This study also comprises data from the exploration wells Benfeito-1, Freixial-1, Lapaduços-2 and Aldeia Grande-2 (Fig. 8).

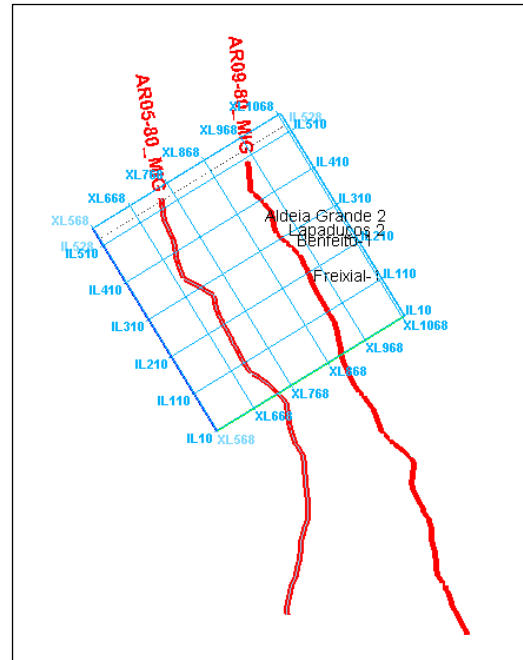


Figure 8 - Seismic acquisition data and wells made available by Petrel®. Software (seismic volume Montejuento 3D, lines AR05-80 e AR09-80 and wells AG-2, Lp-2, Bf-1 e Fr-1).

The seismic reflection data referred as 3D seismic regards part of a 3D volume, Montejuento PSTM, located between *inlines* 10 e 556 and *crosslines* 568 e 1073, with an area of approximately 172 km<sup>2</sup> (13,7 km x 12,6 km).

Vertically, the seismic cube information lies between the surface (0ms) and the lower limit of 4000 ms (TWT – two-way time). This limit allows the visualization of the seismic reflections down to a great depth, far deeper than the lithologic units reached until now by the wells already drilled, and so covering the most interesting seismic units for this study, corresponding to the main geological units of the previously described petroleum systems.

### 4.3 Seismic Interpretation

The *Petrel*® (Schlumberger) interpretation software was used for the interpretation of the seismic cube and seismic lines AR05-80 e AR09-80.

The seismic interpretation was calibrated and tied to the formations tops, indicated in the well logs and final well reports of Benfeito-1, Freixial-1 and Lapaduços-2 wells. The spatial mapping of the main reflectors, corresponding to the top and base of the major seismic units, were oriented based on these well tops.

There are several models of the tectonic evolution of the Basin, and even more complex studies, with longer duration, and teams with experienced professionals of different areas, find the interpretation of the existing data difficult, due to the quality of the seismic reflection data and sub-surface geological complexity.

Some of the available interpretations for line AR09-80, as the accomplished by Tectonics Team ICTE/GG/Geofcul (1995), for the MILUPOBAS project, or carried out by Pimentel & Pena dos Reis (2016), or, still, by Mohave (Uphoff, 2005), were used as a base for the interpretation presented in this study.

The interpreted horizons correspond to the tops of Abadia, Montejunto, Cabaços, Candeeiros/Brenha, Dagorda formations and Basement.

As methodology to the beginning of the interpretation, the vast existing bibliography was analyzed and compiled. Seismic line AR09-80 (Fig. 9) was chosen as starting point based on the study performed in the previous step, since it was considered a good representation of the presented studies and geological hypothesis.

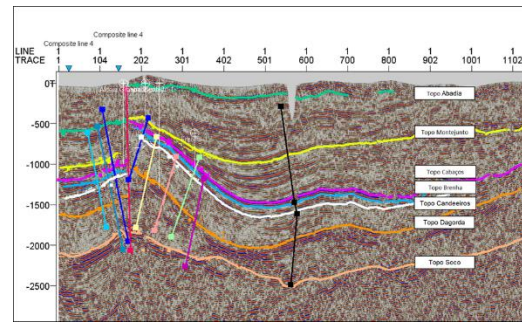


Figure 9 - Image of the proposed interpretation for seismic line AR9-80 (2D), located in the central sector of the Lusitanian Basin.

The seismic interpretation was orientated by the formations tops, indicated in the well logs. The horizons interpreted coincide with the tops in the zone where they are intersected. Figure 10 shows the seismic section of *inline* 190, its spatial location and orientation regarding the seismic cube, the 2D lines, and the Freixial-1 well.

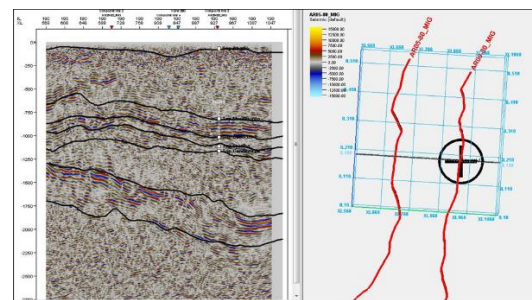


Figure 10 - Image of the seismic section (Inline 190) together with its spatial location, and orientation regarding the seismic cube, 2D lines and Freixial-1 well. (The black lines correspond to the surfaces created, using the interpolation of the int

This methodology was also used regarding the remaining wells of the existing data: Benfeito-1 and Lapaduços-2, with the purpose of better defining the interpretation of AR9-80. The seismic interpretation was then extended to the rest of the available seismic reflection data (Fig. 11).

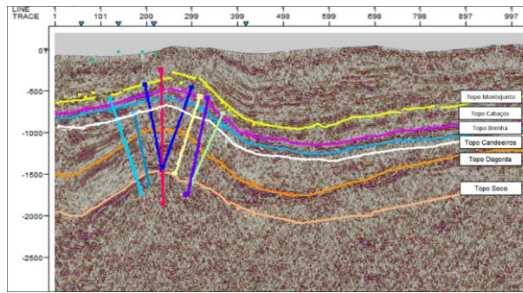


Figure 11 - Image of the proposed interpretation of the seismic line ARO5-80, located in the central sector of the Lusitanian Basin.

#### 4.4 Traps and prospects

There is no doubt that any approach to the study of the Lusitanian Basin, and its potential prospects must consider the influence of the tectonic inversion and its implications as, for example, the impact on the rock integrity, seal and traps, but also the possibility of having enabled the creation of traps, as folds or fault areas and/or favored migration paths.

This work carried out the interpretation and analysis of seismic horizons, to detect possible structures that allowed the accumulation of hydrocarbons or anomalies indicative of its presence.

The seismic quality and the result of the combined interpretations did not reveal extraordinary results and thus no anomalies were identified, neither defined any structures in particular.

Although, possible targets were identified based on the interpretation and also on the knowledge acquired in the bibliographic analysis. Some of the possible targets may be anticline traps, next to blocks of upper faults, particularly those related to formations and sequences of Middle and Late Jurassic (Figs. 12 and 13): fms. Montejunto, Cabaços, Candeeiros, and possibly Brenha.

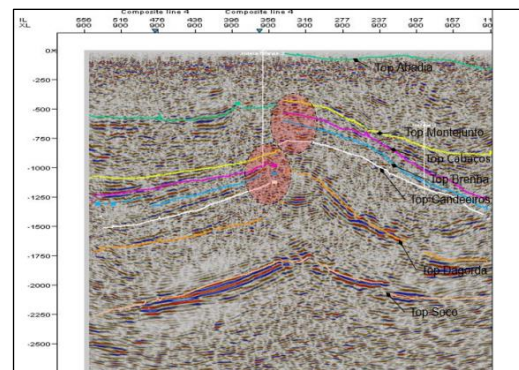


Figure 12 - Image of the seismic section (crossline 900) with indication of possible zones of interest for the study of hydrocarbon accumulation in the formations and sequences of the Middle and Late Jurassic: Fms. Montejunto, Cabaços Candeeiros, and possibly Brenha.

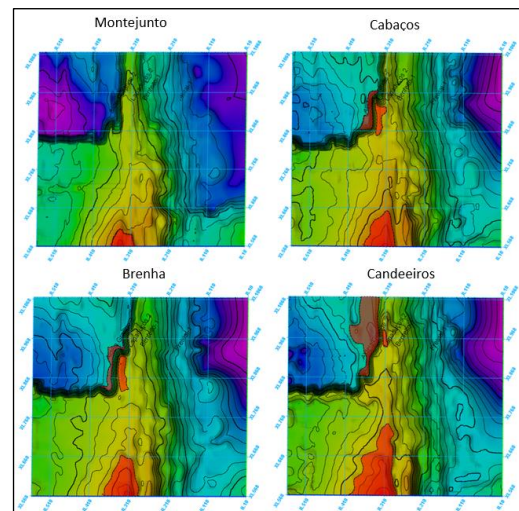


Figure 13 - Identification of possible prospects, in different formations (Montejunto, Cabaços Candeeiros, and Brenha).

The structures considered as potential prospects are those that constitute structural highs, closed in all directions or in three directions against a fault, with characteristics that indicate the possibility of being reservoir rocks.

These structural traps may have been formed after the hydrocarbon migration, or fractured, with the loss of tightness/sealing in the inversion phases, and so, with less probability of containing hydrocarbon, as verified in the wells already drilled, with evidences of oil and gas concentrations, in small quantities, which didn't justified exploitation. Older traps, created before the hydrocarbons migration, and that have not



been fractured or affected by tectonic inversions have also been taken into account.

The Brenha formation constitutes a *shale gas* type rock with potential for its exploitation by non-conventional methods, and it may be, simultaneously, a source rock and a reservoir.

Dagorda fm. (Hettangian evaporites), composed mainly of salt with intercalations of marl and black mudstones (rich in organic matter) as well as clastic rocks of Silves fm. (Pre-salt system), may also constitute some interesting prospect targets (Figs. 66 and 67).

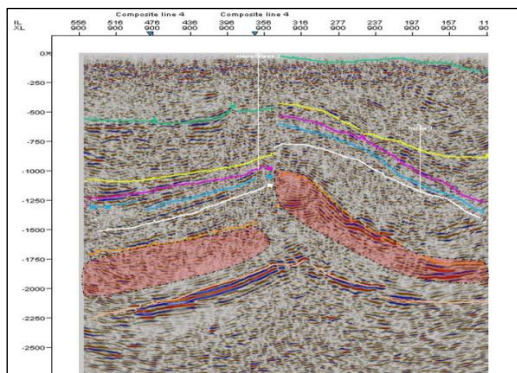


Figure 14 - Image of the seismic section (crossline 900) with indication of possible zones of interest for the study of hydrocarbon accumulation in the Lower Jurassic formations and sequences: Fm. Dagorda and Silves (pre-salt system).

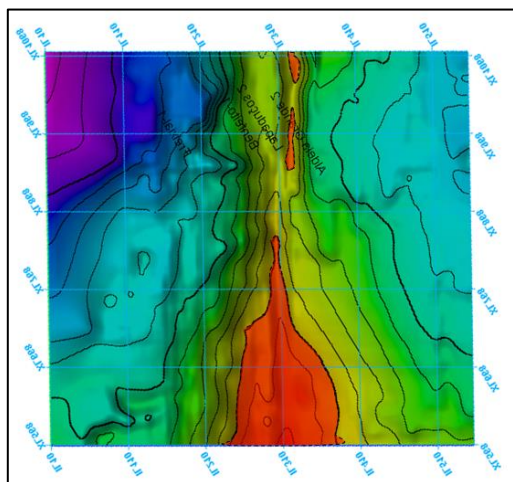


Figure 15 - Identification of possible prospects (marked with red colored polygon), in Lower Jurassic formations and sequences: Fm. Dagorda and Silves (Pre-salt system).

Although the seismic below the zone marked as basement does not allow the analysis of structures, carboniferous sedimentary rocks with potential may still exist (Figure 69 e 69), even if limited by very low values of porosity or permeability. Anyway, its existence has not yet been confirmed by any exploration well or evidences in outcrop.

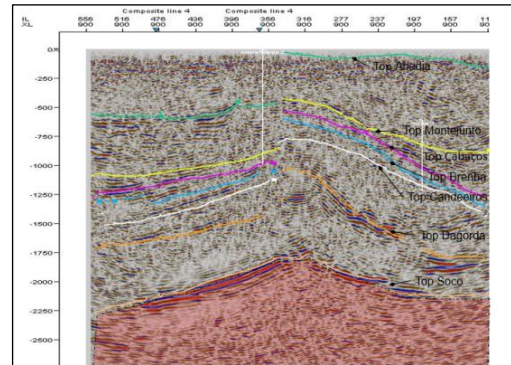


Figure 16 - Image of seismic section (crossline 900) with indication of possible zones of interest for the study of hydrocarbon accumulation in Paleozoic Formations.

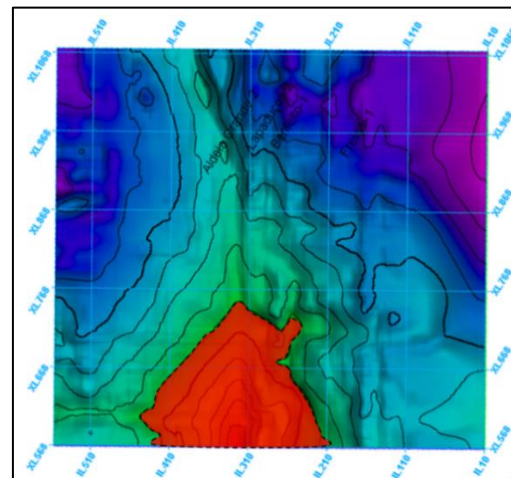


Figure 17 - Identification of possible prospects (red colored polygon) in Paleozoic Formations.

## 5. Final Remarks and Future Work

In the exploration phase, interpretation is a time consuming and meticulous work. The Seismic phenomena, as the interaction of seismic waves with different formations and discontinuities, must be very well understood, and it is also necessary a deep knowledge of the local geology to be able to integrate all available information during seismic interpretation, in order to transform it into a geological section. The time spent in

this phase of the project is directly related to the improvement of future results. The model presented under the scope of this thesis can only be considered as a suggestion and a simplified model of reality, which might not respect all existing knowledge of the sub-surface.

The main goal of this study was the analysis and interpretation of seismic data to identify potential interesting formations for possible hydrocarbon accumulation.

Based on the lines AR09-80 and AR05-80 and the 3D seismic volume, the seismic interpretation of the main horizons was accomplished, being representative of the principal seismic units considered for the study of the region petroliferous potential, and, as final result, allow the presentation of structural maps for the tops of Abadia, Montejunto, Cabaços, Brenha, Candeeiros and Dagorda formations and also the Basement, in time (ms), as well as the identification of some of the main existing discontinuities (faults) and indication of possible prospects.

It was also an objective the improvement of personal competences on the seismic interpretation subject/field, and the study of the methodology to integrate different information on the study of the petroleum potential of this particular region.

The outcome of this study is the first approach and interpretation in the academy, of the recent 3D seismic of the Montejunto region (2010), outlining a possible methodology and guidelines on the subject.

The next steps will certainly be the conversion of surfaces from time to depth and the quantitative analysis of the available data using the petrophysical properties (e.g. porosity, lithology and hydrocarbon saturation).

The analysis of these properties, together with the interpreted horizons, may be used to estimate and for the inference of the sub-surface properties through the geostatistical inversion of the seismic reflection data. The accomplishment of the inversion analysis, conditioned by the well logs data and seismic interpretation, will allow the achievement of distribution models of the petro-elastic properties, as acoustic

impedance or porosity, for the region under study. This will enable the identification of interest zones; define thresholds values auxiliary to the analysis, and later, data statistical treatment and quantification of the spatial uncertainty of these models. This approach and step forward in the analysis of data obtained through seismic acquisition, with the integration of other elements obtained directly from wells, will be even more essential in the future, for the exploration of new fields, to keep up with the increasing complexity of petroliferous reservoirs, reducing exploration and production risks and costs.

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