Universidade de Coimbra

Faculdade de Ciências e Tecnologia

Earth Science Department

# Petroleum Prospectivity of the Peniche Basin, Deepwater Continental Margin off Portugal

Bruno Miguel Leal Duarte

Master of Science thesis in Petroleum Geoscience

Advisors:

Profs. Roberto Fainstein, and Rui Bento Pena dos Reis

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# Abstract

Keywords: Offshore Portugal, Peniche Basin, Seismic, Magnetics, Gravity

This thesis concerns the geophysics delineation of the Peniche Basin that developed in the Atlantic Margin offshore Portugal along the western edge of the Iberia margin. This is essentially an un-explored basin that has attracted considerable interest due to its hydrocarbon potential. The basin formed as a rifted, non-volcanic, Atlantic continental margin type, trending on an N-S orientation that is roughly parallel to the Portuguese coastline between Lisbon and Aveiro. Its stratigraphy is genetically linked to the onshore Lusitanian Basin, these twin basins correspond to the inner (Lusitanian) and outer (Peniche) continental margin segments of West Iberia.

The geophysics outlining of Peniche Basin links its geology framework, to newly acquired state-of-the-art geophysics data. The interpretation is made from seismic reflection records and tied to wells with significant Oil & Gas shows, gravity and magnetics interpretation. To this effect, seismic reflectors representing interfaces along the sedimentary deposition of siliciclastics and carbonates are clearly expressed on the seismic records leading to the mapping of petroleum leads. Key reflectors were interpreted above and beneath the original Triassic salt-rich unit, the Dagorda Fm. Faults and fractures affected the structuring of Peniche Basin, both the large Nazare Fault to the south and the northern Aveiro Fault are linked to major tectonic events and have been clearly identified on seismic, gravity and magnetics.

In the Peniche basin the Late Triassic rift is overlain by a Jurassic sag capped by a Callovian unconformity. Above it, the Late Jurassic/Early Cretaceous rift is filled by clastics progradation under the Late Aptian break-up unconformity. Salt diapirs rose through fractures and deformed the Mesozoic sequences. These events and the structural fabric imprint from several episodes of tectonic inversions, Campanian, Late Eocene and Late Miocene, are identifiable on seismic leading to an overall comprehensive interpretation of structuring and the role of salt tectonics in the deepwater realm of the basin.

Deepwater leads are encountered at more than 1,500 meters of water depth, these are well defined structural anticlines with four-way dip closures shaped recently by late Miocene tectonic inversion of the Jurassic-Cretaceous depocenters. All of these features are readily recognized by the integrated interpretation of the newly acquired geophysics data and impact for an attractive the risk/reward ratio prospectivity of the Peniche basin.

# Resumo

Palavras-chave: Offshore Portugal, Bacia de Peniche, Sísmica, Magnética, Gravimetria

Esta tese diz respeito ao delineamento geofísico da Bacia de Peniche que se desenvolveu na Margem Atlântica ao largo de Portugal ao longo da margem ocidental da margem da Península Ibérica. Esta é essencialmente uma bacia não explorada que atraiu um interesse considerável devido ao seu potencial petrolífero. A bacia foi formada como margem continental do Atlântico, não vulcânica, com tendência a uma orientação N-S que é aproximadamente paralela à costa portuguesa entre Lisboa e Aveiro. A sua estratigrafia está geneticamente ligada à Bacia Lusitânica, estas bacias gémeas correspondem aos segmentos da margem continental interior (Lusitânica) e externa (Peniche) da Península Ibérica.

O delineamento geofísico da bacia de Peniche liga a sua estrutura geológica aos recém-adquiridos dados de geofísica. A interpretação é feita a partir de registos de reflexão sísmica e ligados à interpretação da gravidade e do magnetismo. Para isso, os reflectores sísmicos que representam as interfaces ao longo da deposição sedimentar de sedimentos siliciclásticos e carbonatados são claramente expressos nos registos sísmicos que levam ao mapeamento de leads e derivações de petróleo. Os reflectores chave foram interpretados acima e abaixo da unidade original rica em sal do Triásico, a fm. Dagorda. As falhas e fracturas afectaram a estruturação da Bacia de Peniche, tanto a grande Falha de Nazaré a sul como a falha de Aveiro estão ligadas a grandes eventos tectónicos e foram claramente identificadas em sísmica, gravidade e magnetismo.

Na bacia offshore de Peniche, a fractura do Triásico Superior é re-coberto pelo jurássico e coberto por uma discordância calloviana. Acima, o Jurássico Superior e do Cretácico Inferior é preenchido por pro-gradação de clásticos sob a discordância de dissolução de Aptiano Superior. Os diapiros de sal subiram através de fraturas e deformaram as sequências mesozóicas. Esses eventos e o tecido estrutural de vários episódios de inversões tectónicas, campaniano, eocénico tardio e Miocénico Superior, são identificáveis em sísmica, levando a uma interpretação global abrangente da componente estrutural e do papel da tectónica de sal no âmbito das águas profundas da bacia.

Os prospetos mapeados encontram-se a mais de 1.500 metros de profundidade de água, estes são anticlinais estruturais bem definidos com fechamento nas 3 direcções, moldados recentemente pela inversão tectónica tardia do Miocénico dos depocentros jurássico-cretácicos. Todas estas características são prontamente reconhecidas pela interpretação integrada dos dados geofísicos recentemente adquiridos e pelo impacto para uma atractiva relação entre a prospectividade do rácio risco / recompensa da bacia de Peniche.

# Acknowledgements

Antes demais gostaria de agradecer à minha família por todo o apoio dado ao longo destes 3 anos, especialmente à minha mãe que sempre me incutiu esta maneira de estar na vida de melhoria constante e de nunca me conformar.

À ENMC, por ter apoiado desde início a elaboração desta tese que irá contribuir um pouco para o conhecimento da Bacia de Peniche. Queria agradecer em particular ao ex-presidente do conselho de administração, Paulo Carmona, vice-presidente José Reis e atual presidente Filipe Meirinho pelo apoio em termos laborais e financeiros para a elaboração desta tese.

Doutor Roberto Fainstein, a pessoa que mais admiro em termos profissionais, incansável no apoio a esta tese e muito exigente com os resultados. É um privilégio trabalhar com uma pessoa com tanto conhecimento e ao mesmo tempo com paciência para ensinar o próximo. Agradeço todos os dias incluindo os sábados e domingos que disponibilizou do seu tempo e conhecimento para dar o seu apoio na elaboração desta tese, muitas vezes entre viagens por todo o mundo. Quando conheci o Roberto, no final do curso de *deepwater seismic interpretation*, decidi imediatamente que queria trabalhar com ele e tentar aprender o máximo possível. Objetivo foi alcançado e superou as espectativas, para além de um profissional exímio e excelente professor levo para a vida um amigo.

Ao Professor Pena Dos Reis da Faculdade de Ciências e Tecnologia da Universidade de Coimbra que no seu vasto conhecimento acerca da Bacia Lusitânica contribui para a realização deste trabalho, é notável a facilidade em explicar conceitos complexos de maneira fácil. Conhecia apenas o seu trabalho desenvolvido, mas foi uma enorme sorte contar com o seu apoio e sapiência na elaboração desta tese.

Álvaro Arnáiz Giménez, responsável pela exploração da Repsol na bacia de Peniche e Algarve pelas conversas acerca deste trabalho numa zona onde a Repsol era operadora de 4 concessões a sua visão académica e industrial foi fundamental. À Repsol pelo financiamento dos vários cursos que permitiram adicionar vários capítulos a esta tese.

Ao professor Nuno Pimentel da Faculdade de Ciências da Universidade de Lisboa, que no 2º ano da Licenciatura em Geologia me colocou o “bichinho” do petróleo com a cadeira de geologia sedimentar. O Nuno é um grande professor que apenas necessita de um papel e uma caneta para explicar assuntos complexos, admiro por ser um professor diferente e que domina os assuntos que ensina.

Doutor Christopher R. Scotese, por ter disponibilizado do seu tempo para me fornecer os dados georreferenciados usados nas reconstruções das placas tectónicas (projeto PALEOMAP) que permitiram a elaboração dos mapas nesta tese.

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# Abbreviations List

**DHI** - Direct Hydrocarbon Indicators
**DSDP -** Deep Sea Drilling Project
**ENMC-** Entidade Nacional para o Mercado de Combustíveis
**NOC** - National Oil Company
**ODP** - Ocean Drilling Project
**SPZ** - South Portuguese Zone
**UPEP** - Unidade Pesquisa e Exploração de Recursos Petrolíferos
**COT –** Continental Ocean Transition
**PSTM-** Pre-Stack Time Migration
**PSDM-** Pre-Stack Depth Migration

# CHAPTER 1 - INTRODUCTION

The scope of this thesis concerns the gathering interpretation of available geophysical data of the Peniche Basin offshore Portugal. This was made in terms of its hydrocarbon exploration with main purpose focused in the identification of petroleum systems and prospects.

Peniche Basin along the west coast of Portugal is mostly a deep-water basin situated to the west of the onshore Peniche region, in Central-West Portugal. Speculative seismic surveys were carried out in the Peniche Basin during in the period 1999 to 2003. The suite of surveys by TGS-NOPEC Company. These surveys that also covered most of the offshore basins in Portugal and modern surveys were acquired by state-of-art techniques, were processed PSTM, PSDM and re-processed later with broadband.

Subsequently several E & P companies have demonstrated keen interest in the Peniche Basin, among these Petrobras (Brazilian N.O.C.) signed in an E & P contract in year 2007 and afterwards a consortium held by Repsol, Kosmos, Galp and Partex inherited this license upon Petrobras relinquishment. At present, these licenses are all relinquished, however, several important companies are interested in bidding for blocks of Peniche Basin.

The Peniche Basin is one of the largest unexplored basins in offshore Europe with fascinating hydrocarbon potential as demonstrated by its active architecture shaped by salt tectonics and volcanics. Many prospects were identified that could be probed by drilling. So far, however, there are no exploration wells drilled in the basin. Regionally the basin was thoroughly investigated by 2D surveys, with 3D seismic directed to the best areas. In addition, marine gravity, magnetics and limited oceanographic studies further add to the database.

This thesis compiles and interpret the geophysical database, mostly focusing on the regional gravity, magnetics, 2D and 3D seismic. It examines the overall tectonic fabric of the basin through interpretation mapping of four-way dip closures and fault closures, stratigraphic terminations against the salt walls, tying the postulated stratigraphy as defined by the onshore exposures and drilling, plus offshore stratigraphy definition obtained from the nearby, genetically linked, Lusitanian Basin. Finally, a study of geometric and physical seismic attributes focusing on amplitude, frequency and phase is presented for possible hydrocarbons detection directly from seismic data.

## Scope and Methods

The main objective of this thesis was to gather, ordain and interpret the available geophysical data in the Peniche Basin to enable for timely access to its main prospects. Although the geophysics database is sufficient for the investigation there is a lack of geological information as the basin has not been probed by drilling. Geological information therefore is derived from its sister basin onshore, the Lusitanian Basin whose petroleum system is proven by numerous drilling and outcrop exposures.

Prospectivity of this basin is compelling in terms of structure and stratigraphy. It is coherent with its conjugate continental margin on the other side of the Atlantic, the Jean D´arc Basin – Offshore Canada, which is an established petroleum producing province.

The interpretation methodology consisted in the hand-interpretation examination of the un-migrated and migrated regional seismic lines and the workstation interpretation of the 2D and 3D seismic data utilizing several software programs such as the Decision Space (Landmark), Petrel (Schlumberger) and GM-SYS from Geosoft to produce the Grav-Mag models. In addition, a series of research papers in the Lusitanian Basin and in the Peniche Basin were also used as basic framework information. Also, several researches of papers and un-published reports were utilized as ancillary information.

In the framework of this thesis were attended several courses such as: Drilling Practices, Well Log Interpretations held by Petroskills Houston, three courses in ArcGis held by ESRI Portugal, three courses in decision space desktop held by Halliburton-United Kingdom, one course in Petrel held by Instituto Superior Técnico, two courses of seismic interpretation held by Universidade de Coimbra and several field trips in Lusitanian Basin.

Geo-referenced maps were produced with the software Arcgis (Esri), this was used in connection with the analysis and visualization of the seismic lines on the Workstation with Decision Space Desktop from Halliburton provided by author´s employer, ENMC. E.P.E. for better identification and interpretation.

The Georeferenced maps used for plate reconstruction slides and animations were produced with basis provided by the research laboratory investigations effected by Chris Scotese.

# Geography & geology

## Geographic Setting

Portugal is situated at the western edge of the Iberia Peninsula, Southwest of Europe surrounded by Spain to the East and by the Atlantic Ocean to the West. The Peniche region is part of the Western Continental Margin of Portugal, Peniche Basin developed in the Atlantic Margin offshore Portugal in the western edge of the Iberia margin. It is a rift, non-volcanic, un-explored basin with hydrocarbon potential embrace the continental platform, slope, rise and basin (Figure 1).

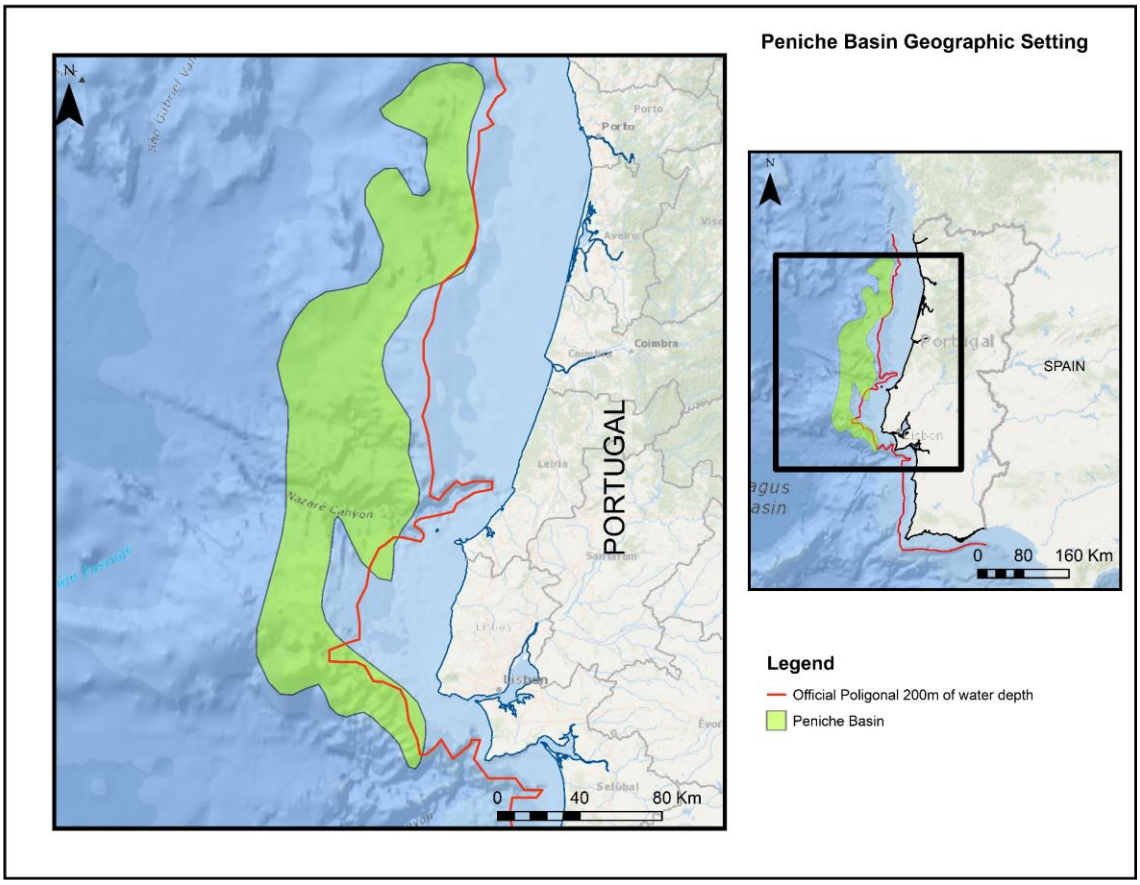


*Figure 1- Geographic setting of Peniche Basin offshore Portugal, roughly parallel to the areas between Lisbon and Aveiro onshore.*

## Geological setting:

The Peniche Basin (Figure 2) is a N-S trending basin outlined as follows:
It is bounded to the east by the Berlenga basement high trend. The western edge of the predominantly Jurassic carbonate platform is coincident with the western limit of the Berlenga basement high trend.

- The basin is separated from the Alentejo Basin to the south by a major strike-slip fault. This fault acted as a transform fault during Atlantic seafloor spreading, utilizing an old zone of weakness in the Paleozoic (SPZ) basement (Ferreira do Alentejo - Ficalho Thrust).
- The western boundary / rift shoulder of the Peniche Basin is a basement high trend inferred from gravity maps. This rift shoulder probably existed as a paleo-high throughout the Jurassic, where platform carbonates could have been deposited.
- This rift basin is on trend with (or the extension of) the Galicia Interior Basin, offshore Spain. The transition between the two basins is not yet adequately covered by seismic data to define a boundary between them.

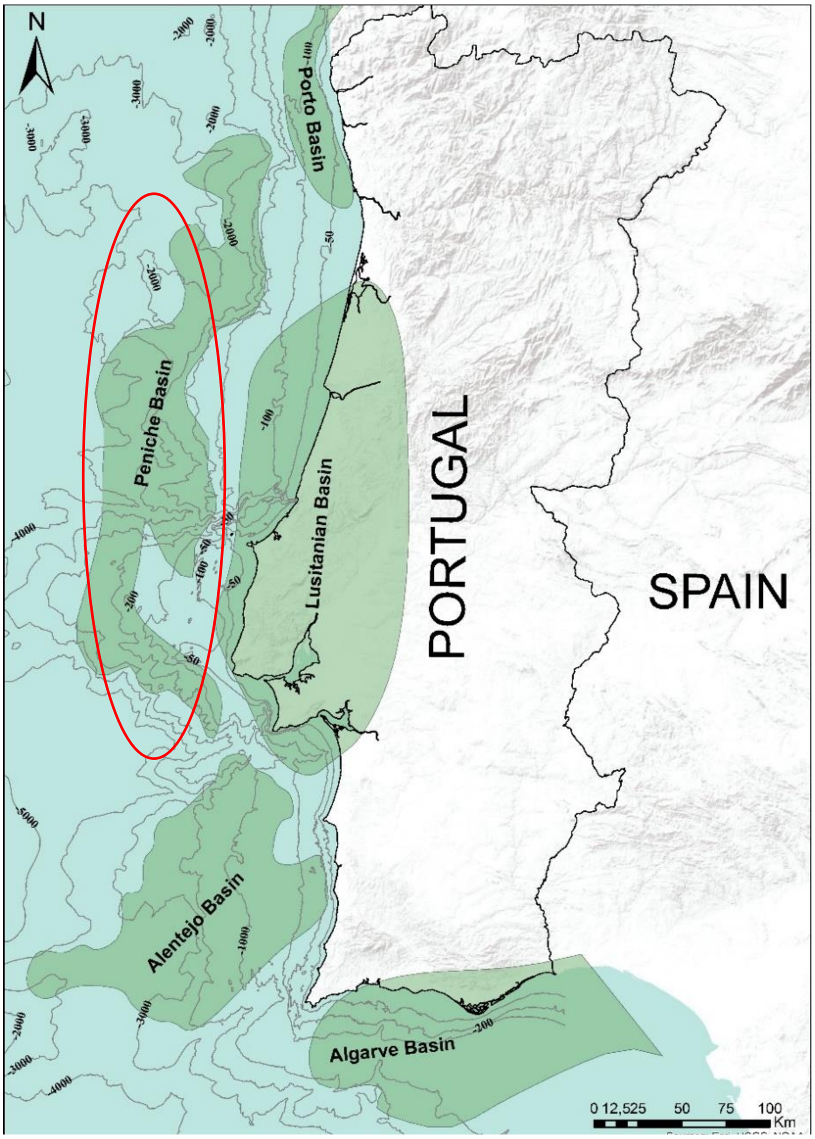


*Figure 2- Map displaying all the of the sedimentary basins offshore Portugal (bathymetry contours are in meters)- In red the outline of the basin.*

## Plate Tectonics Reconstruction of West Portugal (Iberia)

(based on Christopher R. Scotese re-constructions)

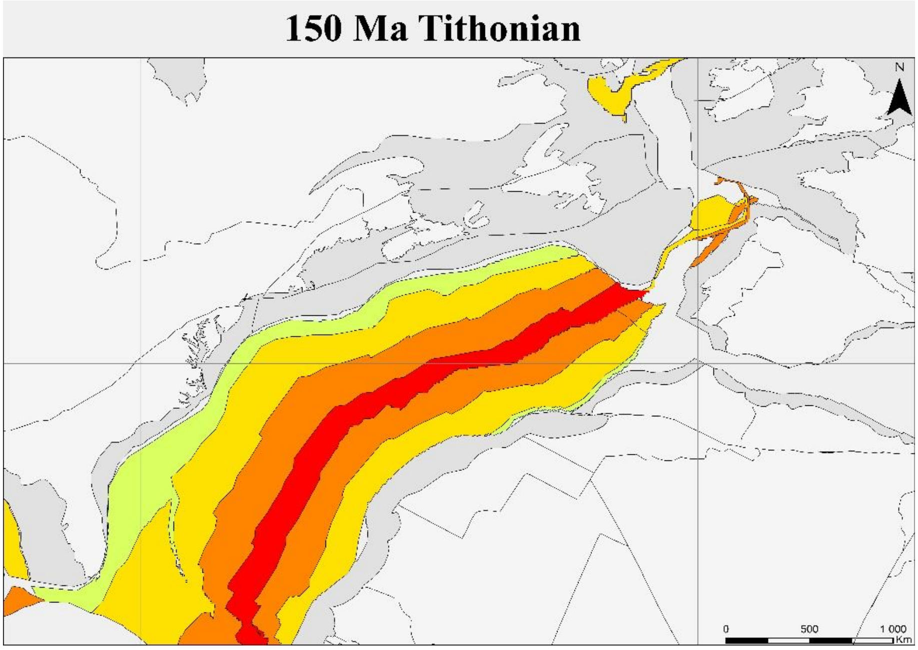


*Figure 3- Plate reconstruction of Iberia 150 Ma - Tithonian (based in Schettino & Scotese, 2002)*

Seafloor spreading has taken place between Africa and North America, (Figure 3) while Iberia is in full contact with North America. The apparent overlaps are probably due to inadequate compensation for later stretching of the continental margins. Thetys is still open through the Atlas Mountains, and the Alboran (ALB) and Kiberyan (KBY) micro-plates are close to the Pelagian Platform.

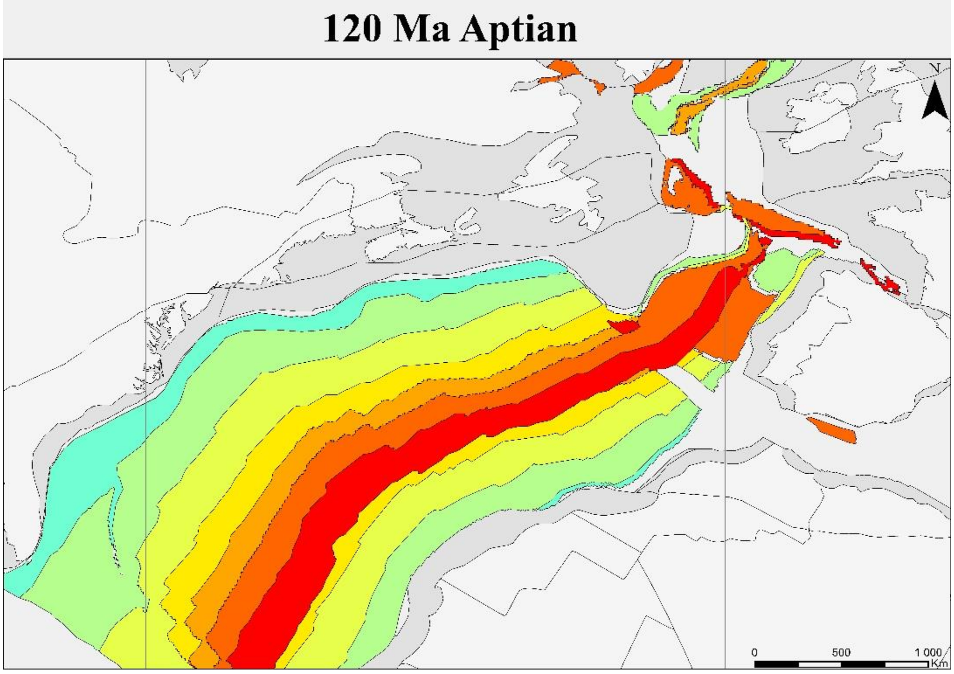


*Figure 4- Plate reconstruction of Iberia 130.0 Ma - Lower/Upper Hauterivian (Schettino & Scotese, 2002)*

Rifting and initial opening has taken place between Iberia and North America. (Figure 4) Seafloor spreading has advanced significantly between Africa and

North America, closing the High-Saharan Atlas portion of Thetys in the process. Thetys was still open through the Middle Tell Atlas.

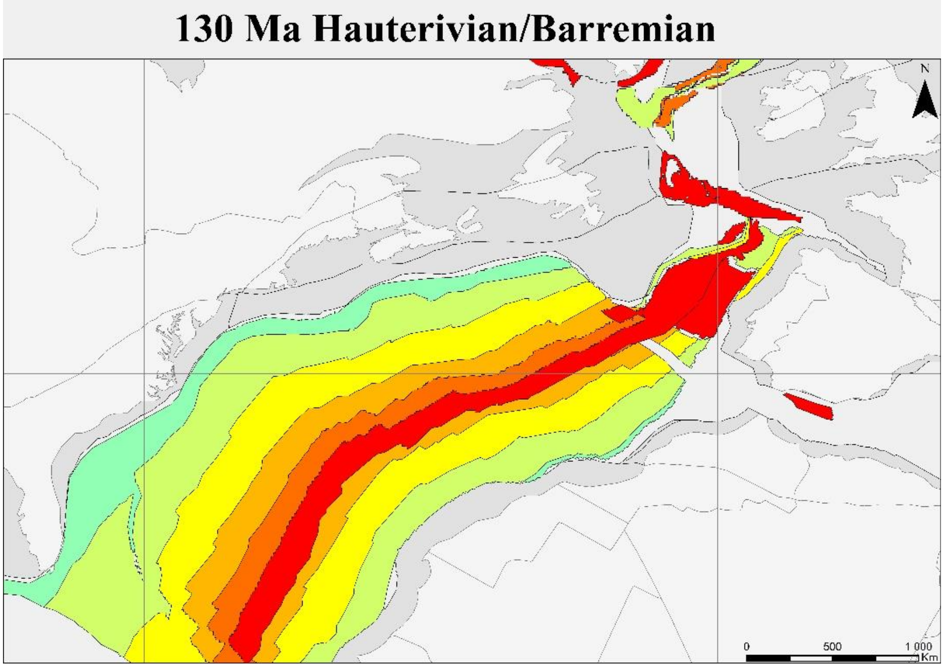


Figure 5- Plate reconstruction of Iberia 120- Ma Lower Aptian (Based in Schettino & Scotese, 2002)

Seafloor spreading has now advanced to the northern Iberian margin. (Figure 5) The Flemish Cap is outside the map frame here but is shown juxtaposed to Galician Bank at this time in other reconstructions. Note the position of Europe relative to Iberia

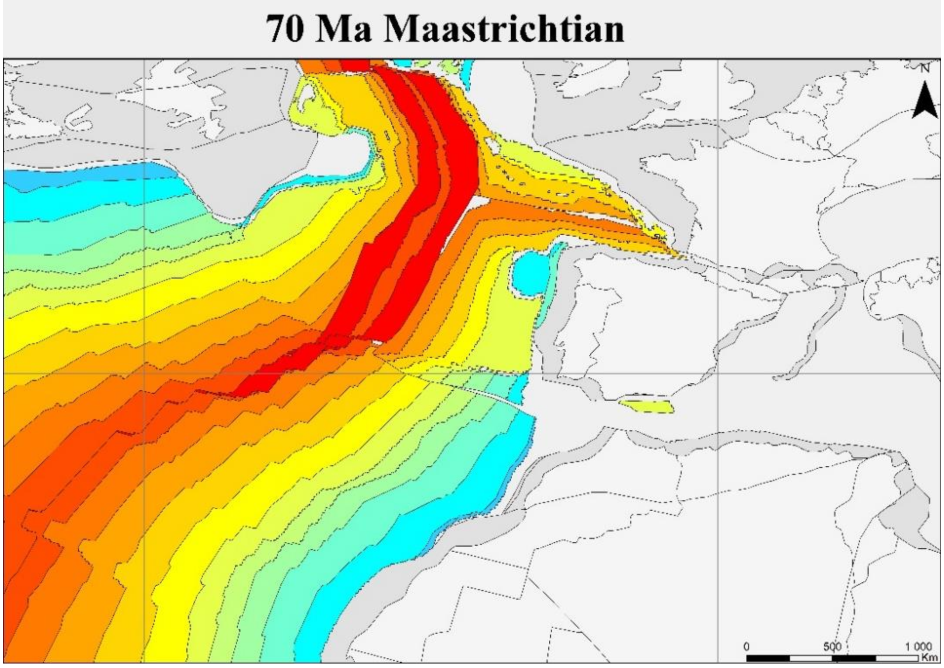


Figure 6- Plate reconstruction of Iberia 70 Ma- Maastrichtian (Based in Schettino & Scotese, 2002)

Extensive seafloor spreading between Europe and North America during Late Cretaceous, created dextral shear through the Pyrenean zone, and opened the Bay of Biscay. (Figure 6) Tethys connection to the Atlantic still exist also south of Iberia as evidenced by outcrops in the Pre-Rif Mountains in Morocco.

## Brief Overview of Portugal offshore Geology

The continental margin edge of the Western Iberian Margin is marked by the Portuguese sedimentary margin basins. These may be distinctively grouped as inner basins such as the, Lusitanian and Algarve and outer basins such Peniche, Porto, and Alentejo offshore basins. These rifted basins originated from the closure of Thetis Ocean. The basins evolved as part of Mesozoic evolution of the Iberia Peninsula, the petroleum geology history of the Lusitanian basin being known through the detailed stratigraphic mapping of outcrop exposures and legacy exploratory drilling. The lesser known basins are western offshore basins of Porto, Peniche and Alentejo and the southernmost basin of Algarve offshore. Knowledge on these Deepwater basins are derived from seismic stratigraphic comparisons with Lusitanian Basin and Algarve onshore.

The better-known Lusitanian Basin is developed over Paleozoic basement terrane amalgamated during Variscan orogeny. Triassic rift siliciclastic infill was followed by thick salt-rich clays deposited in continental and coastal evaporitic sabkhas. Marly and carbonate deposition was predominant during the Early and Middle Jurassic with marine sediments of ramp and platform environments. The late Jurassic characterizes a new rifting episode with realignment of old basement structures and erosion of the margin rift shoulders (Figure 7). Early Cretaceous sedimentation was marked by the break-up of the North Atlantic whereas the late Cretaceous marks the tectonic inversion of the basin and its continued deformation. Salt pillows deforming the Late Triassic date back from Early to Mid-Jurassic, whereas Late Jurassic tectonics and basin inversion are contemporaneous with the rise of salt diapirs and the massive corridor salt walls of Lusitanian Basin. The Late Cretaceous piercing of diapirs and the deformation of the buried and piercing salt features are related to the Alpine compressive events. These deformations continued until recent times with the diapirism being regionally defined by seismic and basin outcrop exposures. The Peniche and Alentejo basins offshore also display thick sections of Triassic (With salt in Peniche basin), Jurassic and Lower Cretaceous sediments. By contrast the Algarve basin has remarkable influences from Atlantic and from the Pelagian Platform of North Africa in resemblance with oblique slip features of a transform margin. (Pena dos Reis *et al*, 2017)

In this thesis, the interpretation of regional seismic lines over Peniche basin outlines the main events such as the breakup unconformities, the pre-salt section, the Triassic salt, the early and upper Jurassic carbonates and the Lower and Upper Cretaceous sediments.

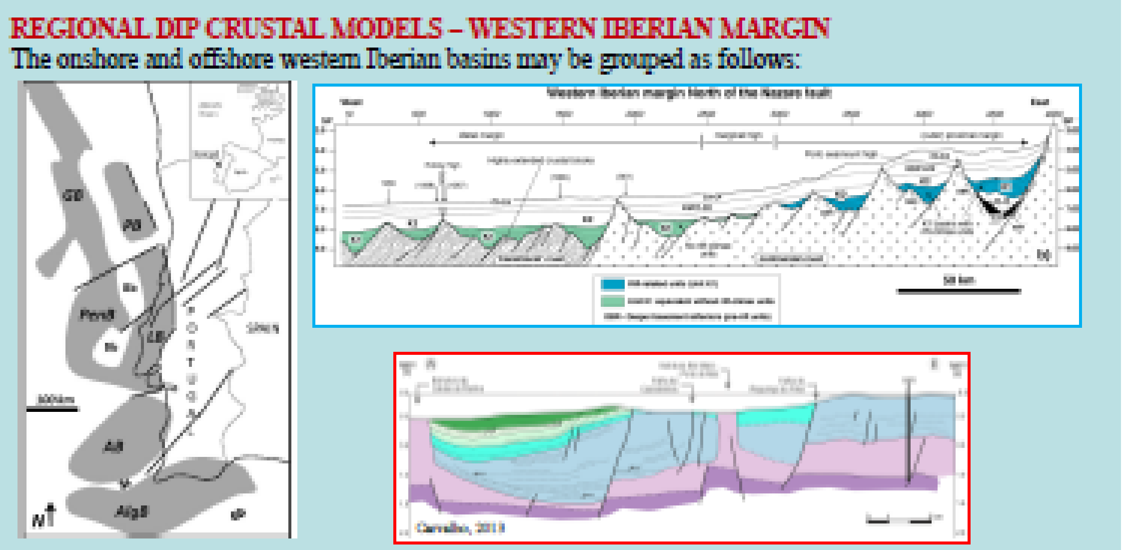


*Figure 7- Regional Dip crustal models Western Iberian Margin After Pereira, 2013. (Left figure) After Alves et al., 2006 (right figures)*

## Peniche basin evolution and stratigraphy

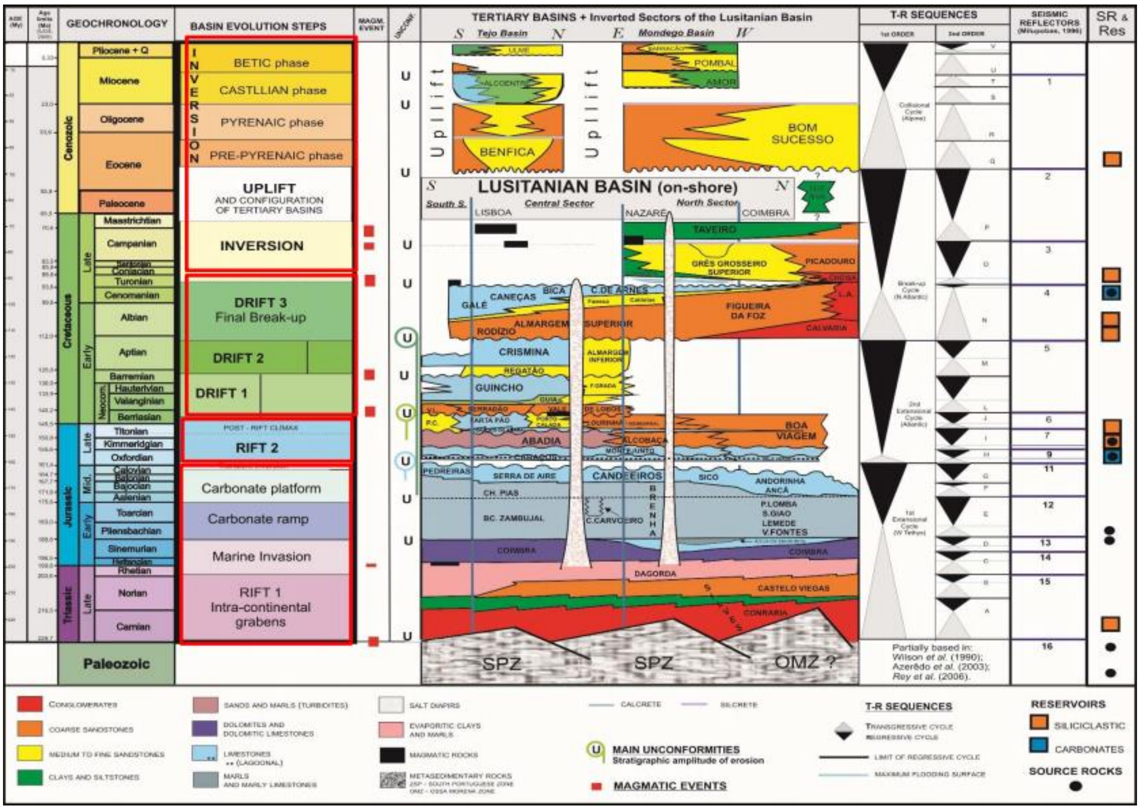


*Figure 8- Lusitanian Basin Stratigraphic chart - Pena Dos Reis & Pimentel, 2016*

In Upper Triassic the basin differed as result of crustal thickening which gave rise to a “groove” of intra-continental rift (in e.g. Alves *et al*, 2002). This structure evolved quickly to epicontinental sea depression (from siliciclastic deposits to carbonates), in connection with the western Tethys domain, following an increase in subsidence at the beginning of the lower Jurassic. There was a second extensional event with a distinct geodynamic control that triggered the Atlantic reorientation of the basin from the Upper Jurassic (Pena dos Reis *et al*, 2000).

This reorientation has meant that there has been an evolution during the lower Cretaceous to a passive margin along three segments aligned from South to North and temporarily successive. From the Middle Cretaceous, the tectonic inversion of the basin originated uplift, with exposure of vast areas of the basin and subsequent erosion, which resulted in a significant accumulation of siliciclastic sediments in areas presently immersed (in e.g. Pinheiro *et al*, 1996). The tectono-sedimentary evolution of the basin and the successive paleoenvironments originated, gave origin to the different elements of the petroleum systems recognizable in the Lusitanian Basin. Generating rocks, reservoirs, maturation phases, traps, as well as other integral elements and processes, show close relations with the mentioned phases of the Mesozoic and Cenozoic evolution of the Lusitanian Basin. This understanding is essential for understanding these systems and for the exploratory approach to be developed in the future, both onshore and offshore. Peniche Basin probably has the same evolution but a little bit late and the facies were more deeply than the Lusitanian Basin.

## Petroleum systems

In the Portuguese basins, petroleum source rocks and live migrated hydrocarbons are encountered in the pre-salt and in the post-salt sequences.

a) Pre-salt: Source Rocks are Silurian and Carboniferous Shales; Reservoir Rocks are Late Triassic Alluvial Sandstones; Regional Seals are Hettangian Marls and Evaporites.

b) Lower Jurassic Petroleum System: Source Rocks are Pliensbachian marine marls; Reservoir Rocks are Cretaceous Alluvial Sandstones; Seal made by Maastrichian transitional clays; Trap delineated by salt architecture.

c) Upper Jurassic Petroleum System. Source Rocks are Middle Oxfordian lagoonal limestones;

Reservoir Rocks are Oxfordian/Kimmeridgian fractured limestones and turbiditic deltaic sandstones;

Seal are Kimmeridgian Marls; Trap defined by inverted anticlines.

These three petroleum Systems have been identified onshore and are expected to be present along the offshore basins, probably with some stratigraphic and shifts related with their inner/outer position regarding the margin's evolution. The Peniche Basin appears for most intervals to contain similar siliciclastic reservoir units as the Alentejo Basin (or the Jeanne d'Arc Basin) due to similar rift basin development. The interpreted Lower Cretaceous (Alves *et al*., 2006) delta sequence that built out into the Central Peniche Basin is the most notable difference. This sequence is probably the equivalent of the Torres Vedras Formation in the Porto Basin.

Another difference is the extremely thick Upper Cretaceous succession that has been interpreted in the South Peniche Basin (Estremadura Spur), where massive sandstone units could be encountered. Turbidites of the same age are seen further to the north. The Tertiary succession is thin. Massive submarine erosion has taken place. Seismic data indicate possible carbonate build-ups in the Upper Cretaceous that may form reservoirs.

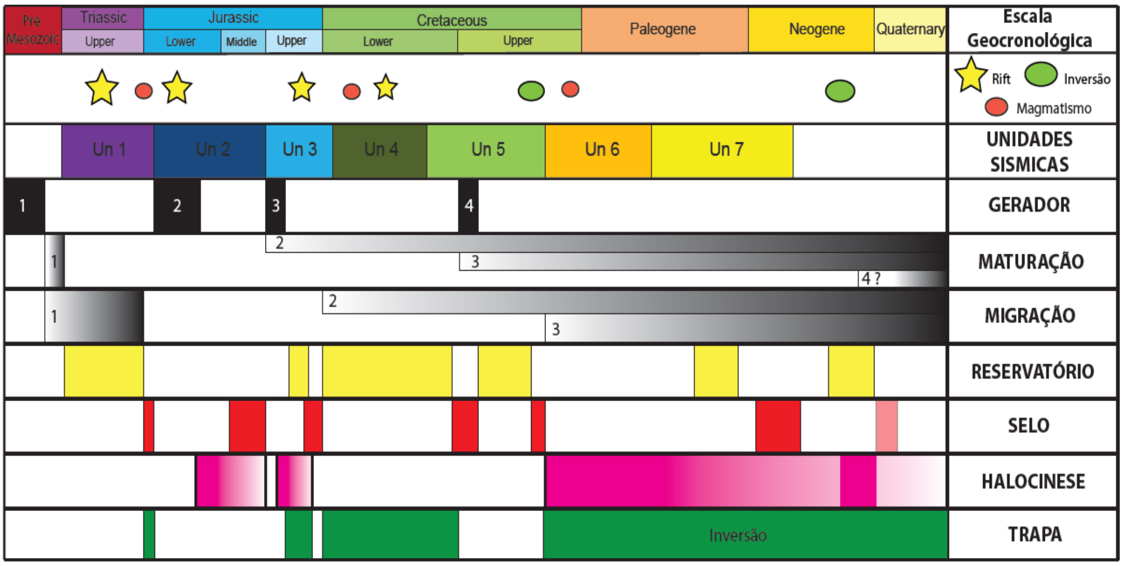


*Figure 9- Peniche Basin Petroleum system chart from Petrobras Exploration report 2010.*

## Continental margin overview

Amongst the several un-explored basins that developed along the western Iberia margin, the most important are the Lusitanian Basin and the offshore Peniche Basin, geographically linked and parallel to each other and both being the focus of contemporaneous exploratory efforts. They are situated along the western Portuguese coast and their origin are related to the opening of the North Atlantic Ocean.

These basins formed as a rifted, essentially non-volcanic, Atlantic continental margin type, trending dominantly on an N-S orientation. The basins are geographically near and roughly parallel to each other, corresponding to the inner and outer marginal sectors. Sedimentary infill comprises siliciclastic, carbonate and hybrid sediments, with deposition and unconformities related to major tectonic events. Among these, the Late Triassic intra-continental rifting, the Early and Middle Jurassic sag basin development, the Callovian Unconformity, the following Late Jurassic rifting and intense subsidence, the Early Cretaceous siliciclastic progradation, the Late Aptian Break-up Unconformity and the Campanian early inversion Unconformity, may be identified with different signatures all over the margin’s basins. Tertiary deposits are significant in most of the offshore basins and tectonic inversion affecting these basins had Late Eocene and Late Miocene alpine climaxes (Pena Reis, Pimentel, Fainstein, Neves, 2016).

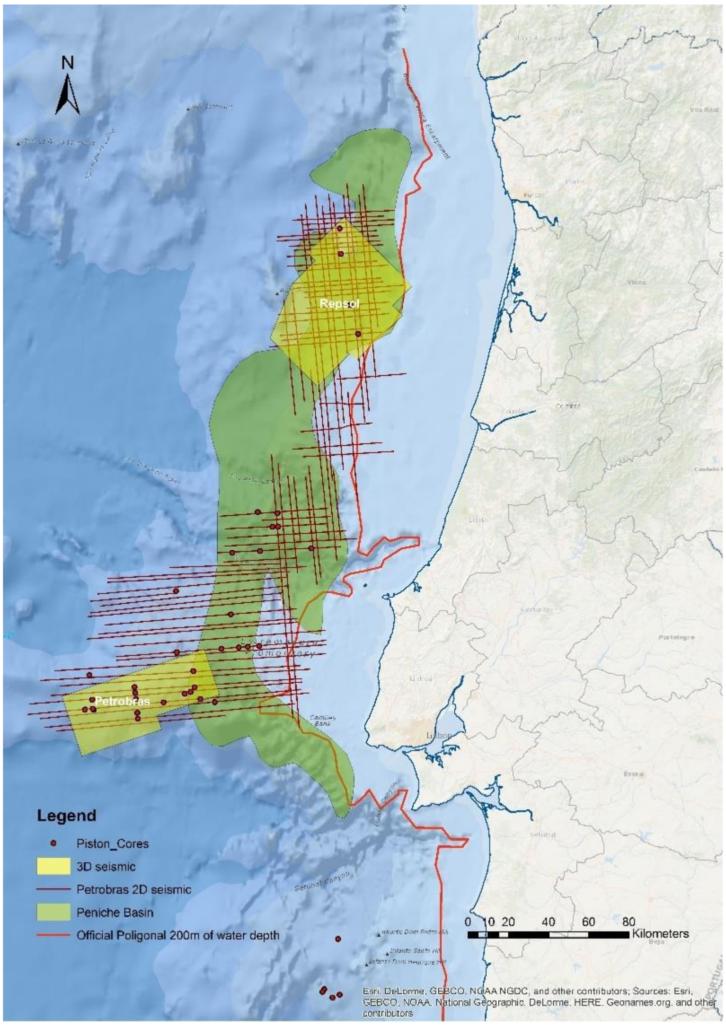
In the western Iberian Portuguese Margin evaporites sequences are seen throughout the whole of Lusitanian Basin on outcrop exposures and concepts inferred from these deposits may be extended towards the overall view of basin architecture both onshore and offshore. Interpreting these offshore deep-water basins with modern data recently acquired for seismic exploration leads to an overall comprehensive view of the salt tectonics in the Peniche Basin and in the offshore continuation of the Lusitanian Basin. Towards south the Algarve´s Basin structural shaping is also strongly affected by active salt motions.

## Petroleum Exploration History in Peniche Basin

In this thesis, the discussion is around the petroleum potential and prospectivity of the Peniche Basin, and identification of the petroleum system(s) existing in the basin.

As an un-explored basin, without any wells drilled, the identification of its petroleum potential is made through geophysics analyses and interpretation also with the surrounding nearby Lusitanian Basin and conjugate analogue, Jeanne D´arc Basin.

Below there is a brief description of its exploration history and potential hydrocarbon assessment.Peniche Basin as a deep offshore basin, has a short but very interesting history of petroleum exploration.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors; Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

*Figure 10- Base map with the latest data acquired in (Petrobras*

The first concession acquired in this basin (same areas of Figure 1) was in 2007 by the consortium led by Petrobras. This company shown interest after their huge Pre-salt discovery in Tupi field – Brazil.

Under this concession were acquired 2000 km$^2$ of 3D seismic, 42 Piston cores to collect samples of sea floor to obtain geochemical, dating and heat flow analysis and almost 9000 km of 2D seismic (Figure 10 ) and were identified several potential prospects. One year before the Petrobras scandal, the concessions were transferred (farm-in by

Repsol and farm-out by Petrobas) to its new operator Repsol, and in 2015 were acquired 3000 km$^2$ of 3D seismic.

In the present year (2018) the consortium composed by Repsol (34%), Kosmos (31%), Galp (30%) and Partex (5%) has withdrawn the areas but several important companies have showed interest in Peniche Basin.

## Exploration Wells- Lusitanian Offshore

Juxtaposed basin, offshore Lusitanian Basin has seven exploration wells that showed oil and gas on production tests (Figure 11).

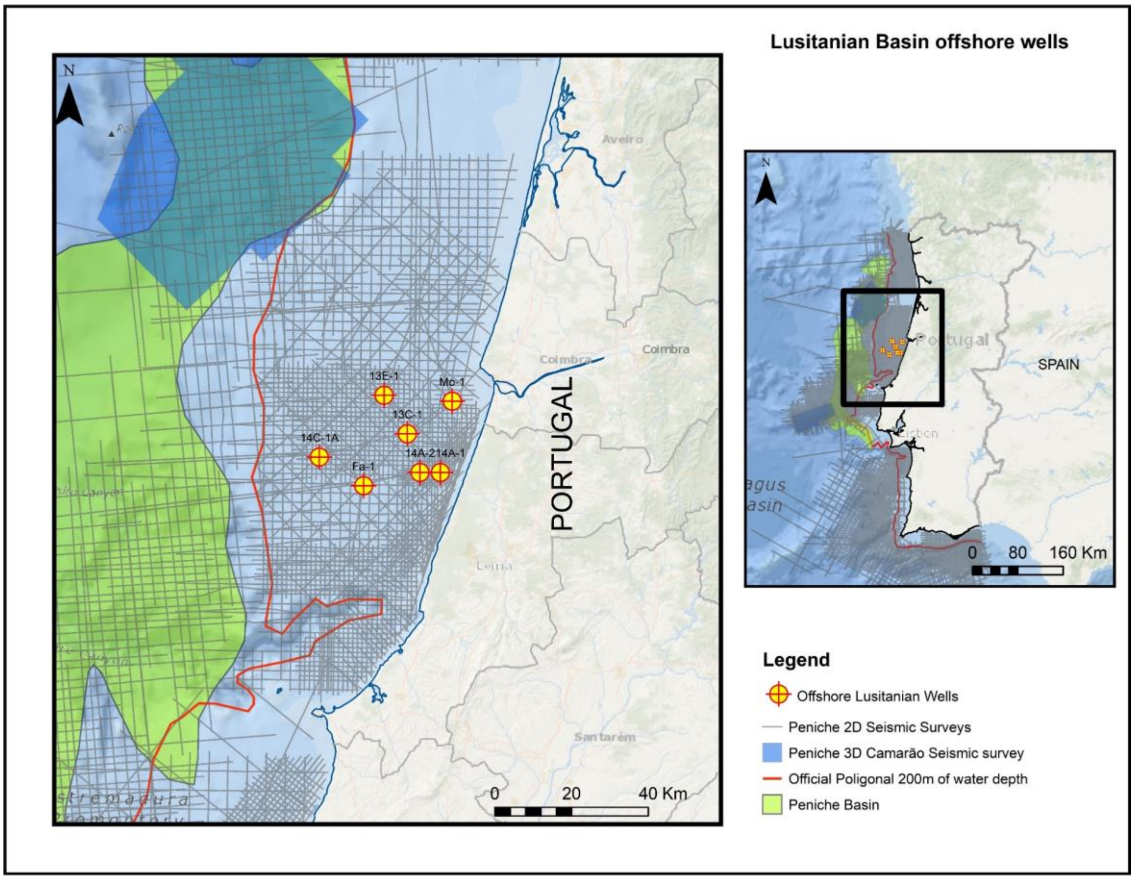


Figure 11- Location of the Lusitanian Offshore wells with significant oil and gas shows

The majority of the offshore wells drilled within the Lusitanian Basin are found within this province (Figure 11 and Figure 12). The most active operator in the 1970 was Shell which drilled six wells in this area during a short period from 1974 to 1977. This geological province is seen on seismic sections to display a structural style characterized mainly by salt movements, and the wells have been drilled mainly on such structures.

The first offshore well in Portugal was the Moreia-1 (Mo-1) well (Figure 11 and Figure 12), spudded in March 1974. It was drilled on an anticlinal fold bounded on the east by a fault. The closure comprised the top of the Lower Jurassic and the Middle Jurassic and fault closure was probably present on the Cretaceous. Oil was recovered on the drillstem test of the Upper Jurassic with good porosity and was therefore considered as a potentially commercial hydrocarbon reservoir for offshore Portugal.

The Faneca-1 (Fa-1) well (Figure 11 and Figure 12) was expected to evaluate the pre-Upper Cretaceous Mesozoic series involved in an anticlinal closure, which is faulted below the Cimmerian Unconformity. The main objective was the Lower Jurassic carbonate section. The secondary objective was the Pre-Salt Triassic continental sands. Although generally tight, the Lower Jurassic limestones and dolomites make up a total of net porous reservoir of 33.8 m. However they are in thin intervals and entirely water saturated.

The main drilling objective for well 13C-1 (Figure 11 and Figure 12) was the post-salt sequence, in particular the Cretaceous and Upper Jurassic clastics. The well was also, however, planned to investigate the pre-salt sequence, with the Triassic clastics as the secondary objective.

The 13E-1 well (Figure 11 and Figure 12) drilled the crest of the second largest anticline, located some 12 km NW of well 13C-1. The well 13E-1 tested the Lower Cretaceous and Upper Jurassic clastics, the Lower Jurassic carbonates and drilled through to the Upper Triassic salt. The well tested both the Lower Cretaceous and Upper Jurassic clastics in a good structural position. Although reservoir characteristics were favorable, only some very weak asphaltic stains were observed in the Lower Cretaceous and no hydrocarbon indications were recorded in the Upper Jurassic. Well logs proved both intervals to be water-bearing.

Well 14A-1 (Figure 11 and Figure 12) located on a complex overthrust anticline in a deep paleo-basin, tested a thick Jurassic carbonate sequence down to the salt. The well reached a total depth of 2862 m. While drilling some oil and gas shows were detected. Subsequent testing, consisting of 2 DST’s (recovery 290 litres of oil from tight Lower Jurassic carbonates) and 5 FIT’s (Formation Integrety Tests) in the Upper Jurassic (no hydrocarbons recovered) failed to encounter any significant quantities of hydrocarbons and the well was plugged and abandoned.

Well 14A-2 (Figure 11 and Figure 12) tested the primary objective, the Coimbra Formation in a crestal position and in a lower fault-block but found in both cases the carbonates to be tight.

Well 14C-1/14C-1A (Figure 11 and Figure 12) tested the post-salt sequence near the apex of a fault-bounded anticline, at the western margin of the salt basin. The well encountered no hydrocarbon indications and was abandoned as a dry hole. The temperatures recorded in the well are relatively low, and no good source rocks were observed.

Well 16A-1(Figure 11 and Figure 12) tested the post-salt Mesozoic and Cenozoic sequence of the Lusitanian basin at the crest of an anticline situated near the western basin margin. High resistivities were encountered in fractured limestones of the Cacém Formation but subsequent DST’s recovered only water. Minor oil stains were observed in tight dolomotic limestones of the Lower Jurassic Coimbra Formation.

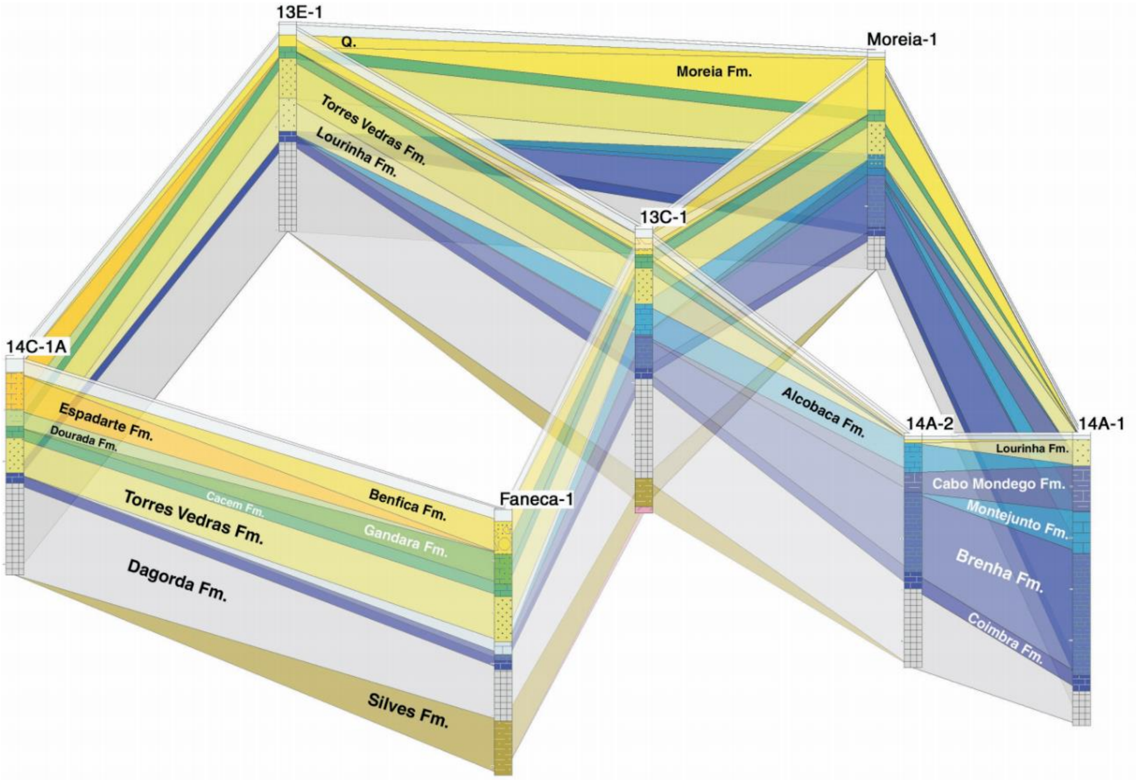


*Figure 12- Fence diagram showing the correlation of informal formations and groups for the wells in the central salt region in the Lusitanian Basin. Blue: Jurassic, green: Cretaceous and yellow: Tertiary to Recent units. A thick Dagorda salt section dominates at the expense of Jurassic units. This may be partly an effect of the wells being drilled on salt cored anticlines that have been truncated by the Base Cretaceous Unconformity. The Jurassic succession generally thickens towards the coast, while the opposite is the case for the Cretaceous succession. – image taken from TGS-NOPEC Evaluation Report*

## Salt Tectonics

Evaporites accumulation in the Western Iberian Margin, took place since the Late Triassic (Norian?) until the Early Jurassic. Salt resulted from intra-continental playa lakes and mudflats with evaporites and clays, gradually passing into costal sabkhas with evaporites and dolomites. Original thickness of this salt-rich unit (Dagorda Formation) is believed to have reached hundreds of meters, eventually up to 1 km or more in some depocentric areas. Massive salt originated below the Jurassic originated salt diapirs rise through basement rooted fractures, crossing and deforming the whole Mesozoic sequence.

Salt tectonics may have started since the Early to Middle Jurassic, as salt irregular pillows accommodating differential subsidence. This incipient stage has been strongly incremented during the Late Jurassic, in relation with the rifting phase and intense extension, subsidence, infill and overburden. Salt pillows have been accentuated and significant salt motion begun. The role of late-hercynean basement faults, affecting the Mesozoic cover, has been crucial in defining the locus of the salt pillows. Salt withdrawal and vertical up-rise of the salt units. Vertical motion continued throughout the Cretaceous and in some diapirs piercing has been attained. The timing of this piercing is well constrained by onshore lithostratigraphic references and may be dated from the Maastrichtian. This indicates that piercing is mostly related with the beginning of tectonic inversion that continued throughout the Cenozoic.

The relationships between salt and hydrocarbon accumulations were recognized from the very beginning of oil and gas exploration. Basin's architecture clearly reflects the influence of salt tectonics, including structural anticlinal traps and stratigraphic facies variations traps. Salt pillows may have acted as regional seals for underlying units, whereas diapirs' walls have been important migration pathways, as observed in several oil-seeps (Pena Reis, Pimentel, Fainstein, Neves, 2016).

## Tectonic Evolution of Peniche Basin

The initial rifting took place during the Triassic. Above the redbeds and local lacustrine shales, a thick section of Dagorda Salt (Argo Salt equivalent) was deposited.

The basin was filled, and the topography was levelled prior to thermal subsidence leading to marine environment in the Lower to Middle Jurassic. Solid carbonate deposition took place on the rift shoulder. Some carbonates may have been deposited in the rift basin during this period, but siliciclastic sedimentation was more likely prevalent as in the Jeanne d'Arc Basin.

Carbonate growth continued the rift shoulder during the Upper Jurassic (ODP Site 901). Renewed rifting in the Upper Jurassic created accommodation space for siliciclastic sedimentation into the basin (by-passing the carbonate platform). Reservoir quality sands and organic rich mudstone (Kimmeridge Clay) were probably deposited in restrictive environments through the rift system.

A major rift phase occurred at the Jurassic – Cretaceous transition. Major rotation of fault blocks occurred, and large sub-basins were developed. Accommodation space was created for significant deposition of Lower Cretaceous siliciclastics in a marine environment; reservoir sands and intervals of mudstone with high organic content. These sediments do not show significant thickening into major bounding faults, but onlap is prevalent on all flanks of the sub-basins. Sediment influx appears not to have could keep up with subsidence.

Sediment supply was generally low during Late Cretaceous. Deep marine anoxic environment existed during the Cenomanian - Turonian throughout the Atlantic region, and a blanket of excellent source rock was deposited (DSDP Site 398). Turbidite deposition of coarse siliciclastic sediments took place in these areas. The southern end of the Peniche Basin received large volumes of sediments from the Lusitanian Basin that bypassed the carbonate platform.

Deep marine sedimentation continued during the Paleogene. Turbidites / basin floor fans were deposited, extending into the Iberia Abyssal Plain. Carbonate build-ups occurred on intra-basin highs, created by Pyrenean inversion.

Miocene sedimentation appears to have been similar to what took place in the Alentejo Basin. A substantial section is preserved in some areas, while several phases of submarine erosion have removed much of this section in extensive areas and re-deposited this material in the abyssal basins.

# CHAPTER 2 - DISCUSSION AND DATA INTERPRETATION

## Gravity and magnetics – regional interpretation mapping

Gravity and magnetics datasets were compiled and re-interpreted in this thesis for better understanding of the main structures, salt bodies, faults and fractures all within these enhanced data that were used to identify the potential prospects.

## Digital Elevation Model

The several datasets available from all distinct sources were merged with the available seismic surveys for an integrated interpretation of the geophysical data from Peniche Basin. This study therefore represents a state of art re-interpretation of all data.

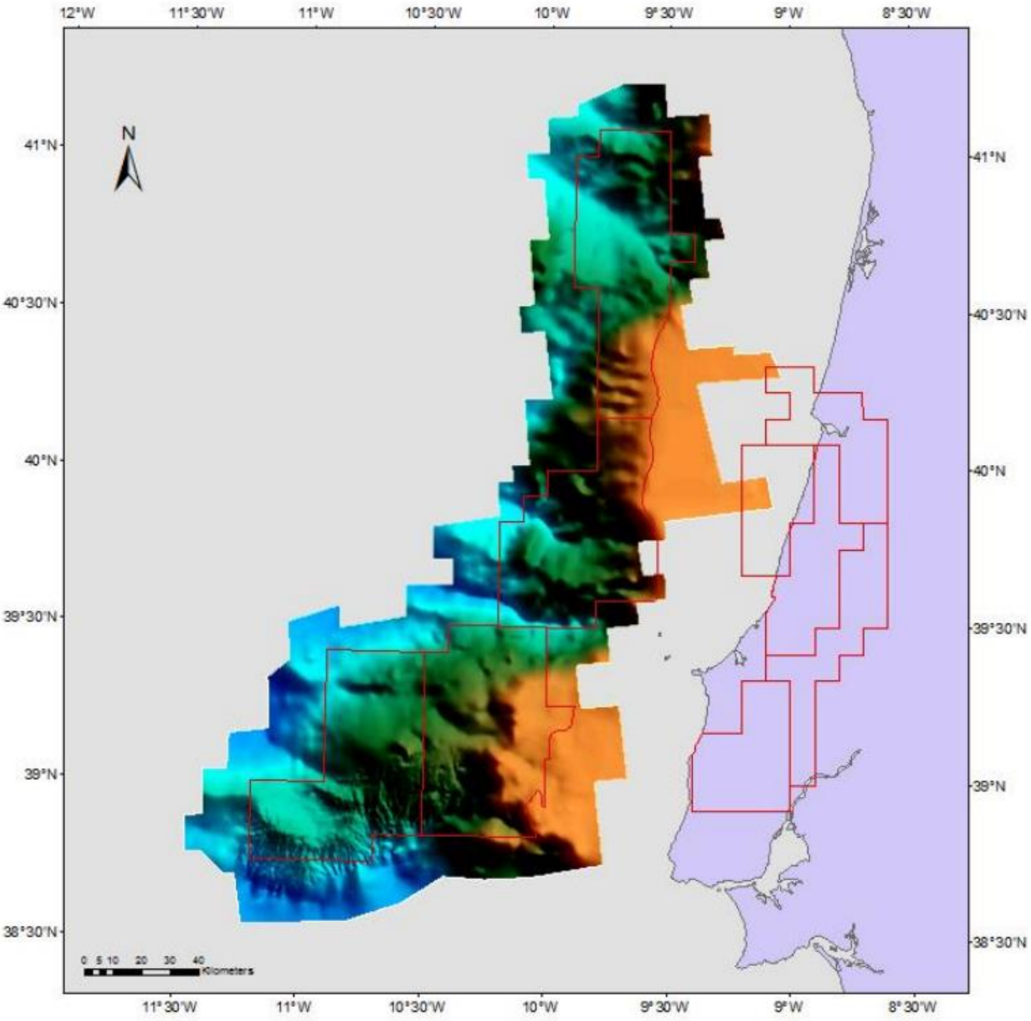


*Figure 13- Digital Elevation Model of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin.*

Gravity modelling of profiles was performed using mainly the 2D marine gravity data acquired and processed by TGS-Nopec between 1999 and 2002. Shipborne gravity and magnetic data acquired on 3D seismic survey over the Peniche Basin in 2010 and merged with 2008 2D marine gravity and magnetic data can be integrated to this gravity and magnetic modelling (figures from 29 to 37).

## Satellite Free Air Gravity

Public domain satellite derived data (Figure 14) are shown here to have a sense of structural continuity at regional scale. The map bellow shows free air gravity, measured gravity at sea level after a few basic corrections. These data are strongly affected by topographic gravity effect generated by the high-density contrast between air/water and surrounding sediments. As consequence the shelf break generates a strong gravity signature and local topographic depressions generates localized gravity lows.

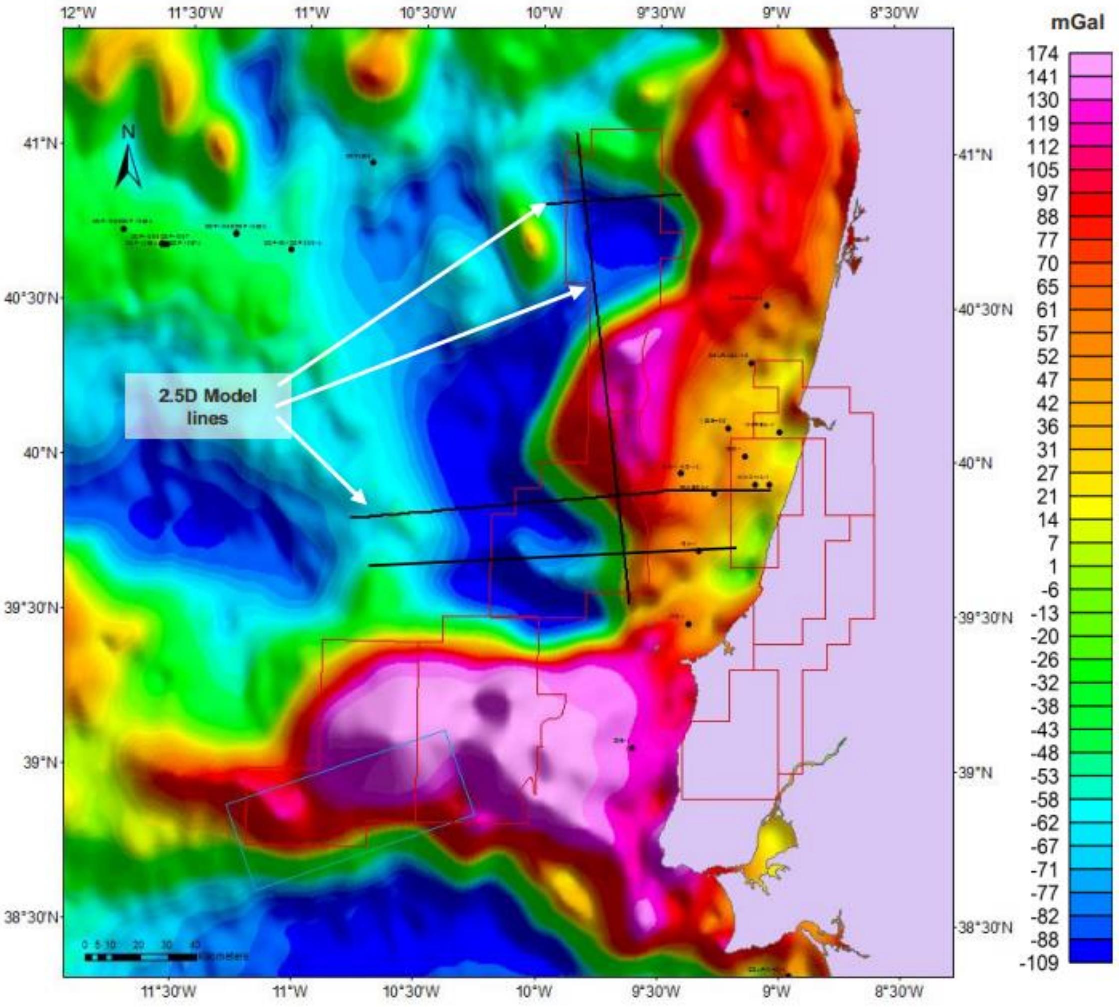


*Figure 14- Satellite Free Air Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

## Free air Marine Gravity

The map below (Figure 15) is the free air gravity, measured at sea level, corrected to produce the definitive free-air anomaly (milli gals).

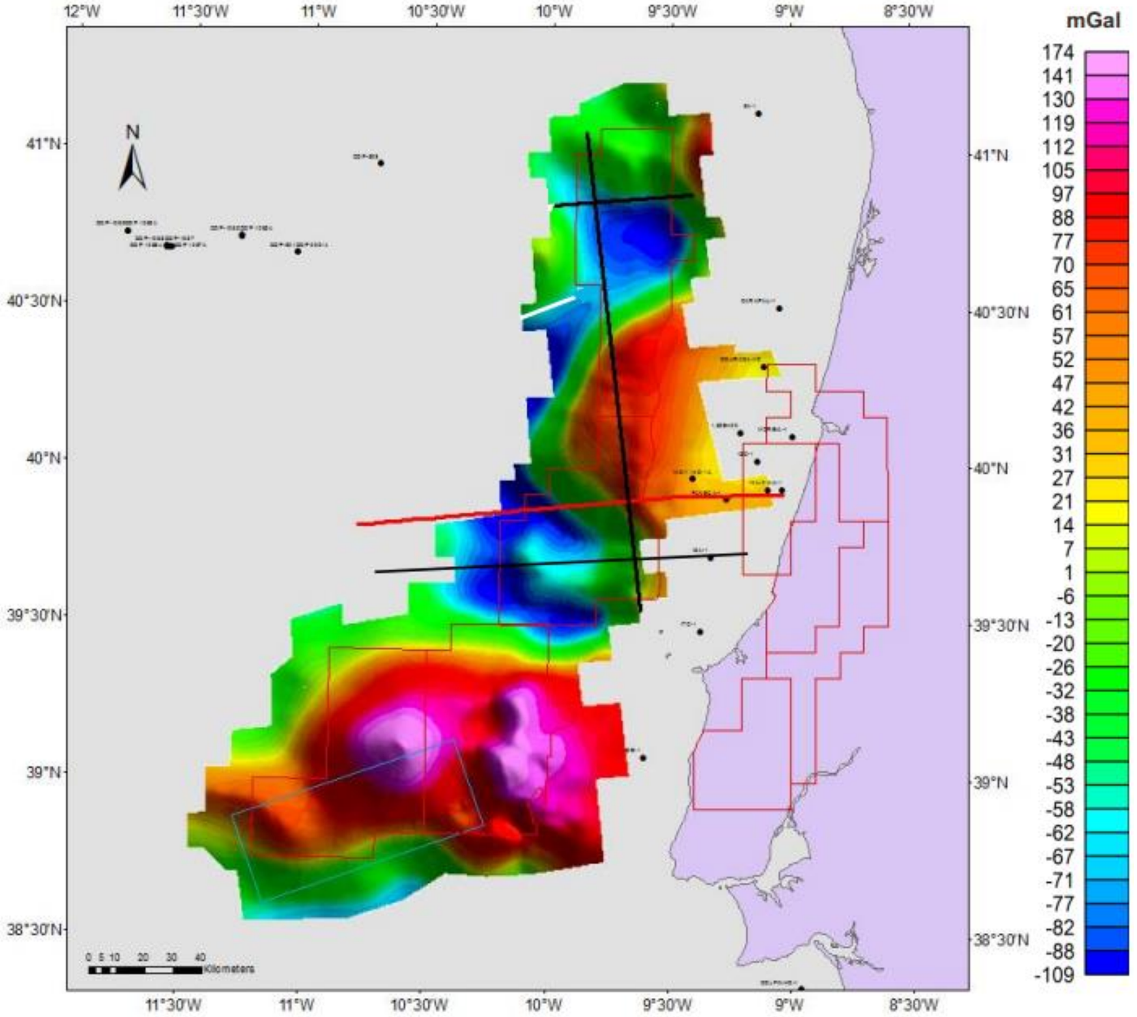


*Figure 15- Free Air Marine Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

The map strongly accentuates the topographic gravity effect generated by the high-density contrast between water and substratum sediments. The shelf break is represented by a strong gravity signature roughly parallel to the coastline and highs and lows correlate with the sea-floor topography. Fractures are seen as boundaries generally normal to the coast and delimiting the density blocks. A remarkable feature roughly in east-west direction is the signature of the Nazaré Fault.

## Satellite Bouguer Gravity

The NOAA public domain satellite derived data (Figure 16) is displayed herein below again for better sense of the main structural tectonic features and the continuity of events at regional scale.

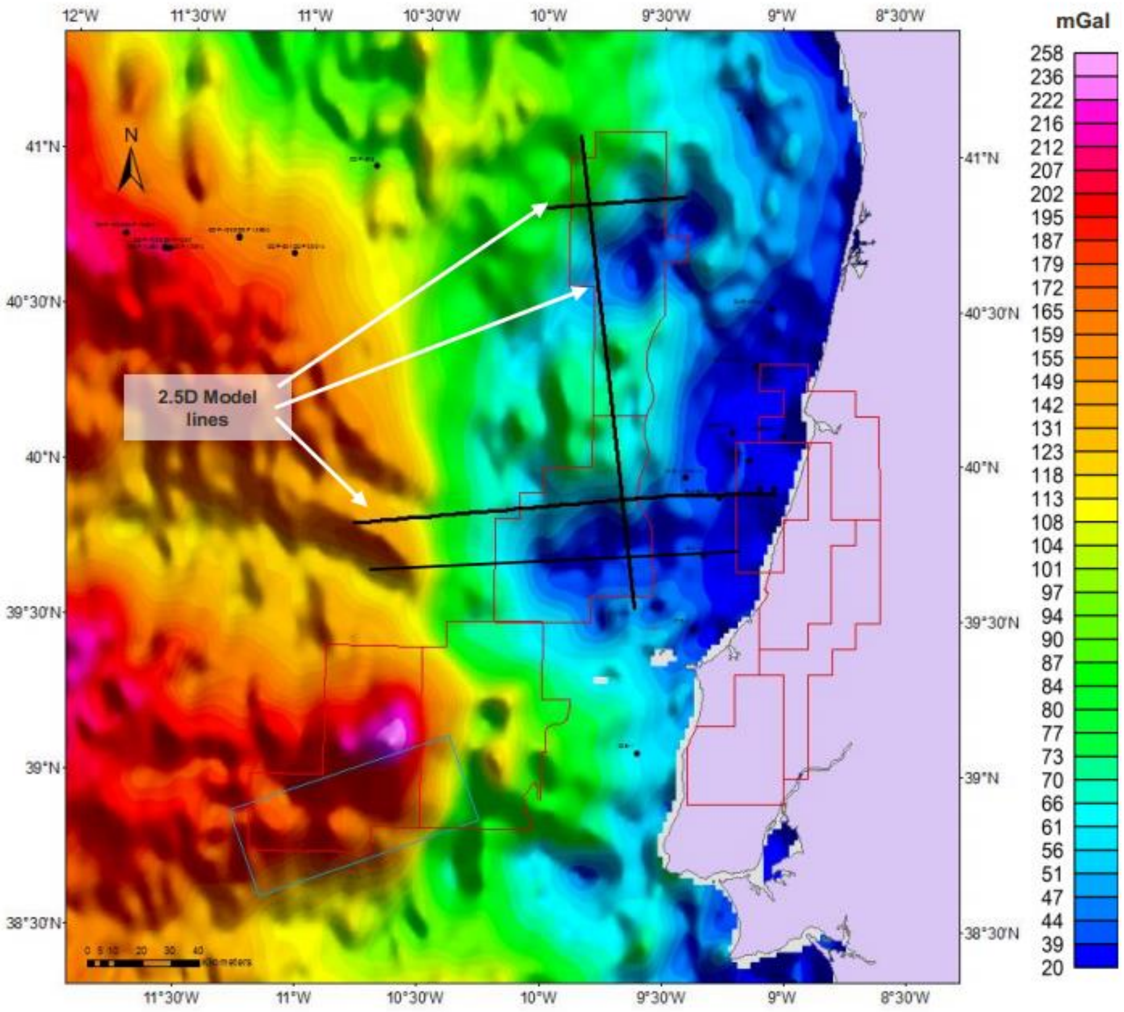


*Figure 16-- Satellite Bouguer Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

## Bouguer Marine Gravity

Bouguer gravity map is displayed below (Figure 17) strictly about Peniche Basin. The map accounts for all the corrections effected to obtain the marine Bouguer anomaly map.

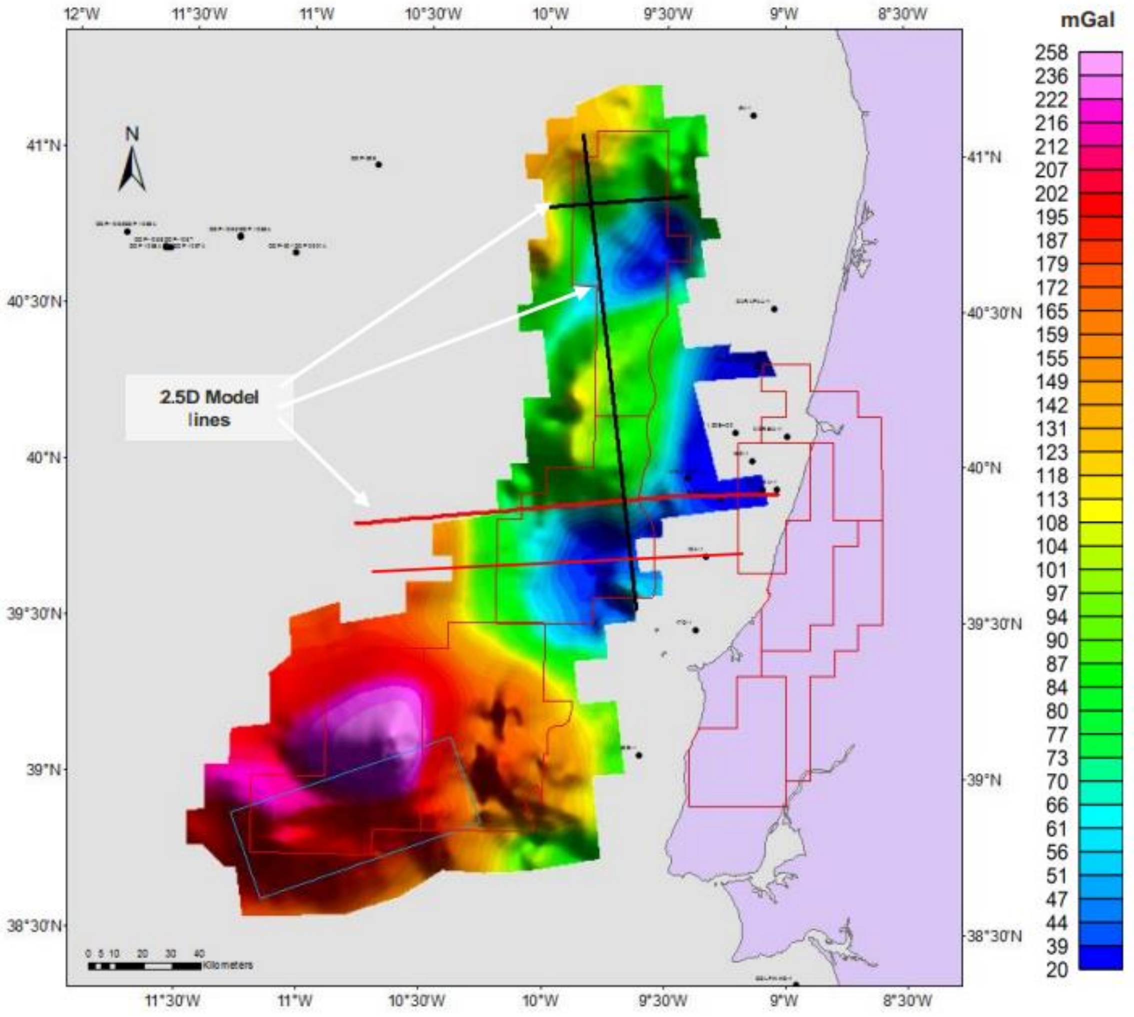


*Figure 17- Bouguer Marine Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Bouguer gravity is corrected from gravity effects generated by significant density contrasts between water/air and rocks at topography level.

Areas of minima are possibly related to basement lows and maxima to basement highs or volcanic intrusions. Long wavelengths signature related to Moho may still affect the data.

## Total Magnetic Intensity (TMI)

The map below displays the measured Total Magnetic Field at sea level not corrected to the pole (Figure 18). By contrast with the gravity maps, this is a dipole map showing pairs of anomalies (positive and negatives) for the buried bodies with larger magnetic susceptibility.

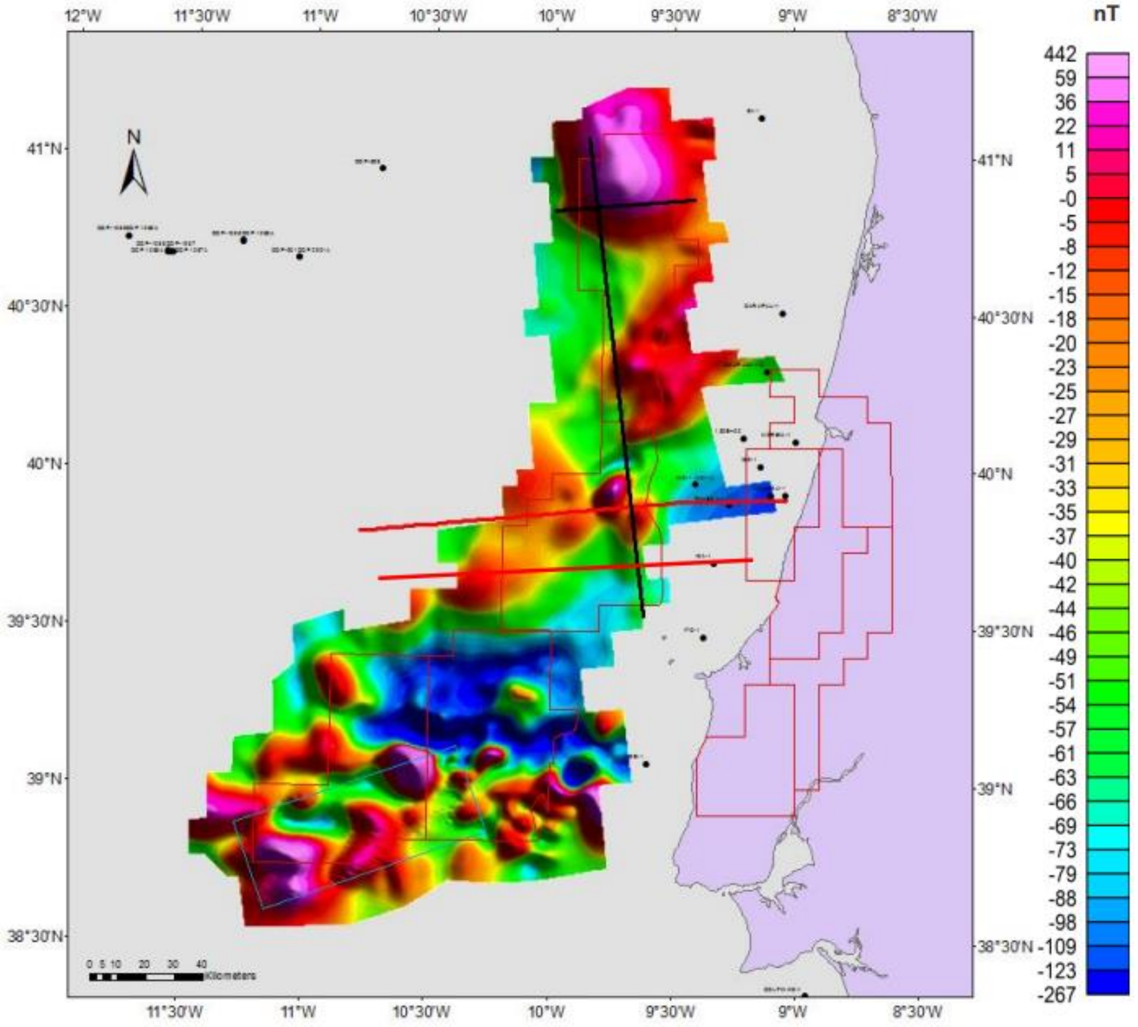


*Figure 18- Total Magnetic Intensity (TMI) of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Due to the inclination and declination of the magnetic field, TMI anomalies appear as a peak-trough pair (dipole) over the causative body, interesting to note the signature of the main fractures such as the Nazaré Fault.

The main assumption is that volcanic intrusives and basement have larger magnetization compared with the layered sediments, therefore anomalies are strictly related to such lithology.

## Vertical Gradient of Bouguer Gravity

Vertical gradient (Figure 19) is used to sharpen up anomalies, further highlight low/high gravity areas adding detailed understanding of tectonic expressions of faults and fractures.

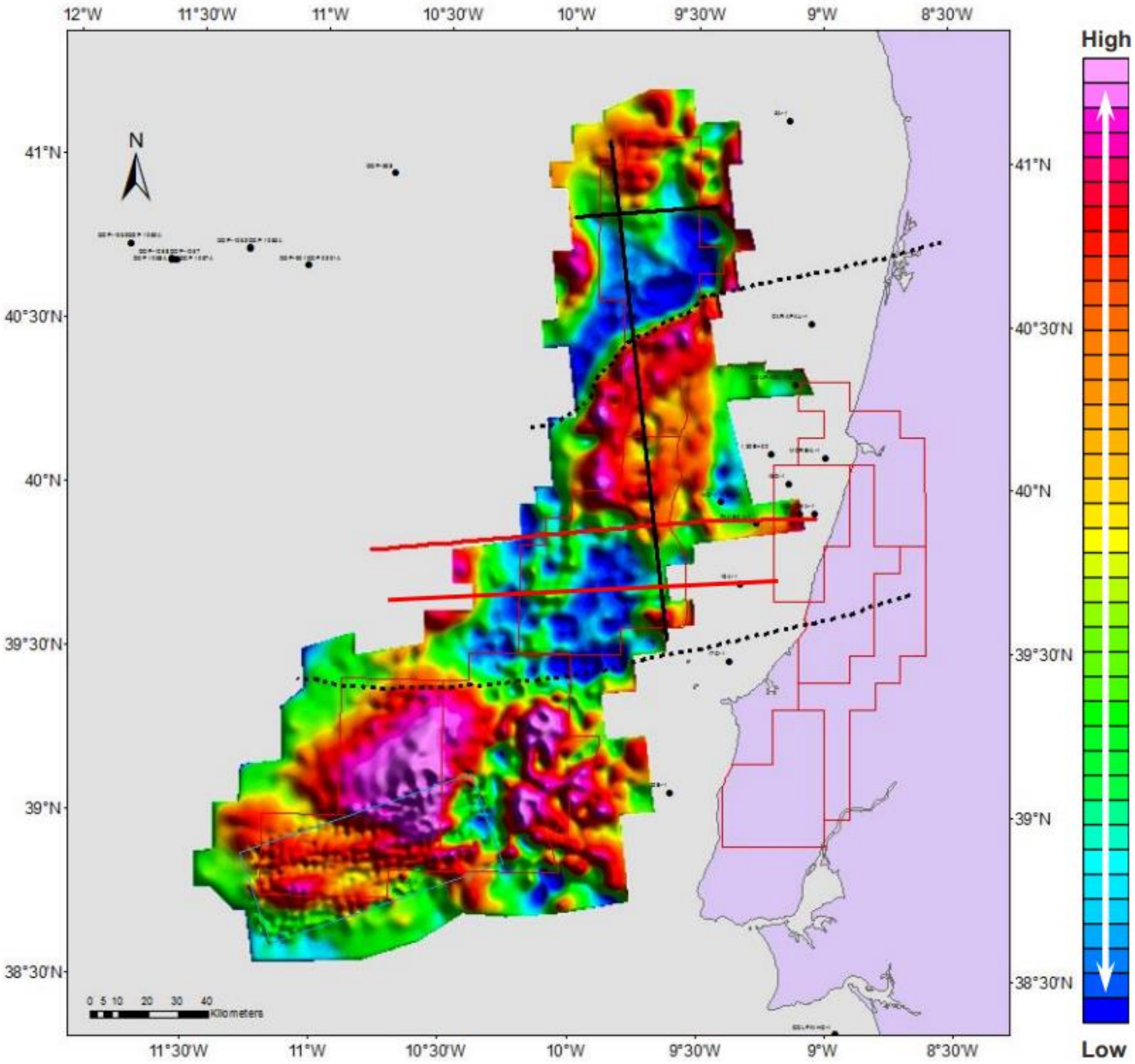


*Figure 19- Vertical Gradient of Bouguer Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Maxima relate to the body source of the anomaly, possibly tilted blocks, horst structures or anticlines, while lows may show a relationship with the basin troughs.

## Grav-Mag Data Derivatives

### Signal Derivatives:

Signal derivatives are often used to sharpen up anomalies over bodies and to reduce anomaly complexity, allowing a clearer imaging of the causative structures, e.g. VDR - First Vertical Derivative (a). However, derivatives can be noisy since it will amplify short wavelength noise.

The Horizontal Derivative HDR (b) is designed to look at fault and contact features. Its maxima indicate source edges and it is complementary to the signal filtering. It usually produces a more exact location for faults than the first vertical derivative, but for magnetic data it must be used in conjunction with the other transformations (e.g. reduction to pole RTP or pseudo-gravity). Specific directional horizontal derivatives can also be generated to highlight features with known strike directions

### Signal Filtering:

Filtering is a way of separating signals of different wavelength to isolate and hence enhance anomalous features with a certain wavelength. Therefore, it can be used to enhance anomalies produced by features in a given depth range.

The signal filtering can be either low pass (Regional) or high pass (Residual).

Band pass filtering can be used to isolate the anomalies generated in the upper crust and discriminate between structural highs and lows.

## Bouguer Gravity Residual

This is a normalized high pass residual (Figure 20) showing areas of relative structural high

These displayed in red colours. Interesting to note the resolution of the main tectonic elements such as the Aveiro Fault to the north and the Nazaré Fault to the south.

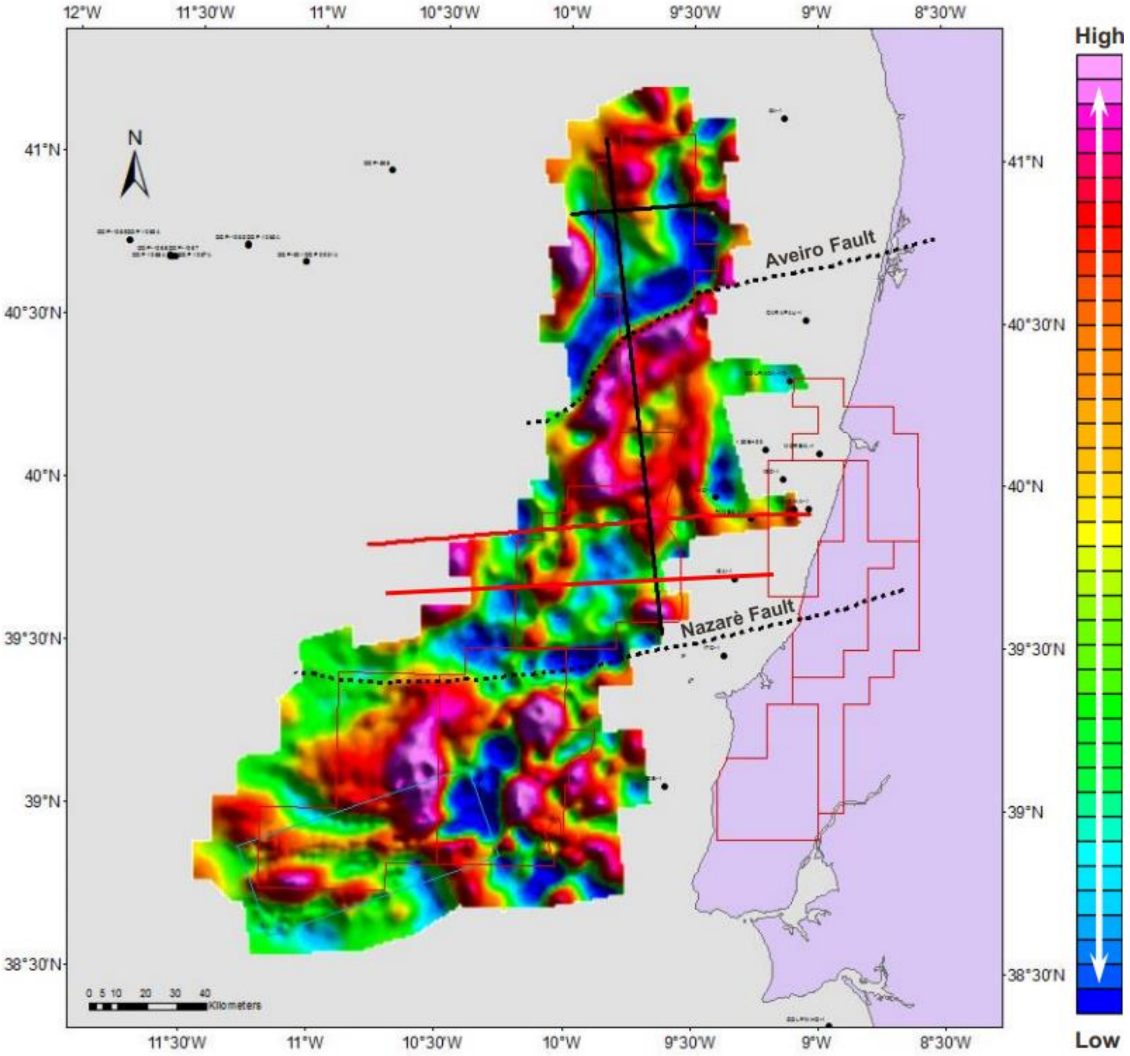


*Figure 20- Bouguer Gravity Residual of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

## Horizontal Gradient of Bouguer Gravity

Total horizontal (Figure 21) gradient is used to sharpen up anomalies to highlight the edges of gravity anomalies.

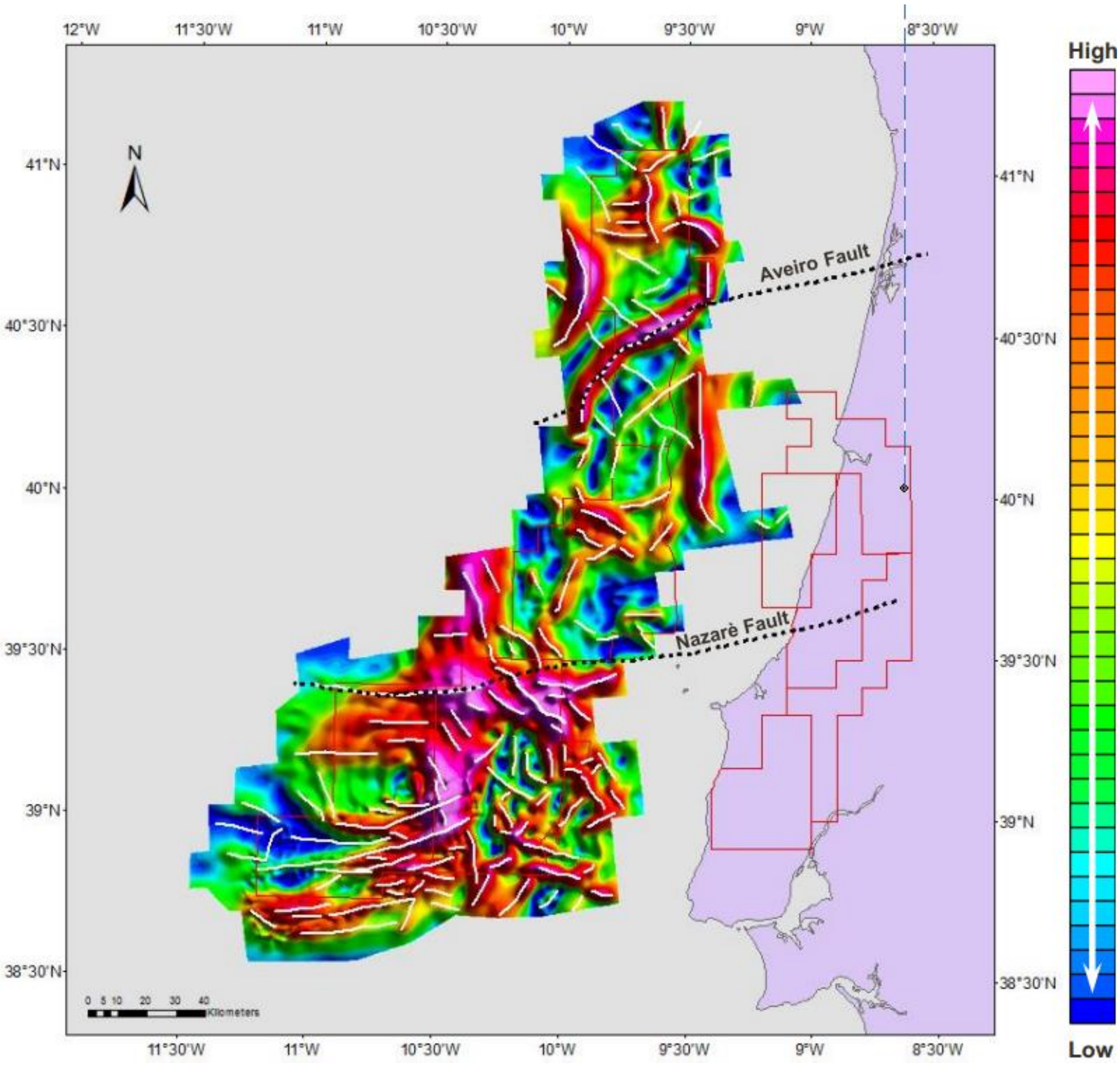


*Figure 21- Horizontal Gradient of Bouguer Gravity of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Maximum values are used to locate the edges of the source of the gravity anomalies, highlighting structural lineaments and edges of tilted blocks or horst structures.

A host of methods can be applied to pick the lineaments from this enhancement or others, however ACLAS method (Cascone *et al*., 2012) is able to compare more than one to achieve the most objective result.

## 50 km Bouguer Gravity Residual

Lineaments (Figure 22) have been mostly picked by looking at the total horizontal gradient magnitude transformation except for the enhancing of the mosaic of minor faults.

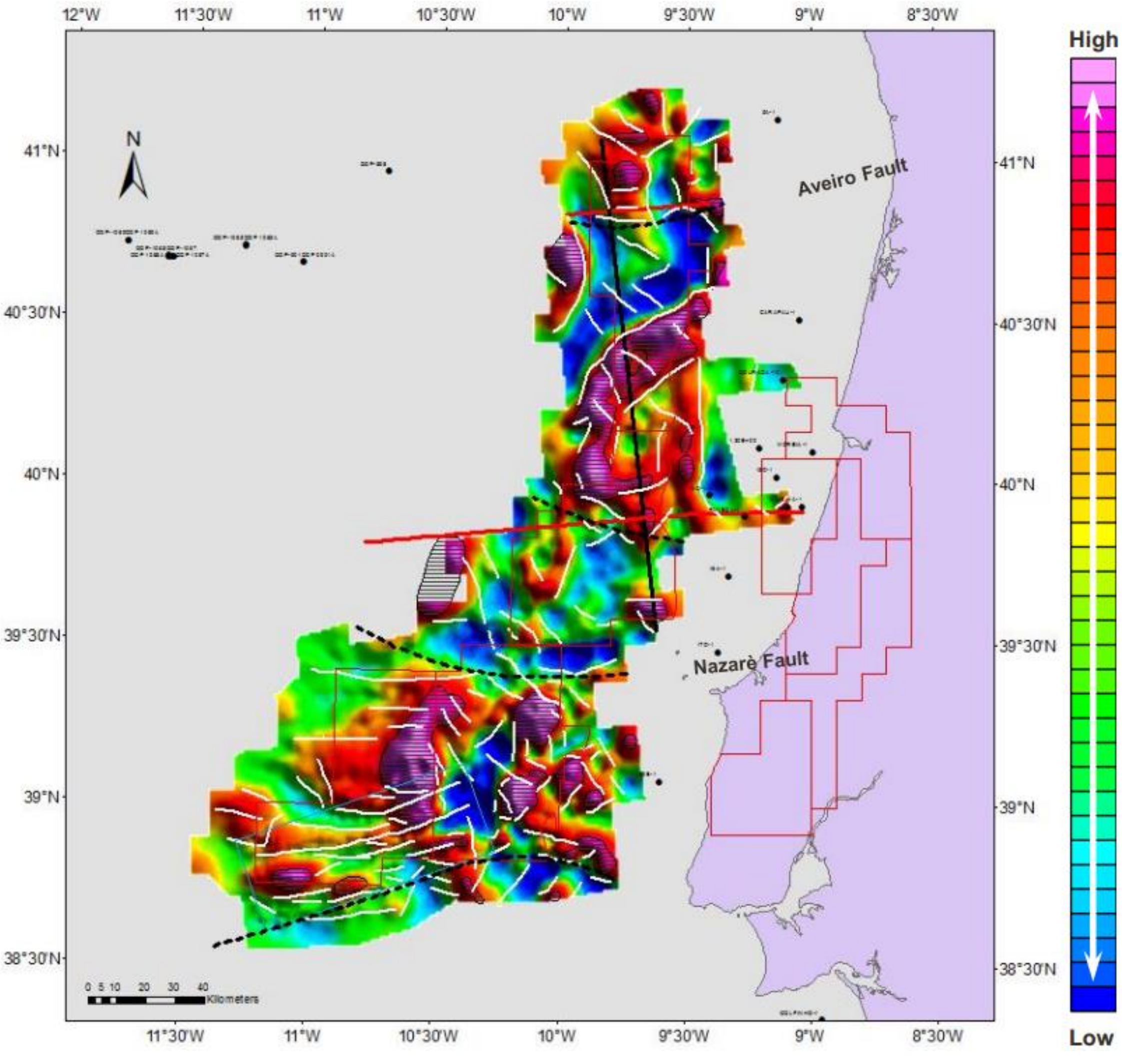


*Figure 22- 50 km Bouguer Gravity Residual of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

The mapped lineaments are very coherent with the previously shown enhanced maps and subsequent structural interpretation.

## Reduced to Pole (RTP) Magnetics

In order to center the anomalies over the source as a monopole, as would occur if the data were recorded at the North Magnetic Pole, a reduction to the pole transformation (Figure 23) is applied. This correction permits the one to one correlation with the gravity maps.

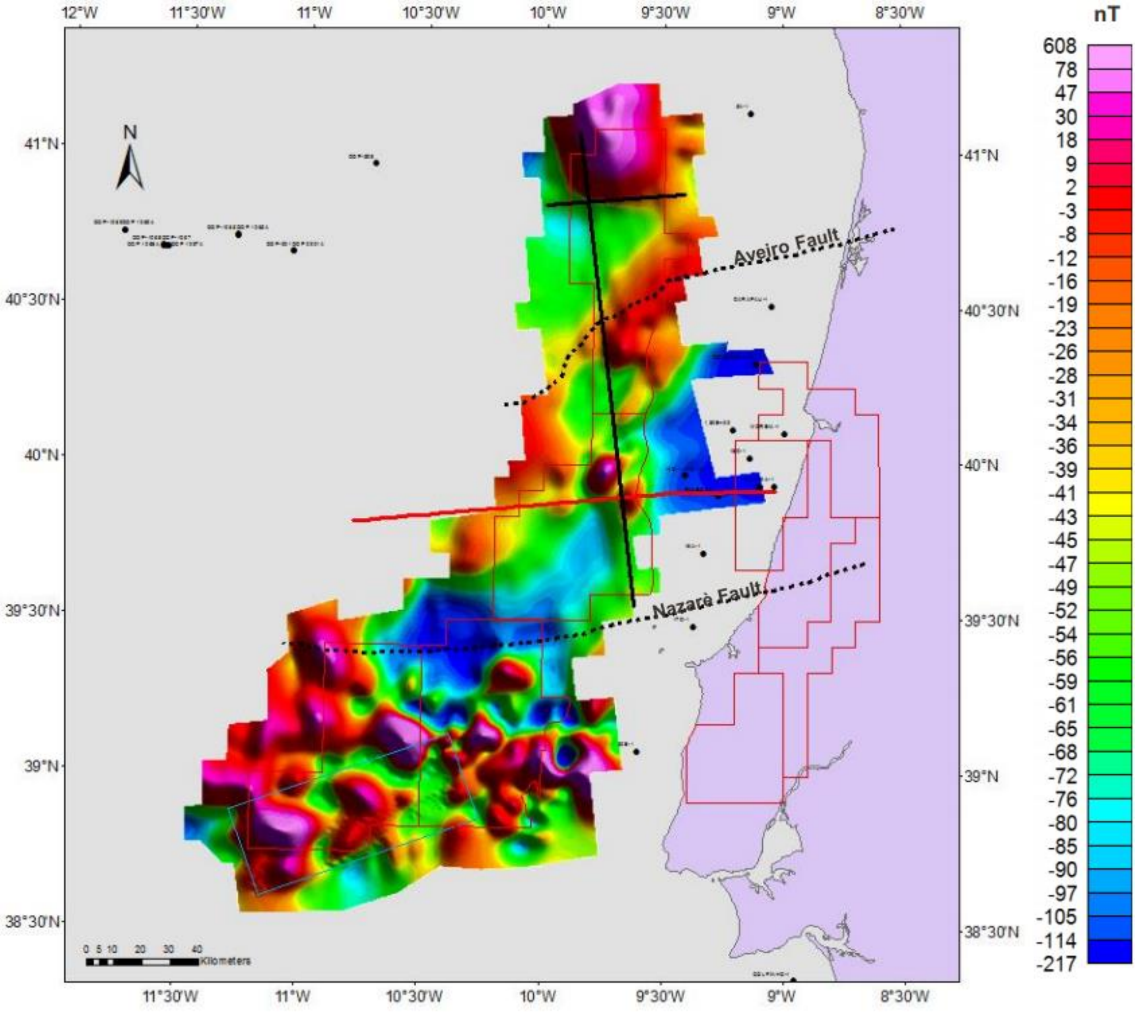


*Figure 23- Reduced to Pole (RTP) Magnetics of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Field parameters possibly used by the contractor CGG for the RTP transformation were:

- Inclination = 38,7°
- Declination = 10,2 °

These are theoretical regional magnetic field parameters at the center of the study area.

## Vertical Gradient of RTP magnetics

Vertical gradient (Figure 24) is used to sharpen up anomalies and further highlight low/high areas.

Maxima locate over the body source of the anomaly, possibly tilted blocks or horst structures, while lows may show a relationship with basins or troughs.

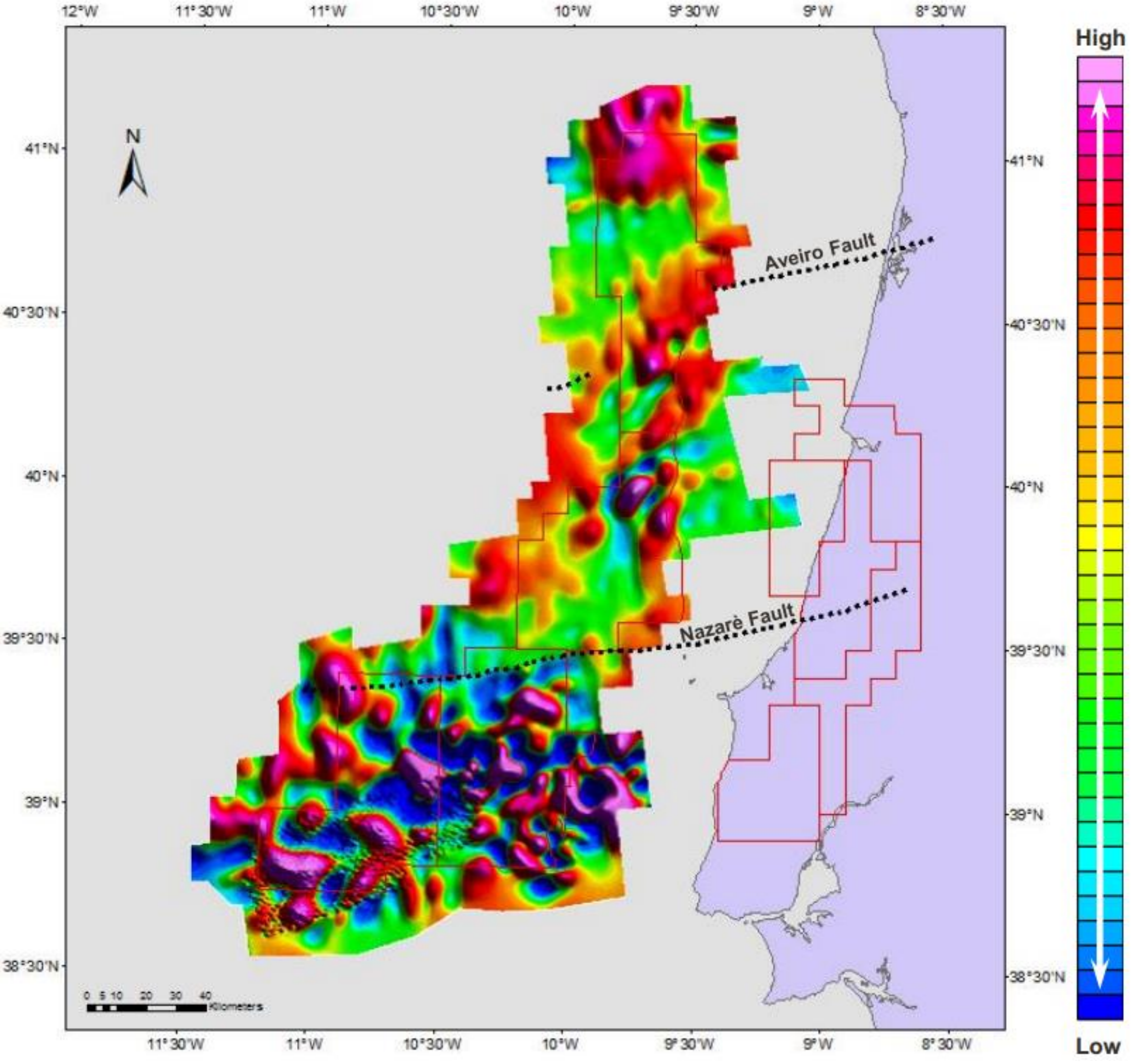


*Figure 24- Vertical Gradient of RTP magnetics of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

## RTP Magnetics Residual

This is a 50 km wavelength high pass filtering (Figure 25) and it is used to sharpen up anomalies and further highlight relative low/high areas.

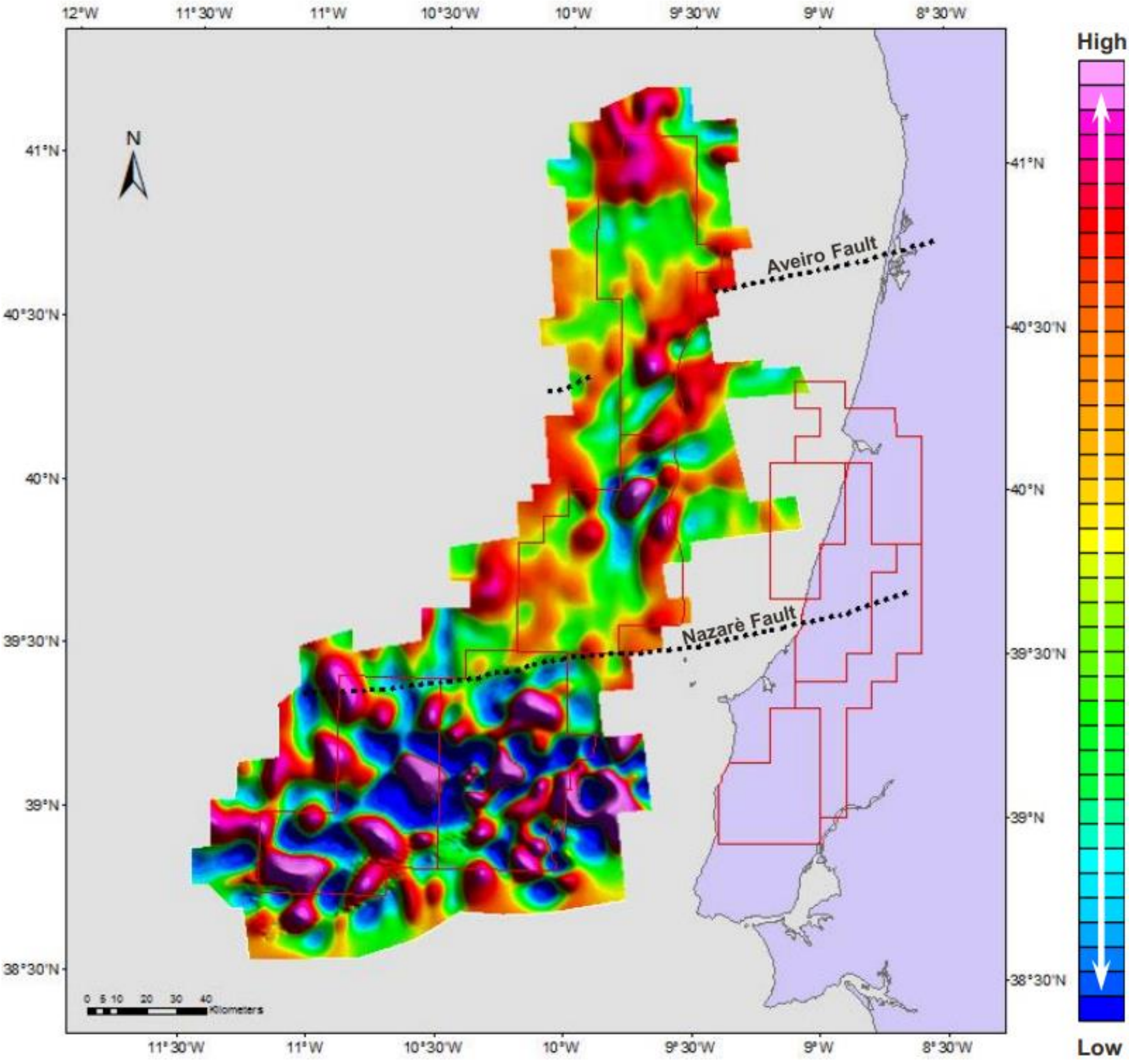


*Figure 25- RTP magnetics Residual of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

Maxima locate over the body source of the anomaly, possibly tilted blocks, horst structures or anticlines, while lows may show a relationship with basins or troughs.

## Basement depth Estimation

The SPI method (Thurston and Smith, 1997) uses second-order derivatives of the total field and a term known as the local wavenumber to provide an estimate of the location of the buried magnetic bodies. The local wavenumber has maxima located over isolated contacts and depths can be estimated without assumptions concerning the thickness of the sources.

The analytic signal method (Salem and Ravat, 2003) is quite good for interpreting magnetic data over 2D geological structures. For these structures, depths can be obtained from the width of the analytic signal anomalies or even based on the ratio of the analytic signal to its higher derivatives once the source type is assumed. The advantage of the analytic signal method is that the method does not require specific knowledge of magnetization direction and, therefore, it is useful in cases of remnant magnetization or for data acquired at low latitudes such as in the Peniche Basin (Figure 26).

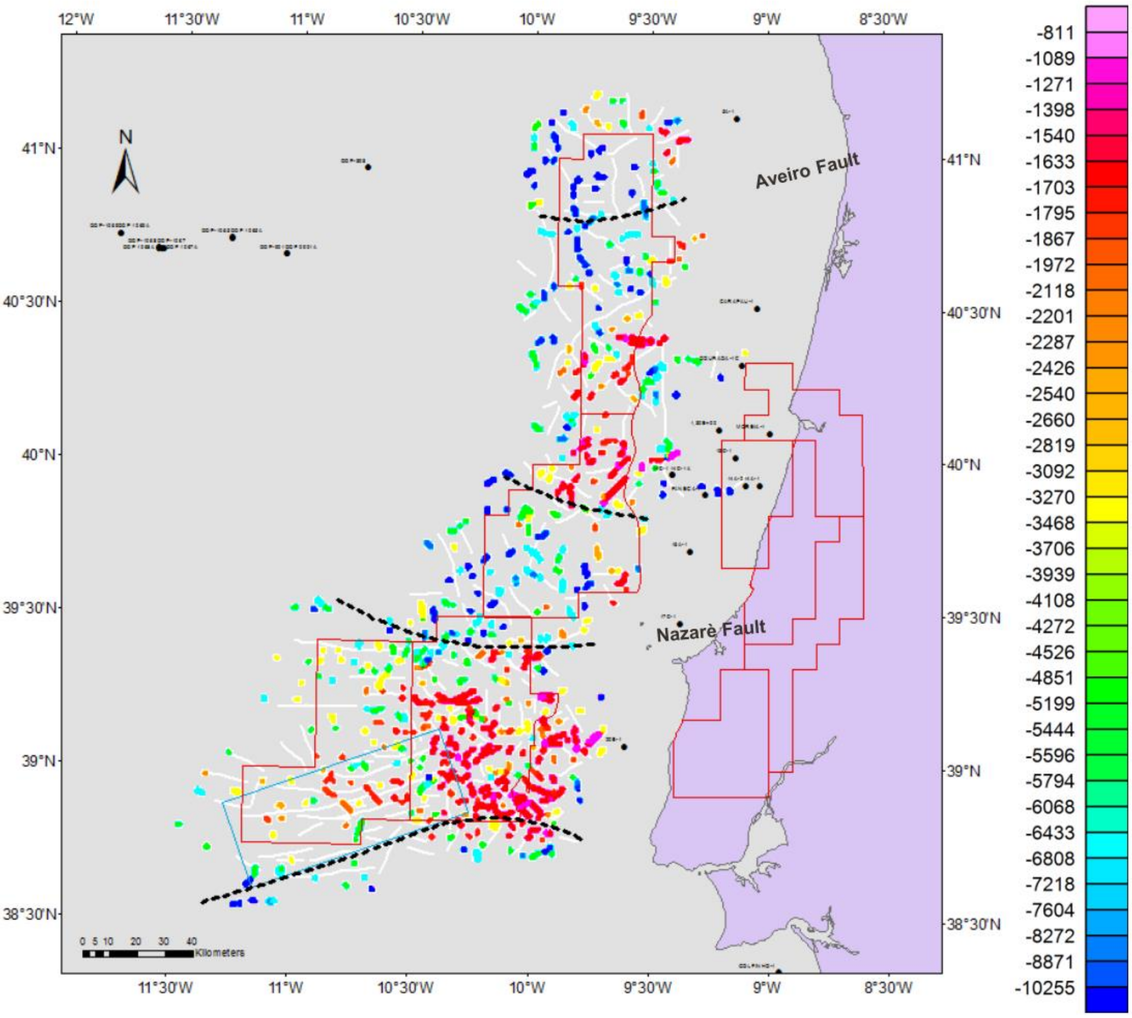


*Figure 26- Magnetics depth estimates upon magnetic lineaments*

Basement depth estimates are more related to the frequency content of the anomalies rather than the amplitude. This allow us to define within a margin of error the depth where anomalies are generated. For example, the large anomaly in the north of the basin area must be generated at intra-crustal level and does not has a clear expression on seismic as well.

With the depth estimation the structural highs, volcanics and mini-basins are better identified. Basement depth estimates highlighted that Aveiro and Nazarè transfer faults divide the regional area into three domains. Orientation of horst and graben structures between the two transfer faults (highlighted by depth estimates and lineaments) are effected by the relative crustal movements between the two transfer faults.

## 2.5d Grav-Mag modelling description

2.5D modelling is a standard way of testing geological models against gravity and magnetic anomaly data.

The model can be interactively adjusted until a satisfactory fit between the theoretical response and the measured fields is achieved.

It helps to define basement depth and geometry especially in areas where seismic has poor resolution at depth. At this broader scale, modelling provides information on crustal\sediment thickness and Moho depth.

Still, this is a non-unique technique (i.e. several models can have a satisfactory gravity and magnetic fit), however the constrained models that utilise several data such as seismic, well and geological data a realistic model can be achieved.

For this investigation several constraints from seismic interpretations, and well data in the area were available, however not all the modelled lines would have adequate constraints.

## 2.5D GravMag modelling- Proposed model’s location

Models location (Figure 27) should be defined as a compromise between available seismic, well data and direction of strike to cross cut Grav-Mag anomalies respecting the 2D assumptions.

In fact, these are 2.5D models (figures 30, 31, 33, 34, 36 and 37) and bidimensional assumptions should be respected, i.e. model's location should be selected to minimize effects of sources out of the modelling plane

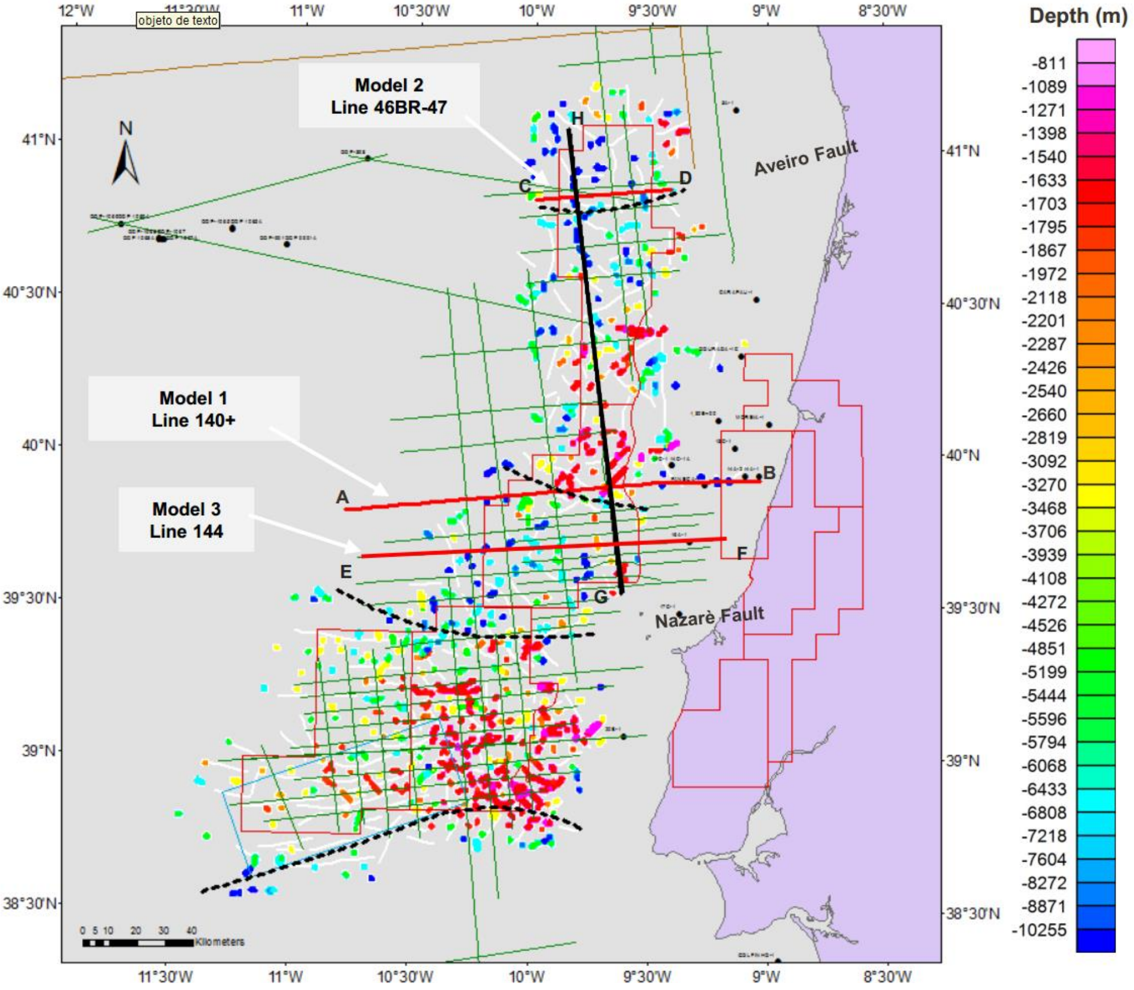


*Figure 27- Proposed models location of Peniche basin from Repsol Annual Exploration Activity Report - Offshore Peniche Basin*

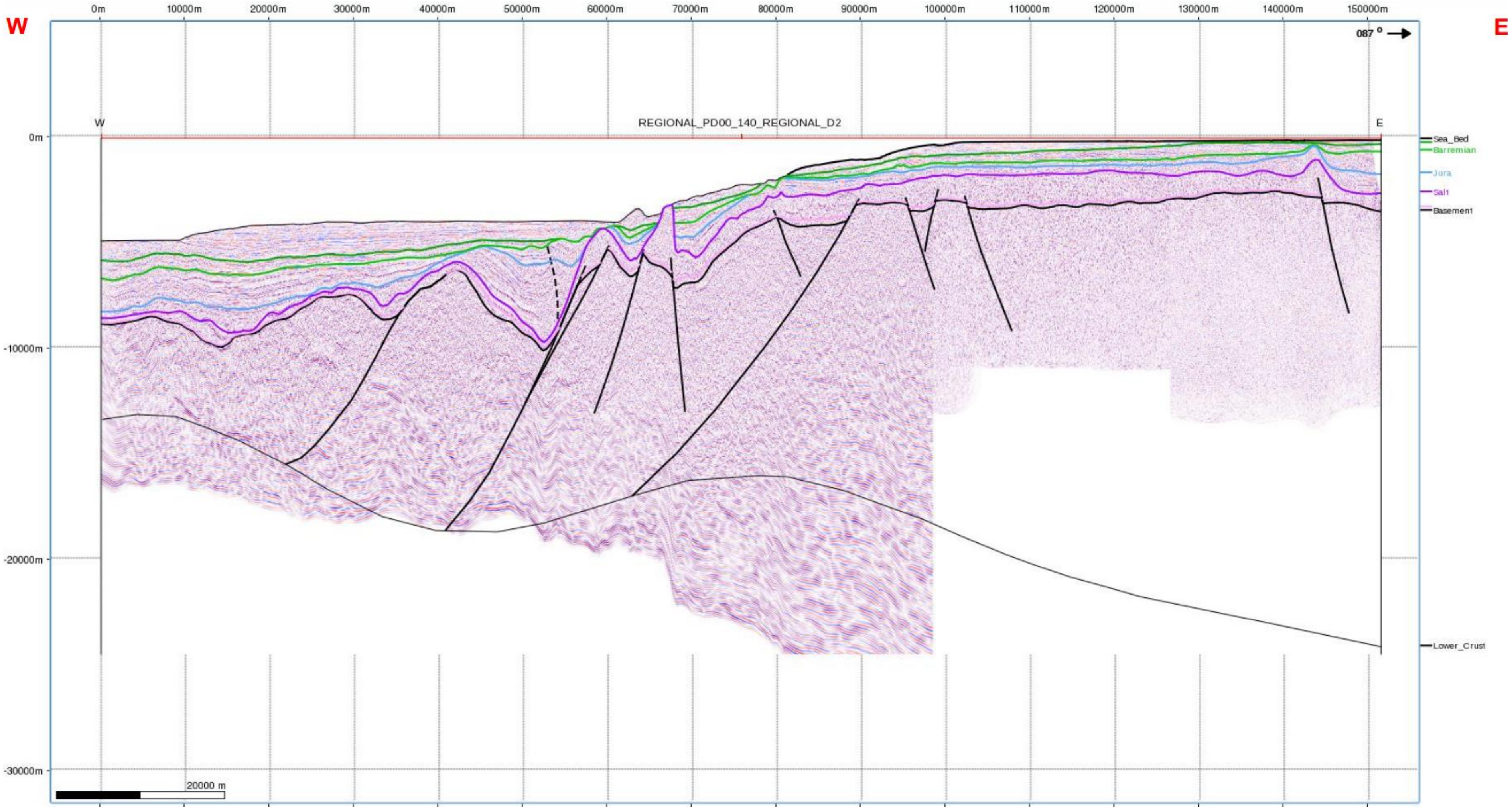


*Figure 28-Figure 12- Composite seismic line 140 +SH73-446W + ESS073-446 – Model 1*

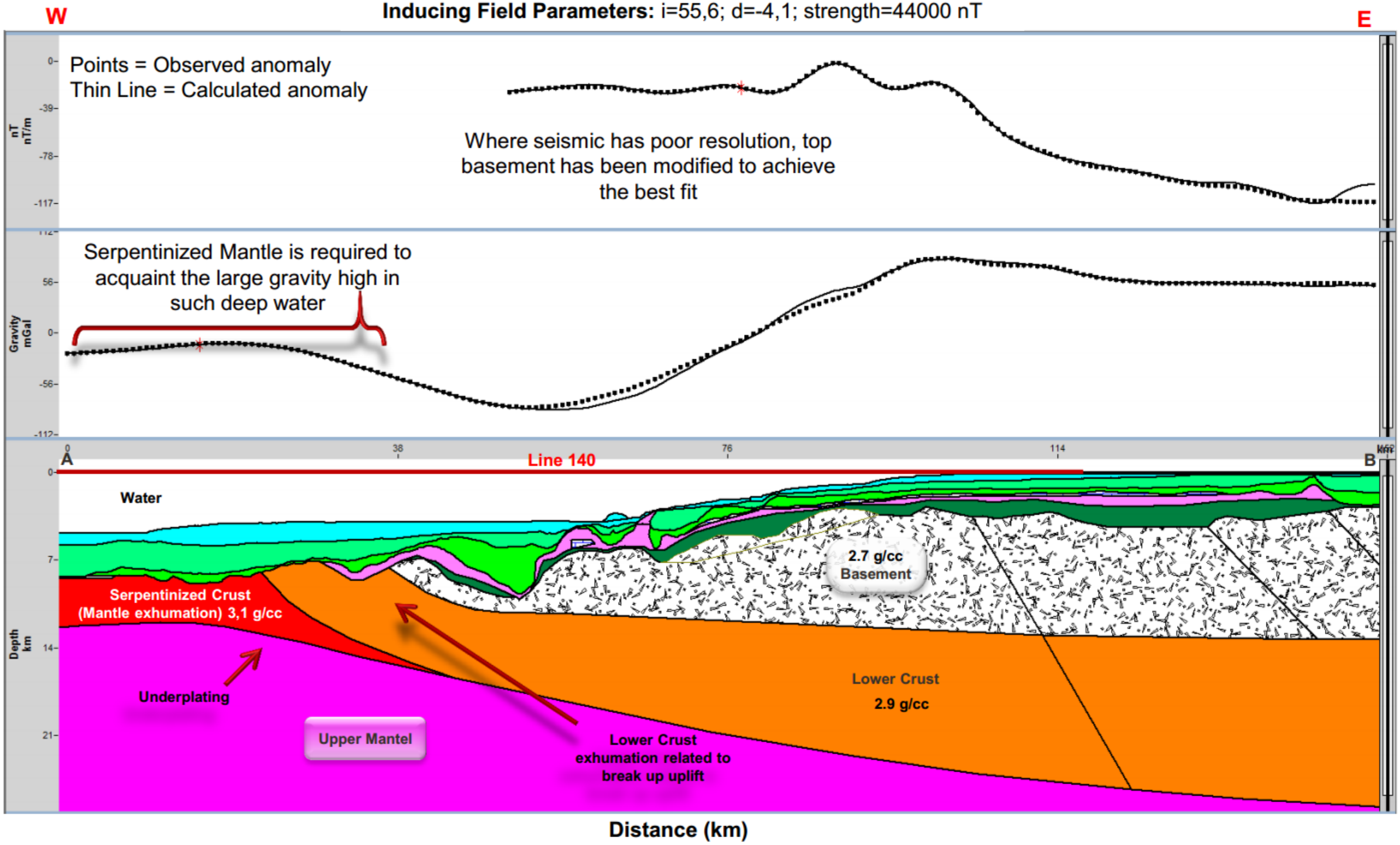


*Figure 29- Deep view Model*

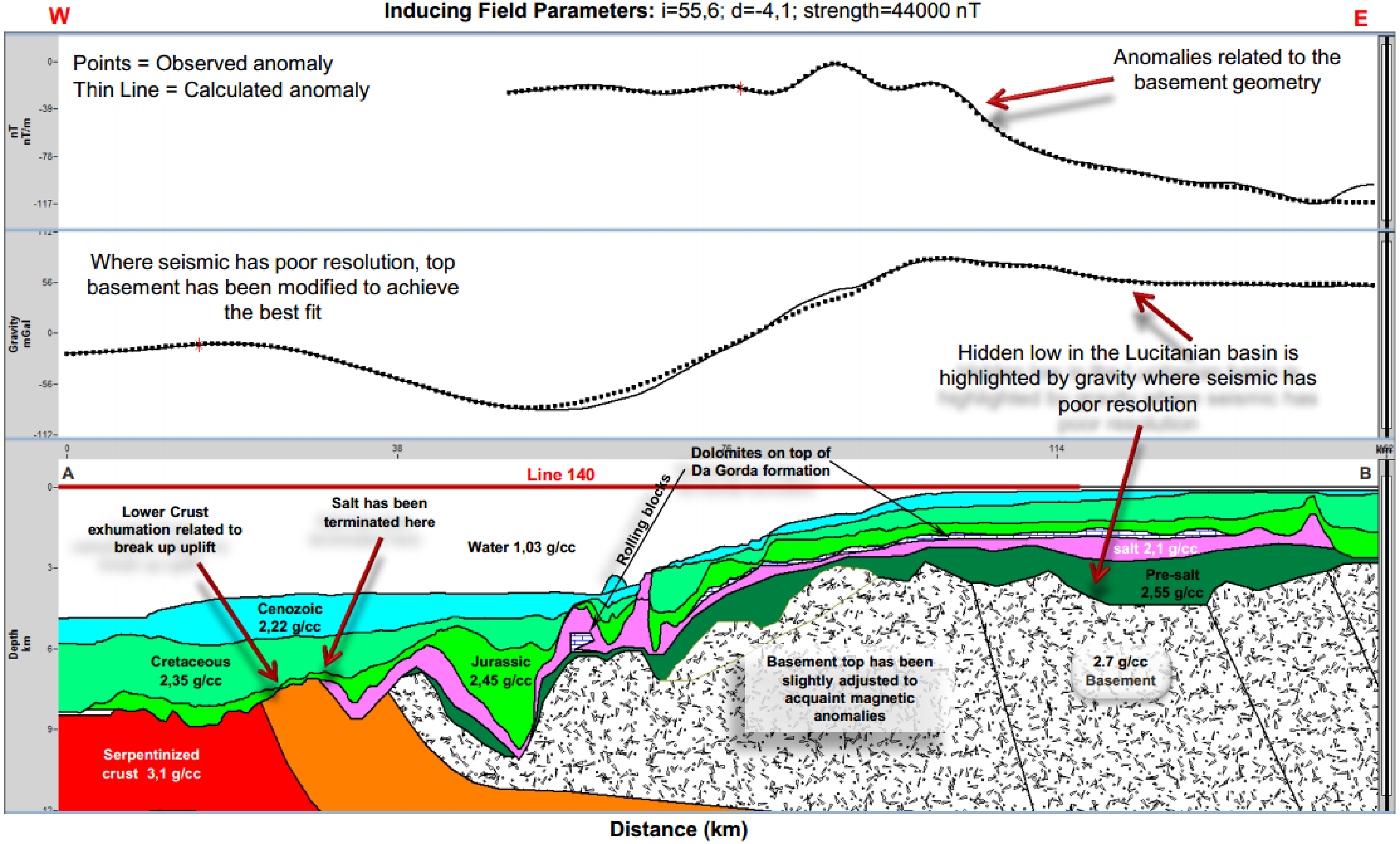


*Figure 30- shallow view model*

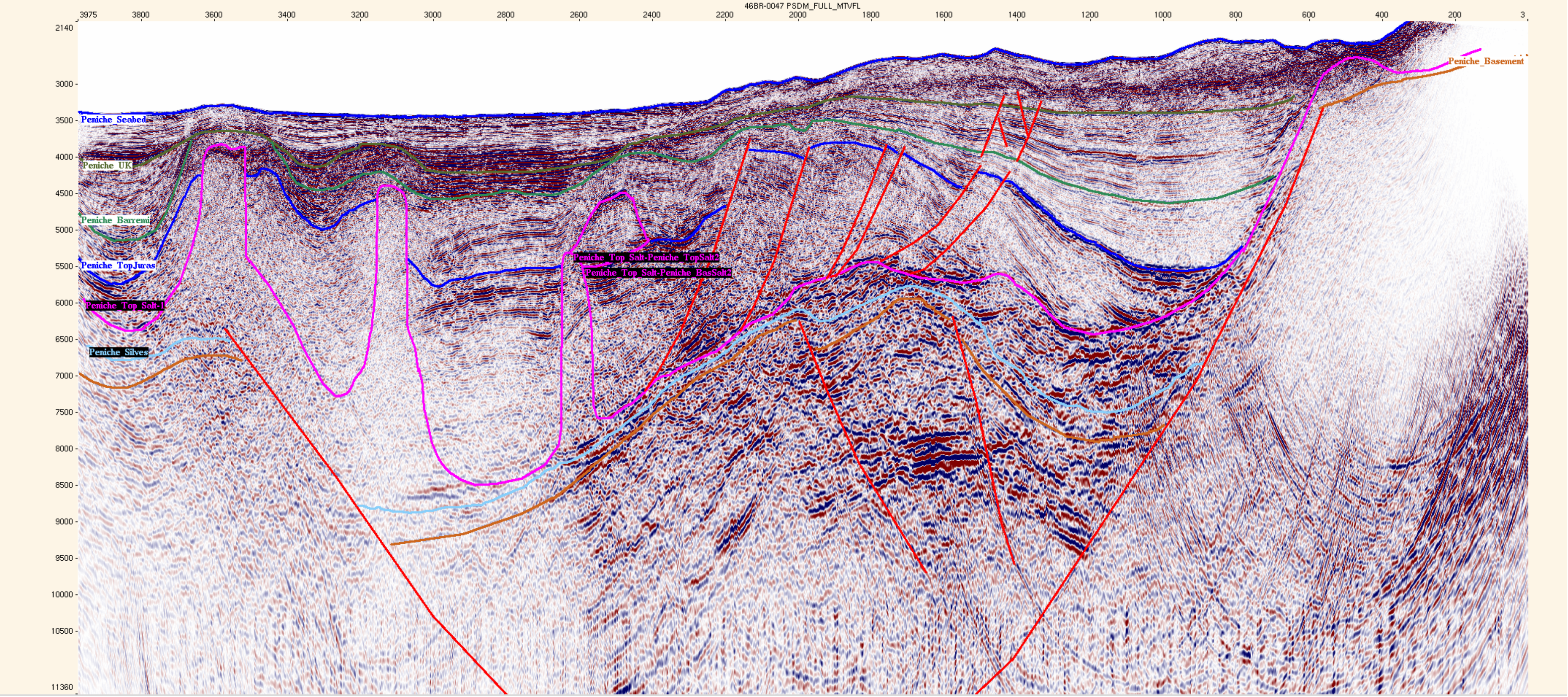
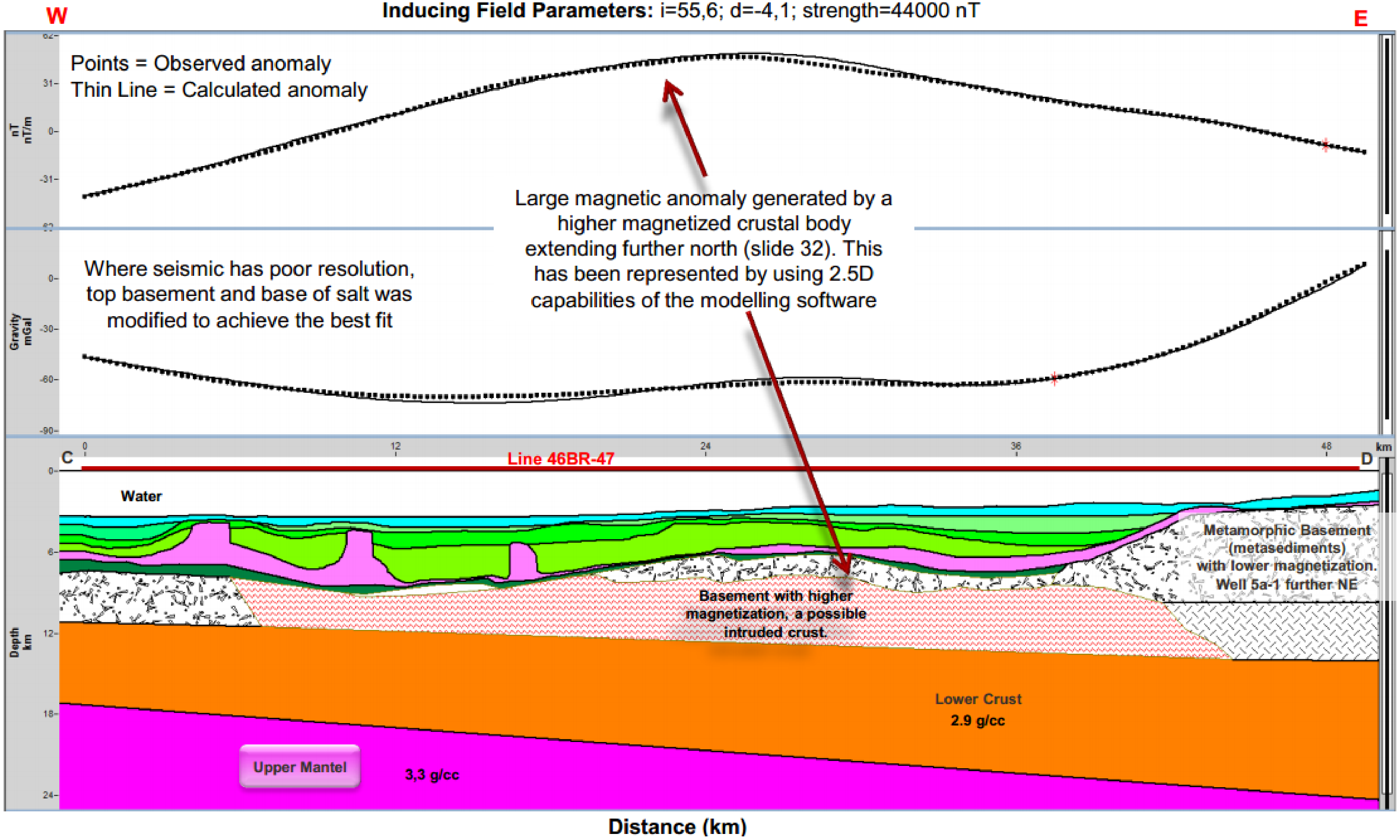


Figure 31- Seismic line 45 BR-47 - shallow model



**Inducing Field Parameters:** i=55,6; d=-4,1; strength=44000 nT

Points = Observed anomaly
Thin Line = Calculated anomaly

Large magnetic anomaly generated by a higher magnetized crustal body extending further north (slide 32). This has been represented by using 2.5D capabilities of the modelling software

Where seismic has poor resolution, top basement and base of salt was modified to achieve the best fit

Basement with higher magnetization, a possible intruded crust.

Metamorphic Basement (metasediments) with lower magnetization. Well 5a-1 further NE

*Figure 32- Model 2 deep view*

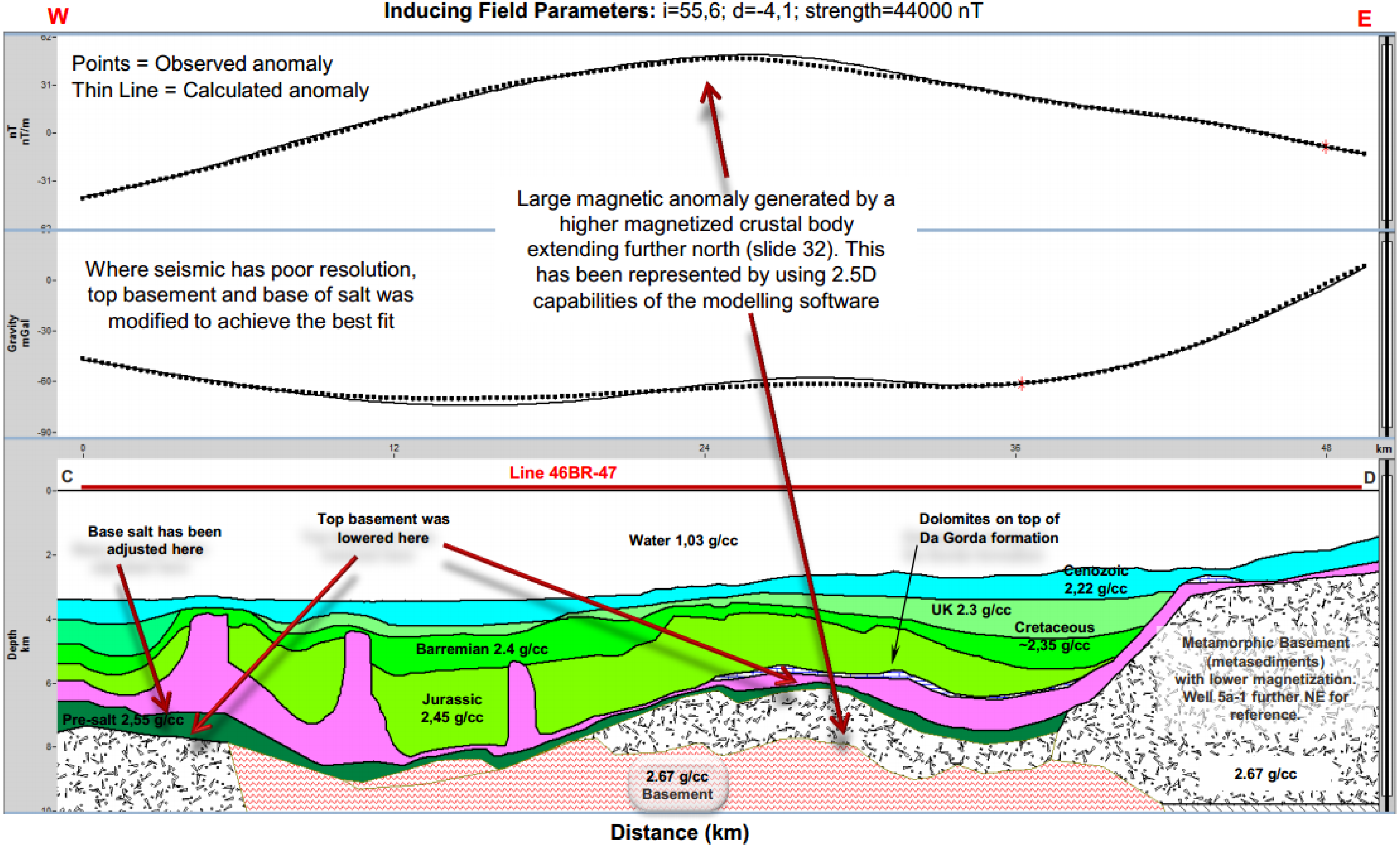


*Figure 33- Model 2 - Shallow view*

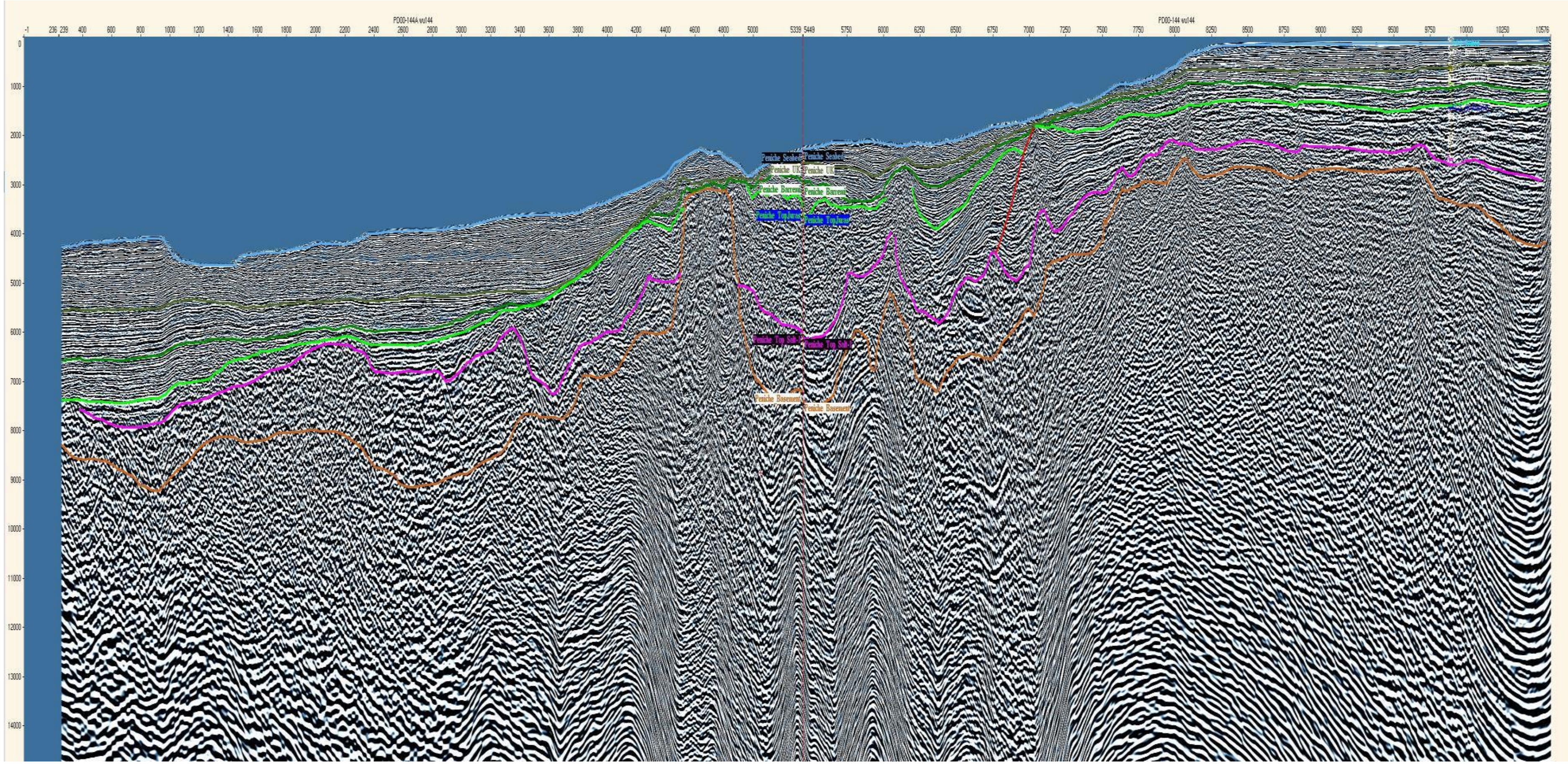


*Figure 34 - Composite seismic line 144 – Model 3*

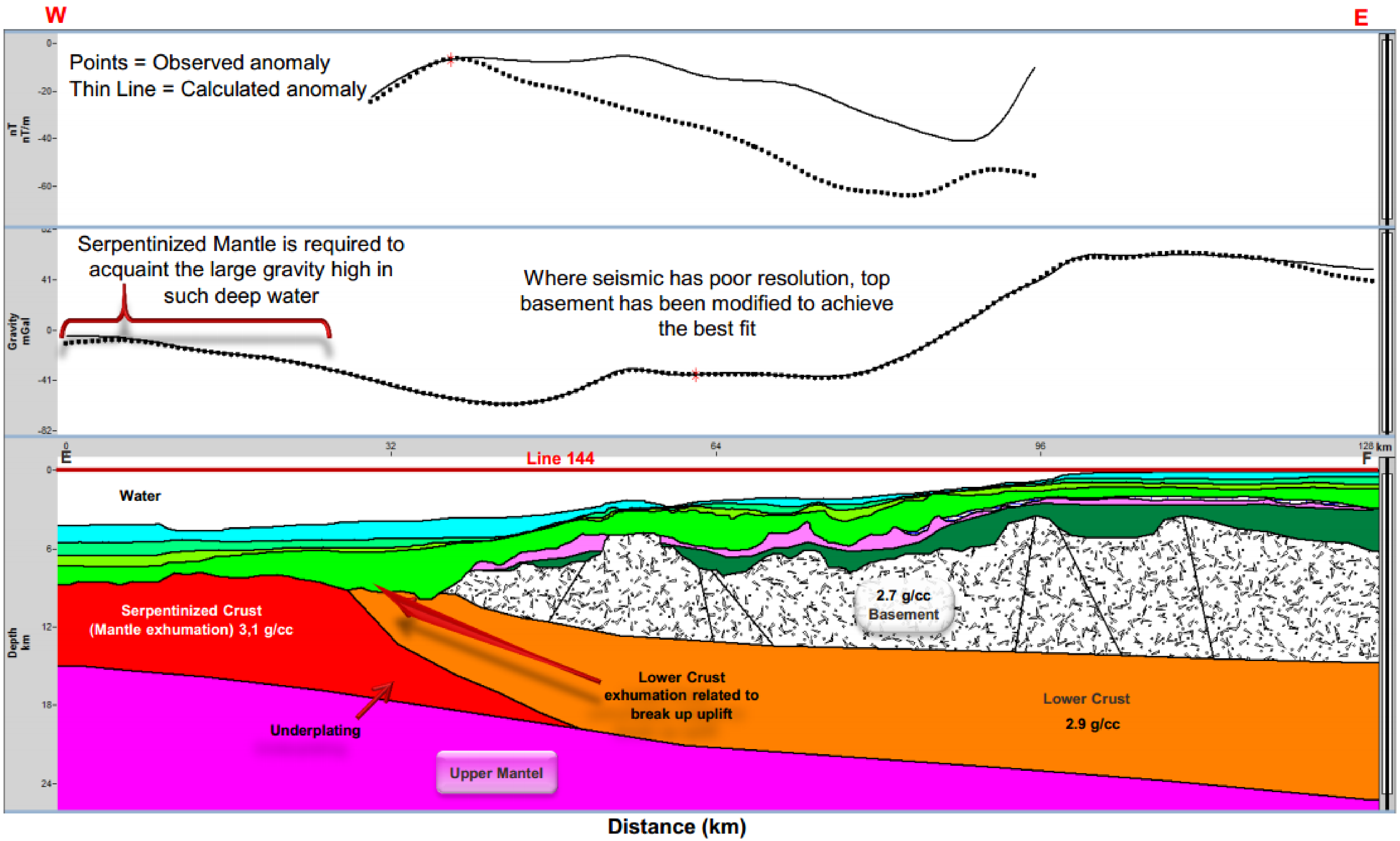
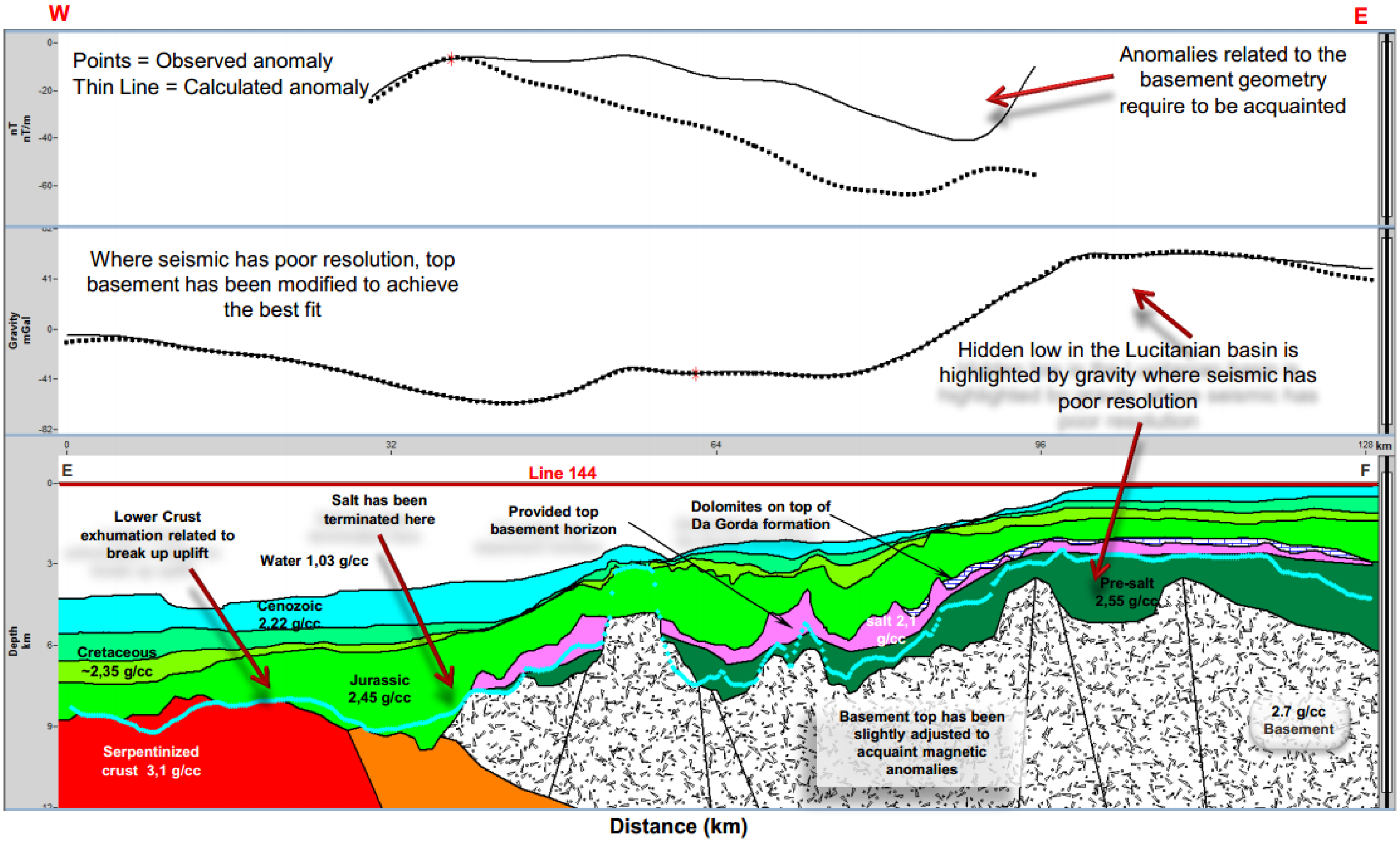


*Figure 35- Model 3 – Deep View Interpretation*



Points = Observed anomaly
Thin Line = Calculated anomaly

Anomalies related to the basement geometry require to be acquainted

Where seismic has poor resolution, top basement has been modified to achieve the best fit

Hidden low in the Lucitanian basin is highlighted by gravity where seismic has poor resolution

Lower Crust exhumation related to break up uplift

Salt has been terminated here

Provided top basement horizon

Dolomites on top of Da Gorda formation

Basement top has been slightly adjusted to acquaint magnetic anomalies

*Figure 36- Model 3 – Deep View Interpretation*

## Grav-Mag Concluding remarks

Several enhanced gravity and magnetic maps have been produced in order to highlight the structural configuration of the area and identify the major structural trends. A good correlation between identified highs and seismic interpretation is observed.

Within the blocks several structural highs aligned along differently oriented trends have been highlighted, also here a good correlation with Alves *et al*. paper is observed.

Lineaments and faults from Grav-Mag have been defined at the edge of structural highs or salt bodies helping to delineate them. Location of the Aveiro and Nazaré transfer faults has also been refined using Grav-Mag. The lineament analysis highlighted three different domains as well between Aveiro and Nazaré transfer faults characterized by differently oriented structures.

Thanks to depth estimation methods structural highs, volcanic centres and basins are better identified. Also, depth to basement estimates are highlighting three domains divided by Aveiro and Nazaré transfer faults. Orientation and depth of horst and graben structures in the three domains is affected by the relative crustal movements between the two transfer faults.

In addition, depth to basement estimations confirmed that the large magnetic anomaly in the north of the studied area is related to a deep-seated body at ~9km depth.

Two W-E oriented 2.5D Grav-Mag models along seismic lines 140extended and 46BR-47 were completed integrating all available constraints. During the modelling process, seismic interpretation has been refined, especially where this has poor resolution. Basement horizons has been modified in places, especially for line 46BR- 47 where it has been lowered in several places. Always for this line we discovered that the large magnetic anomaly is acquainted with a highly magnetized crust (intruded crust?) at contact with a low grade metamorphic basement (the shelf) in agreement with depth to basement estimation and stratigraphy of well 5a-1.

For line 140 underplating and serpentinized mantle as consequence of the crustal stretching is inferred to explain the large gravity anomaly at its western end. Basement and base of salt has been also refined, a hidden low at the eastern end in the Lusitanian basin is highlighted by a gravity drop where seismic has poor resolution.

# Regional (2d) seismic data interpretation

## Seismic Database

Over 3500 km of 2D regional seismic lines within an area of over 125 000 km2 (Figure 37) were available, supplied by ENMC. Their locations are depicted on a base map. The seismic data utilized have also been overlain on the gravity and magnetics maps for reference and correlation purposes.

Line spacing varies from around 10 km to 120 km with the closest line spacing over the shelf margins.

The seismic data are of the same vintage throughout the whole area.

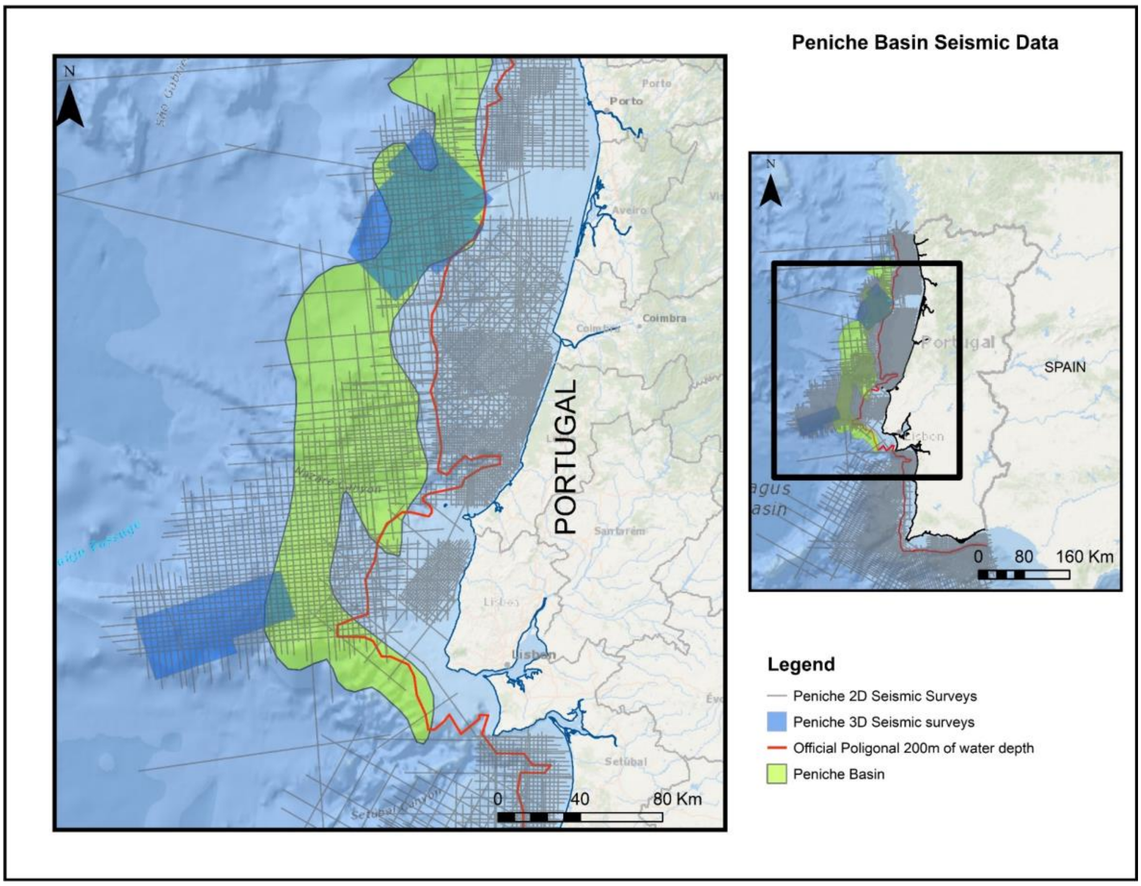


*Figure 37- Location of Peniche Basin Seismic data. Blue lines- 2D Regional Lines; Blue Polygons- 3D seismic data*

**Data quality**

Data quality varies depending on the underlying geology and water depth. Generally, the quality is good to excellent in the Deepwater areas, and relatively poor across the continental shelf due to the multiples not eliminated in processing.

No misties exists within the interpreted data. An Automatic Gain Control (AGC) filter was applied to the data.

Between the wells the regional seismic encompass areas of shelf slope and deep basin making a regional circuit around the basin before reaching the next well. Therefore, several jump correlations of well stratigraphic tops are needed for optimum tying of the wells.

The regional seismic interpretation, on 2D seismic in the basin, were undertaken in order to cover all of the following aspects:

1. Agreement with gravity and magnetic grids
2. Completion of the structural fault pattern
3. Precise production of the structural basin mapping

Mapping detailing started with the Acoustic Basement. This reflector is difficult to interpret on all seismic either being hidden below the salt or just because the signal strength is poor. Gravity and magnetics grids combined with geo-seismic modelling helped uncover most basement features. Depth conversion were based in 2008 2D seismic survey 46-BR velocities extraction, as there are no wells in the area. The resulting depth maps are in good accordance with the geological model.

## Horizon Markers Interfaces

In addition to the well-to-seismic ties, horizons have been identified based on the strength of reflectors, from patterns identified at each level.

Interpretation can be split into two areas, one in the north, the a larger one in the south. The northern area lies north of the 20B-1 well. Interpretation has been aided by well-to-seismic ties. The wells have encountered variable thickness of Tertiary and Cretaceous sections (probably clastic dominated) this above thick Jurassic carbonates.

The larger southern area extends southwest relative to the 20B-1 well. The well contains very thin clastic sequence above the carbonates. Due a change in the style of Deepwater sedimentation, jump correlation from north to south is not entirely feasible. Consequently, reliable horizon correlation in the southern area is problematic. Horizons are picked (Figure 50and Figure 51) to display key aspects of the geology. The horizons identified are described below.

**Seabed-** The seabed is picked over the entire area generally between two troughs.

**Base Oligocene** - The Base Oligocene has been identified in the northern area using a stratigraphic top identified in the DSDP wells. It has been picked as a strong reflector that is part of a sequence of near-parallel reflectors in deep water. It has not been identified in shallow water.

**Top Late Cretaceous -** Top Late Cretaceous has been identified using stratigraphic tops both on the shelf and in deeper water. It is a strong reflector that is part of a sequence of near-parallel reflectors in both shallow and deep water. Well reports generally start within this unit, so the pick is made at the nearest significant reflector above the top at each well. This reflector represents de Cretaceous-Tertiary (K-T) boundary.

**Top Early Cretaceous -** Top Early Cretaceous corresponds with the top of the Albian. The horizon has been identified using stratigraphic tops in the northern area, both on the shelf and in deeper water. It has been picked as a strong peak. The Albian sequence consists of conformable, subparallel reflectors that display patterns of strong and weak strength. The Early Cretaceous has been subdivided into a pre- and post-rift sequence (Casacão *et al*., 2015), commonly associated with the Aptian-Albian boundary.

**Top Aptian** - Top Aptian has been identified as a strong reflector in deep water, at the base of a thin sequence of low amplitude reflectors. The Aptian – Jurassic sequence consists of slightly wavy subparallel reflectors.

In shallow water, the reflector is less distinct and is interpreted with the aid of well-to-seismic ties. This horizon cannot be identified in the southern area.

**Top Late Jurassic -** In shallow water, Top Late Jurassic is identified with the aid of well-to-seismic ties as a peak. In deep water, it has been picked as a high amplitude event between two low amplitude packages. There are no direct well-to-seismic ties, so it has been interpreted in line with previously published interpretations (Casacão *et al*., 2015; Alves *et al*., 2006). On areas of the shelf break, it appears as potential carbonate build-ups barriers.

**Top Middle Jurassic -** Top Middle Jurassic is identified as the prominent Callovian unconformity. It has been interpreted as a high amplitude trough. On the shelf, it has been picked using well-to-seismic ties. There are no direct well-to-seismic ties in deep water, so it has been picked as a high amplitude event at the base of a low amplitude package, in line with previously published interpretations (Casacão *et al*., 2015; Alves *et al*., 2006). At well 20B-1 the Middle Jurassic has been interpreted at a major reflector within the seismic, identified as both a strong trough and an unconformable surface. This may tie to the Middle Jurassic pick identified in the well data but no checkshot or other velocity information is available for 20B-1 and so direct well-to-seismic ties are not possible.

**Top Salt -** Salt diapirs in deep water have been tentatively interpreted. Along the shelf, wells have predominantly been focusing on salt diapirs structures. At Dourada 1-C apparently salt movement occurred during the Late Jurassic.

**Top Basement** - Top Basement has been identified in the deep-water realm as the bottom high amplitude coherent reflector.

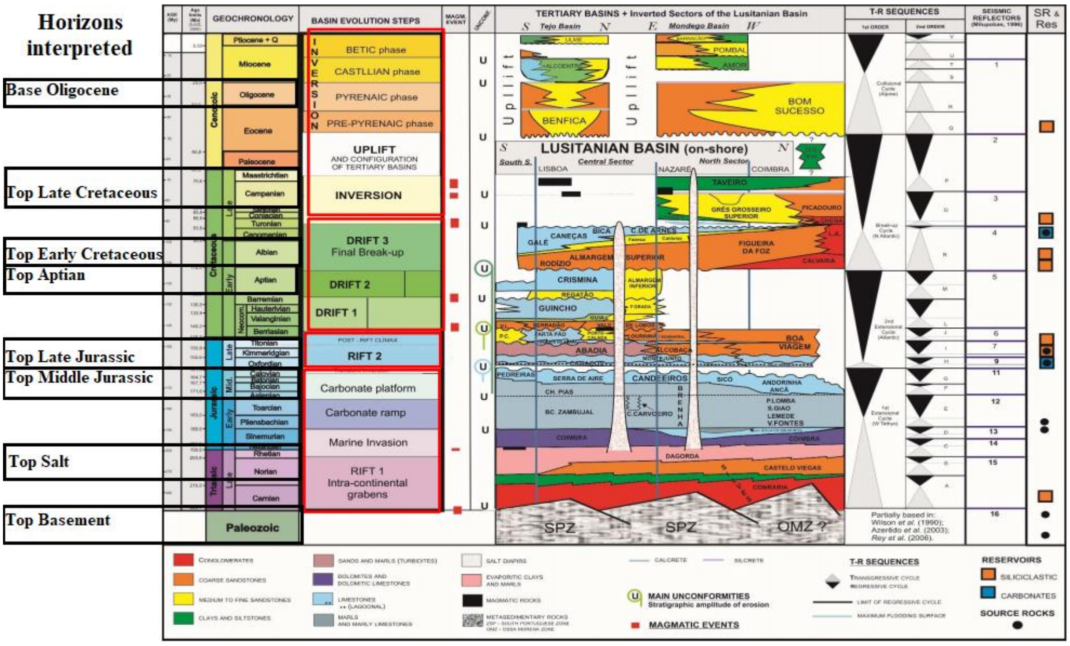


*Figure 38- Lusitanian Basin Stratigraphic chart with key horizons interpreted modified after Pena Dos Reis & Pimentel, 2016*

## Wells-To-Seismic Ties

The well data, in depth, were converted using velocity data to tie to the seismic data in time. Some wells don't have the velocity data, so they were converted using the well reports and its geology. (Figure 39, Figure 40and Figure 41)

Eight wells are located within 1 km of a seismic line, six of which have associated check shot velocity data. These are considered the most reliable wells (Figure 42, Figure 43 and Figure 44).

Two Deep Sea Drilling Project and two Ocean Drilling Program (Figure 45, Figure 46 and Figure 47 ) wells lie close enough to seismic lines to allow correlation. Although no time-depth charts are available to tie the wells to the seismic data, the associated reports allow stratigraphic horizons to be identified.

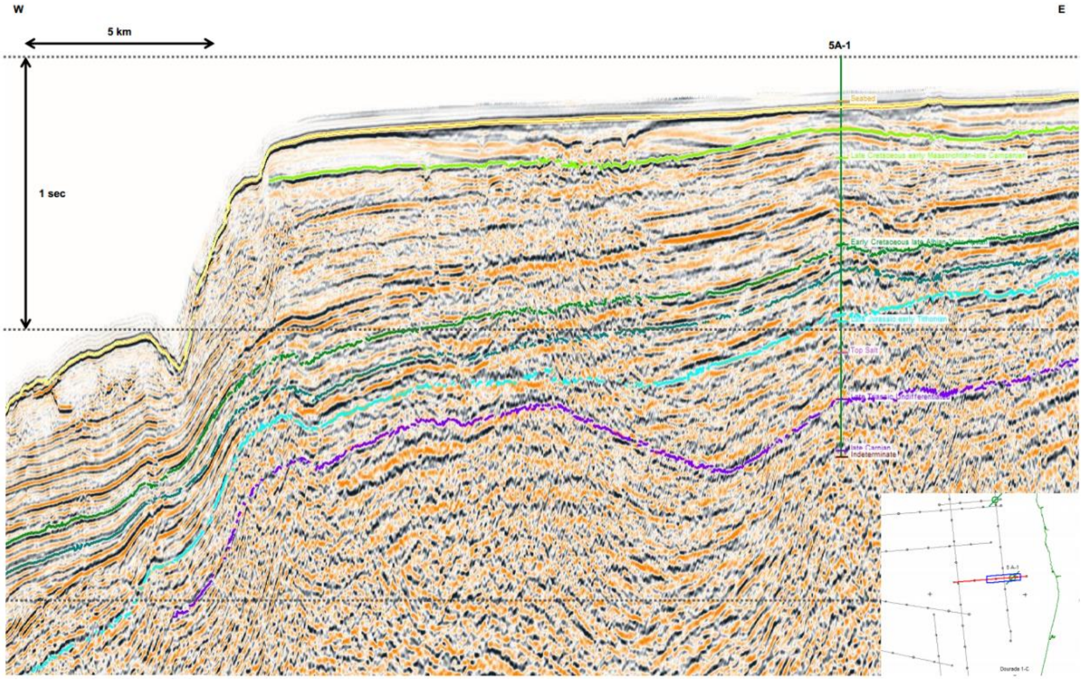


*Figure 39- Seismic line interpreted using the Well-to-seismic ties: 5A-1*

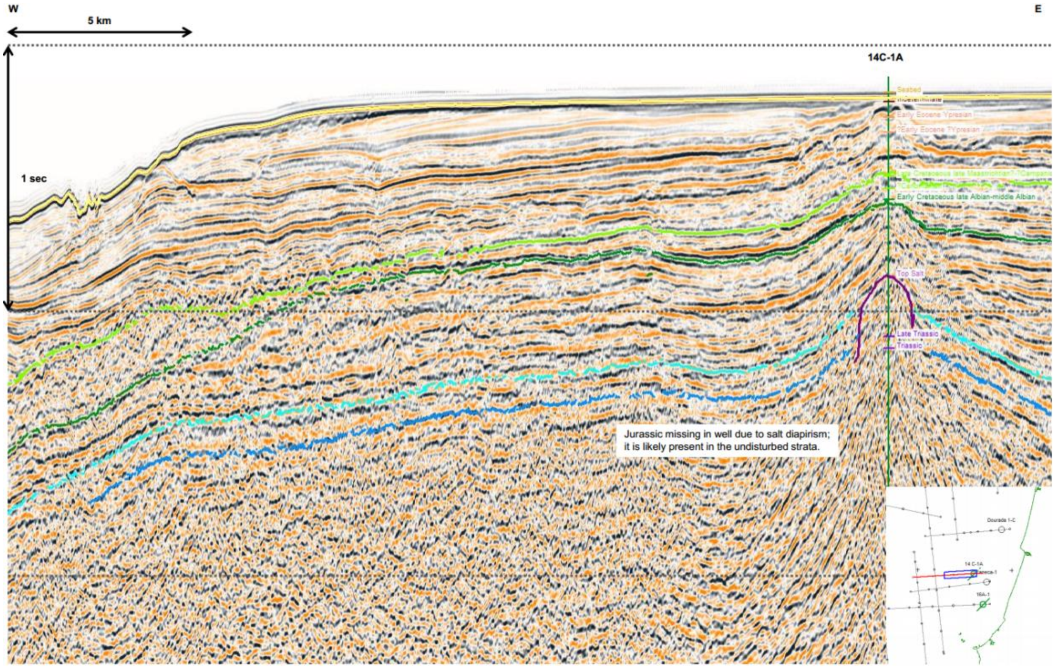


*Figure 40- Shallow water seismic Line interpreted using Well-to-seismic ties: 14C-1A*

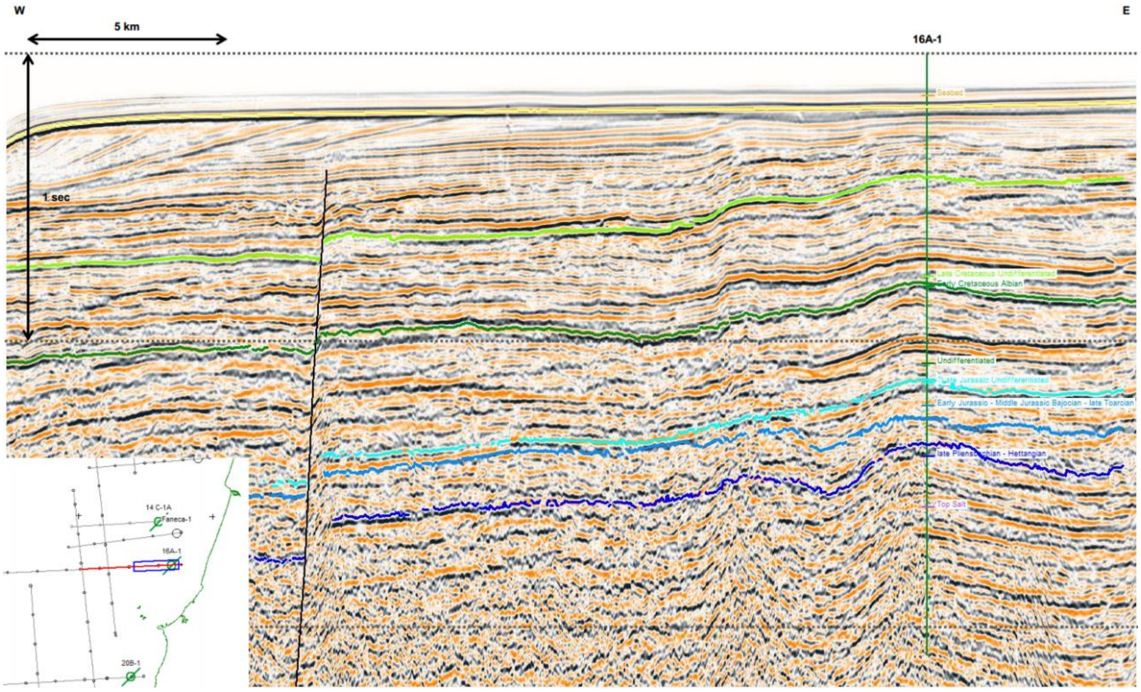
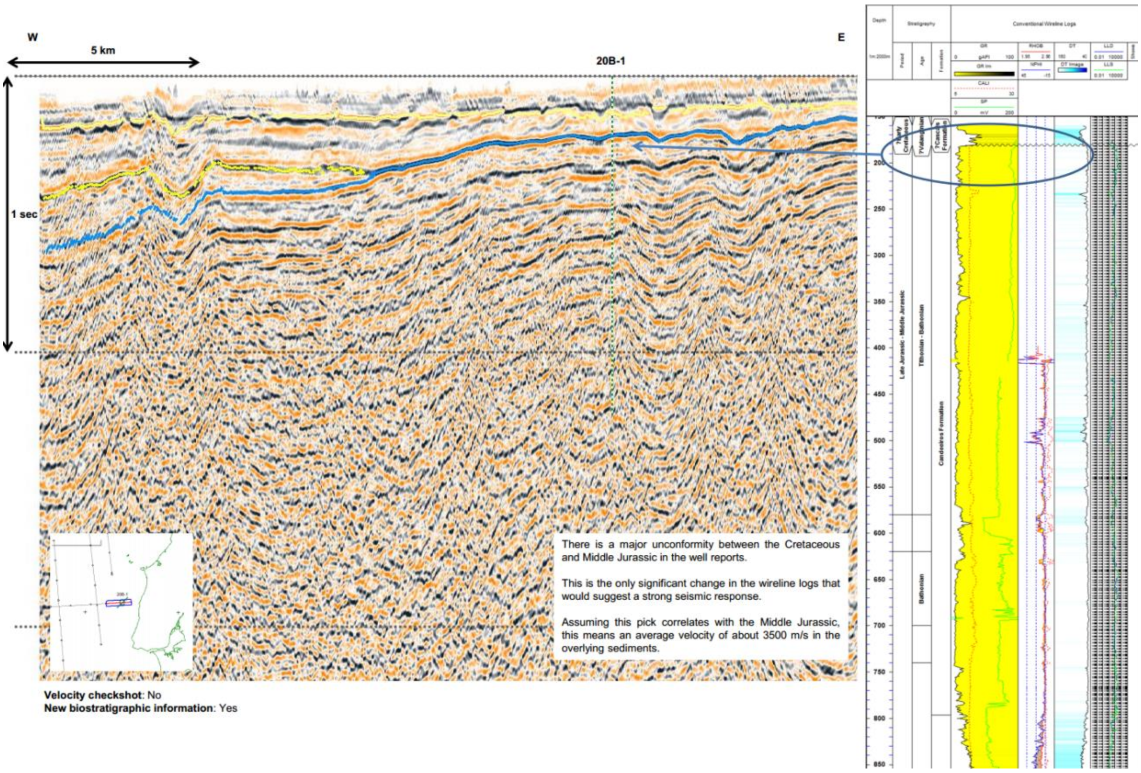


Figure 41- Shallow water seismic Line interpreted using Well-to-seismic ties: 16A-1



There is a major unconformity between the Cretaceous and Middle Jurassic in the well reports.

This is the only significant change in the wireline logs that would suggest a strong seismic response.

Assuming this pick correlates with the Middle Jurassic, this means an average velocity of about 3500 m/s in the overlying sediments.

**Velocity checkshot**: No
**New biostratigraphic information**: Yes

Figure 42- Shallow water seismic Line interpreted using Well-to-seismic ties: 20B-1 with velocity data

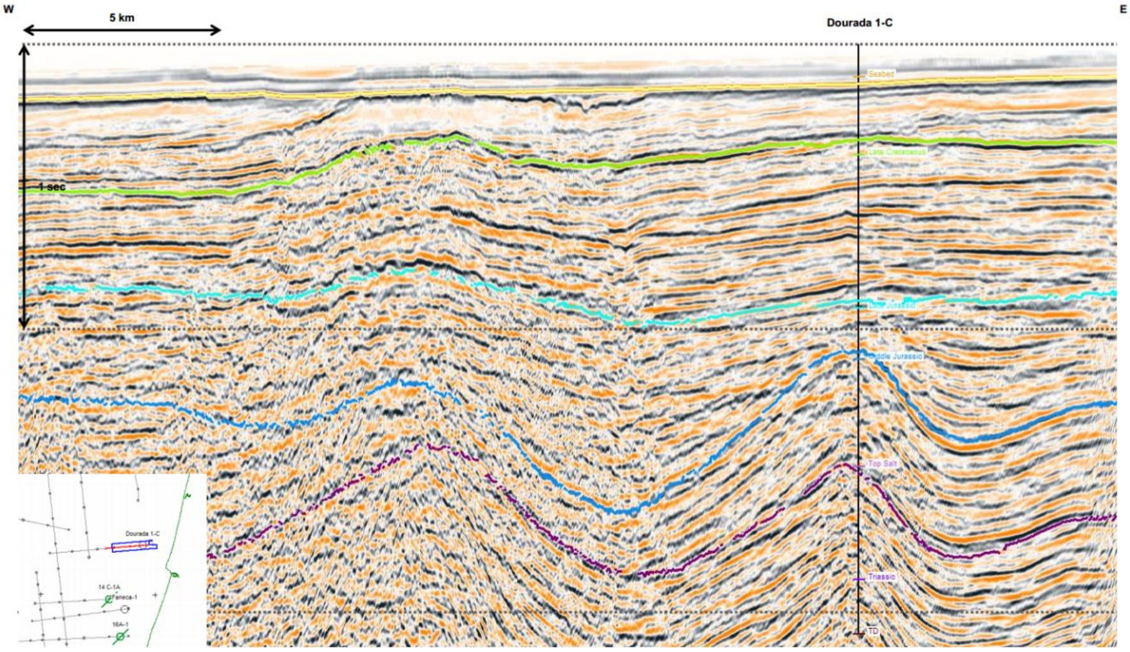


Figure 43- Shallow water seismic Line interpreted using Well-to-seismic ties: Dourada 1-C

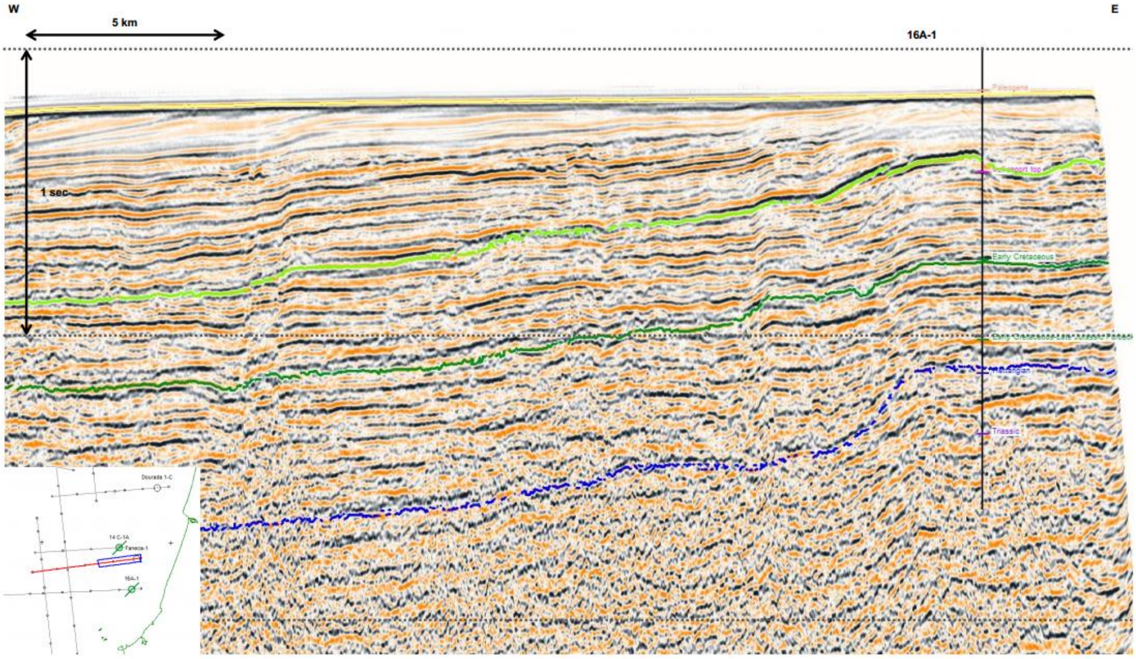
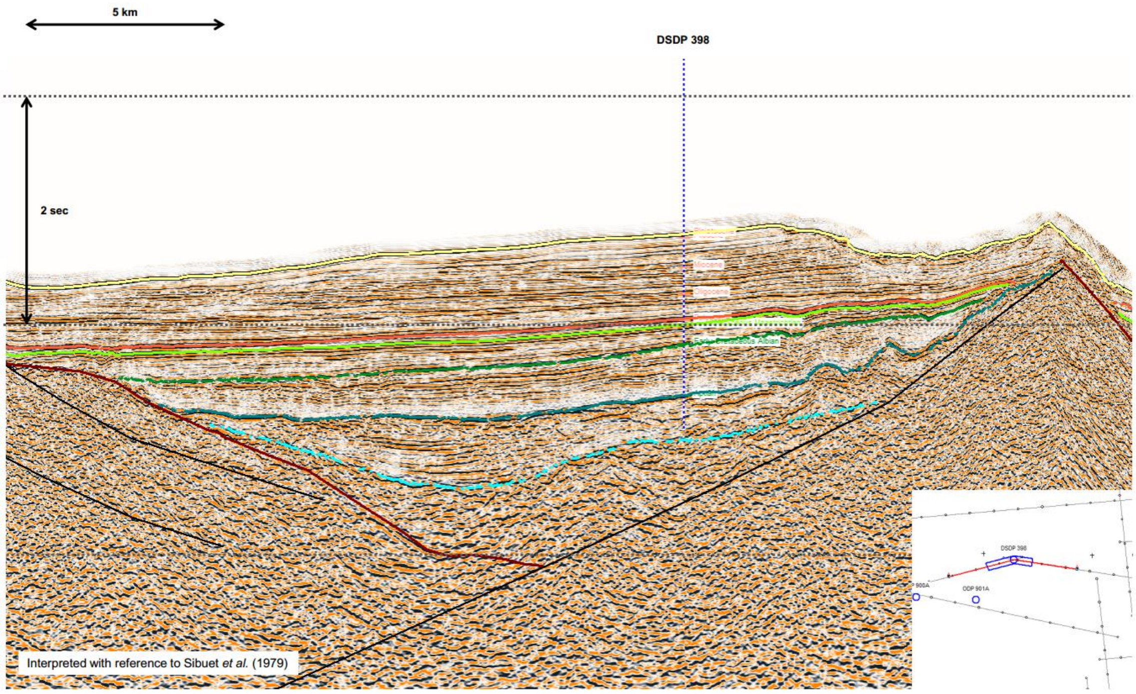
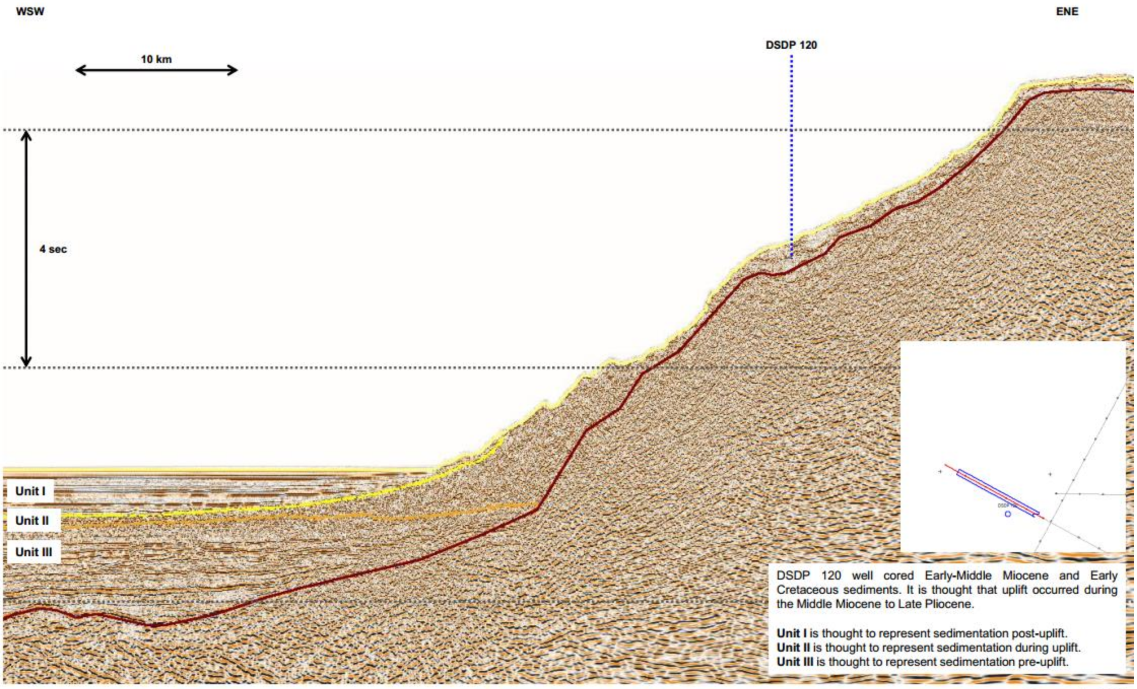


Figure 44- Shallow water seismic Line interpreted using Well-to-seismic ties Faneca-1



Interpreted with reference to Sibuet *et al.* (1979)

*Figure 45- Deepwater seismic Line interpreted using Well-to-seismic ties: DSDP 398 the interpretation refers to Sibuet et al. (1979)*

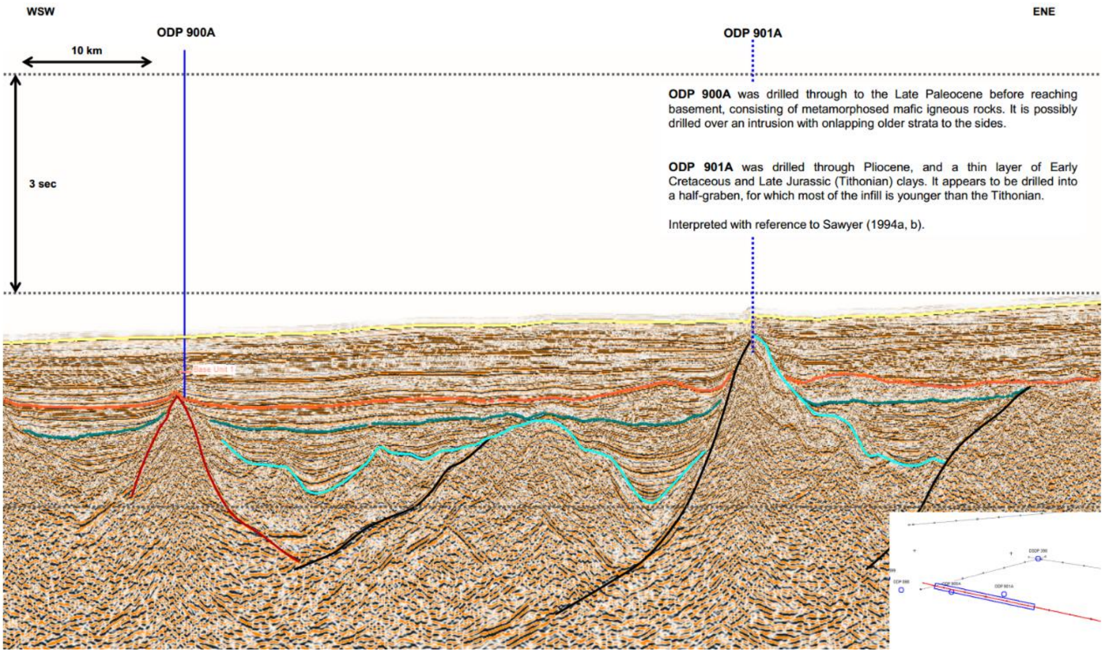


DSDP 120 well cored Early-Middle Miocene and Early Cretaceous sediments. It is thought that uplift occurred during the Middle Miocene to Late Pliocene.

**Unit I** is thought to represent sedimentation post-uplift.
**Unit II** is thought to represent sedimentation during uplift.
**Unit III** is thought to represent sedimentation pre-uplift.

(Ryan *et al.*, 1970)

*Figure 46- Deepwater seismic line with Well-to-seismic ties: DSDP-120*



**ODP 900A** was drilled through to the Late Paleocene before reaching basement, consisting of metamorphosed mafic igneous rocks. It is possibly drilled over an intrusion with onlapping older strata to the sides.

**ODP 901A** was drilled through Pliocene, and a thin layer of Early Cretaceous and Late Jurassic (Tithonian) clays. It appears to be drilled into a half-graben, for which most of the infill is younger than the Tithonian.

Interpreted with reference to Sawyer (1994a, b).

*Figure 47- Deepwater seismic line Well-to-seismic ties: ODP 900A and 901A*

## Salt and Fault Identification

The salt identification was done with auxiliary wells (Figure 48) that crosses the salt formations identifying the seismic signature of the salt. That signature was interpreted throughout the all data.

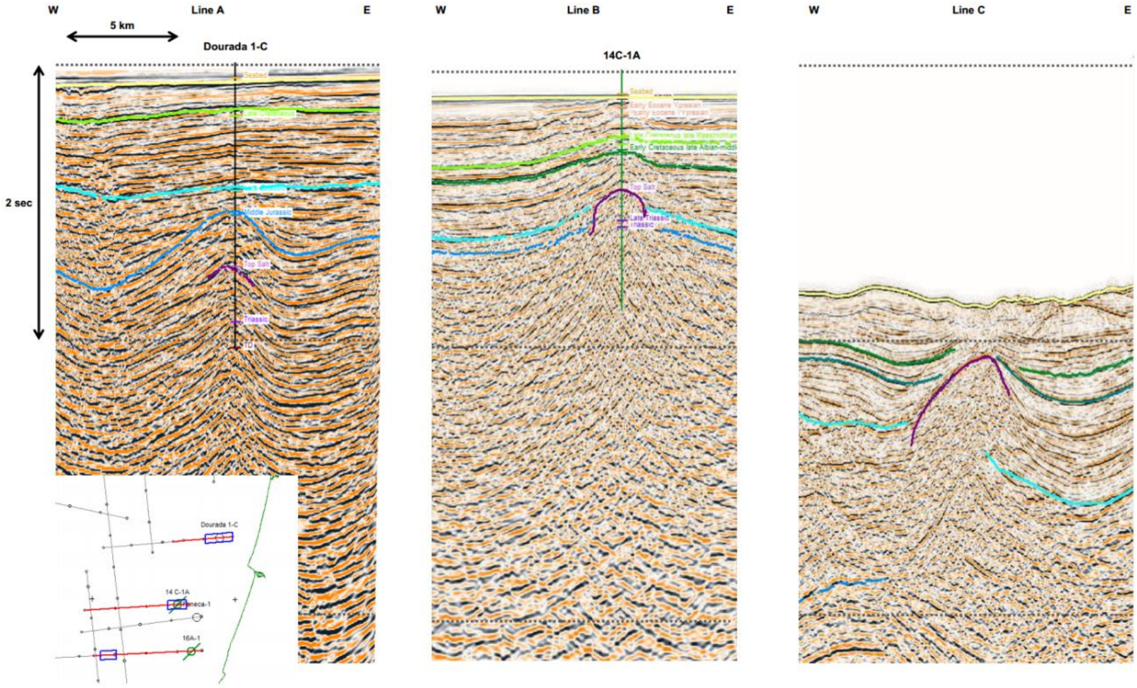
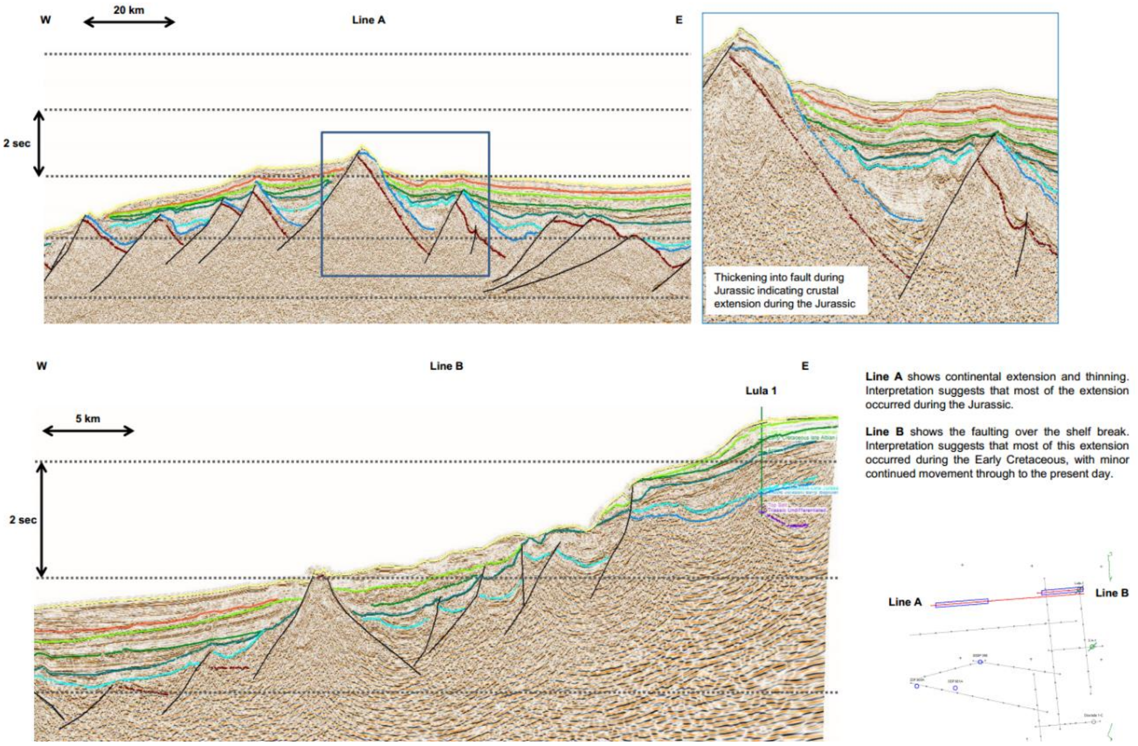


*Figure 48- Seismic line in the northeast of the basin demonstrating the salt Identification process. Note the first two lines with dourada1-1C and 14C-1A wells which has reached the salt*



**Line A** shows continental extension and thinning. Interpretation suggests that most of the extension occurred during the Jurassic.

**Line B** shows the faulting over the shelf break. Interpretation suggests that most of this extension occurred during the Early Cretaceous, with minor continued movement through to the present day.

*Figure 49- Seismic line in the north of the basin demonstrating the fault Identification process Line A shows continental extension and thinning interpretation suggests that most of the extension occurred during the Jurassic. Line B shows the faulting over the shelf break. Interpretation suggests that most of this extension occurred during the Early Cretaceous, with minor continued movement though to the present.*

The dominant structural style offshore Portugal is extension. Basin bounding faults are simple synthetic faults that define the break from shallow to deep water (Figure 49).

In the north of the study area, the extension accommodates a high degree of continental stretching and thinning. Because of this, the Continental Ocean Transition (COT) zone is complex and extends beyond any of the seismic lines in the north. Further south, although seismic lines cross the interpreted ocean-continent boundary, the COT is not identifiable on the seismic.

## Seismic Interpretation - 2D Grids

These data provide a context for understanding the tectonic development, sedimentology, regional stratigraphy and basin evolution. The surveys are of variable quality with a line spacing mostly between 10 and 120 km, but closer over the shelf margins.

Eight dated horizons have been picked where possible across the area. In addition, salt has been identified in diapirs in deep water and on the shelf. Where age dating is not possible, horizons have been interpreted for significant geological reflectors.

Five seismic panels are included as part of this thesis. All are east-west or northeast southwest oriented and cross from the shelf in the east to the deep water in the west.

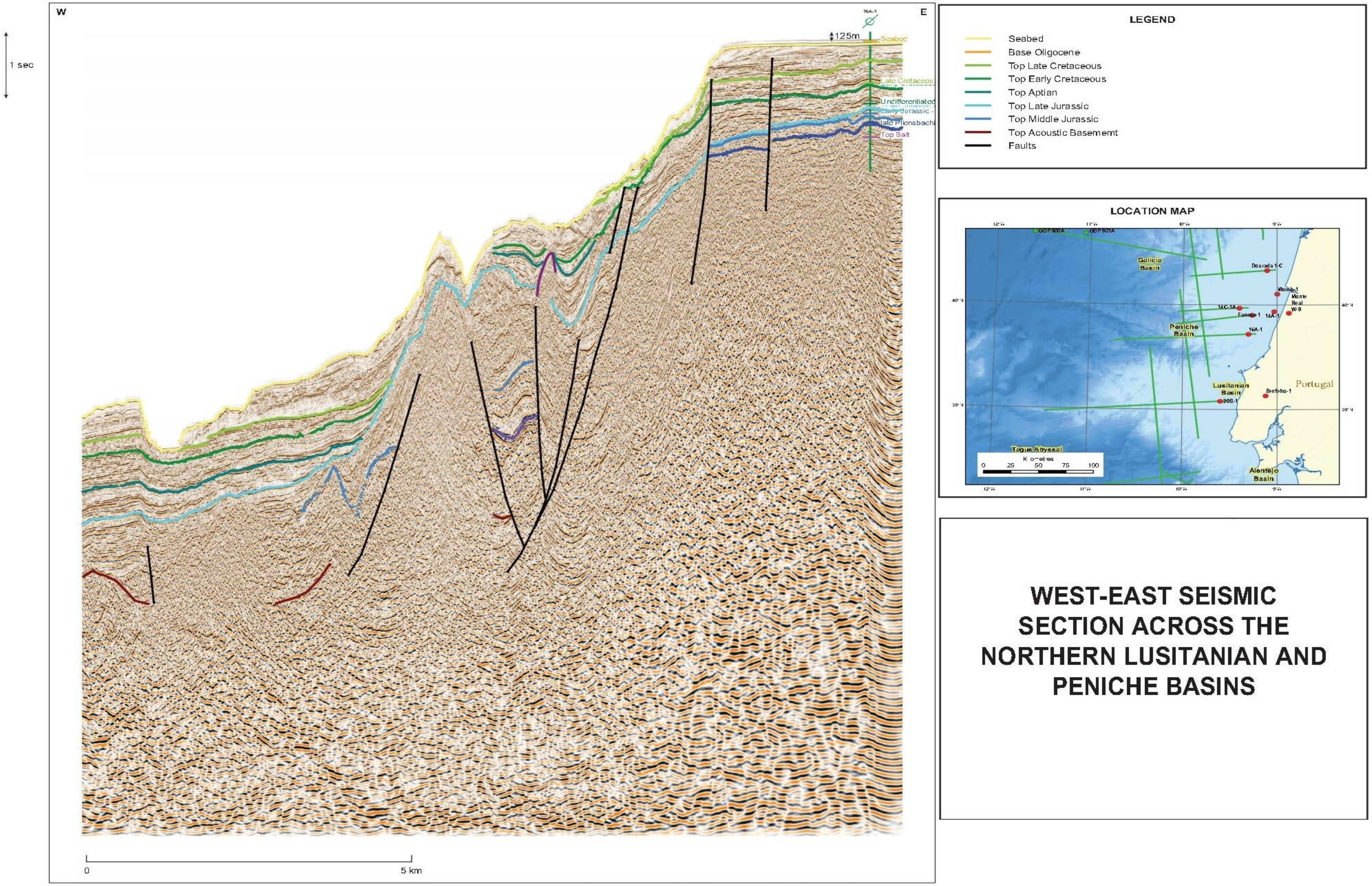


*Figure 50- Seismic section W-E across the Northern Lusinatia Offshore and Peniche Basins - Interpretation with key horizons.*

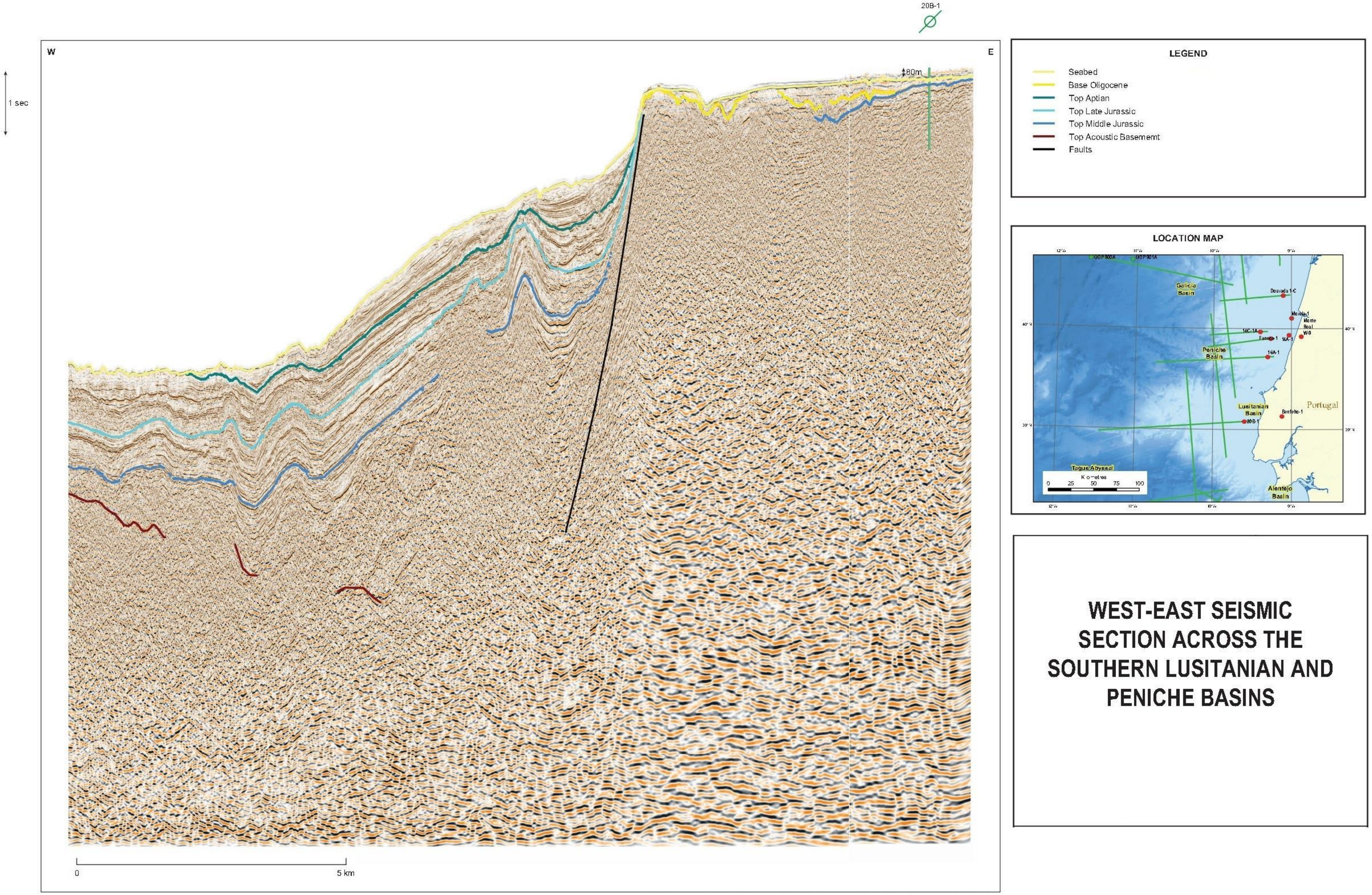


*Figure 51- Seismic section W-E across the Southern Lusitanian Offshore and Peniche Basins - Interpretation with key horizons.*

Two different sets of interpretation grids have been produced (Figure 52):

- Regional grids obtained from the work done on the available 2D.
- Camarão grids, obtained from the 2015 Camarão 3D seismic interpretation

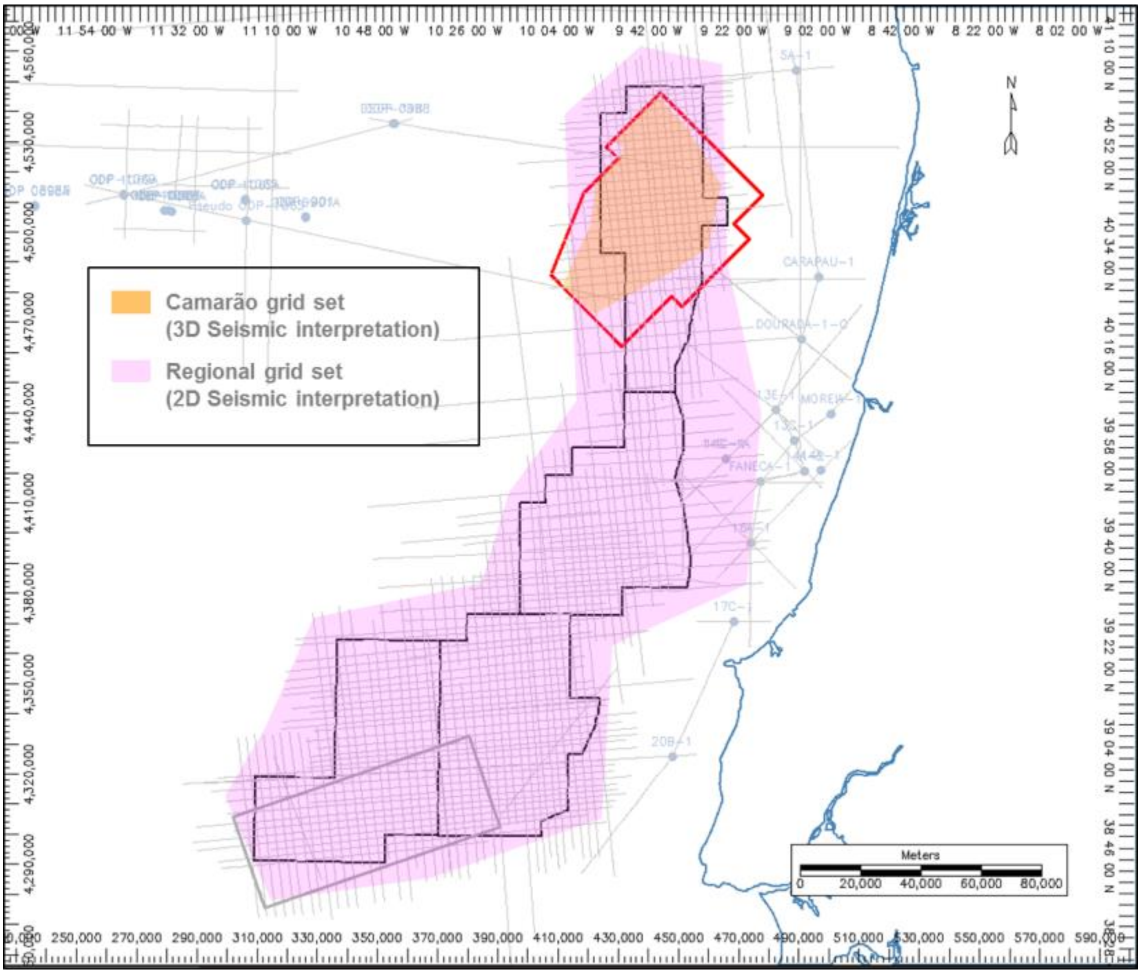


Figure 52- Approx. Grid sets´ extension representing the 2D regional grid and 3D detailed Grids.

## Regional Two-Way-Time Maps

The map bellow (Figure 53) identifies the six TWT maps generated after regional interpretation 2D seismic interpretation.

The Base Oligocene has been identified in the northern area using a stratigraphic top identified in the DSDP wells. It has been picked as a strong reflector that is part of a sequence of near-parallel reflectors in deep water. It has not been identified in shallow water.

Top Early Cretaceous corresponds with the top of the Albian. The horizon has been identified using stratigraphic tops in the northern area, both on the shelf and in deeper water. It has been picked as a strong peak. The Albian sequence consists of conformable, subparallel reflectors that display patterns of strong and weak strength. The Early Cretaceous has been subdivided into a pre- and post-rift sequence (Casacão *et al*., 2015), commonly associated with the Aptian-Albian boundary.

In shallow water, Top Late Jurassic is identified with the aid of well-to-seismic ties as a peak. In deep water, it has been picked as a high amplitude event between two low amplitude packages. There are no direct well-to-seismic ties, so it has been interpreted in line with previously published interpretations (Casacão *et al*., 2015; Alves *et al*., 2006). On areas of the shelf break, it appears as potential carbonate build-ups barriers.

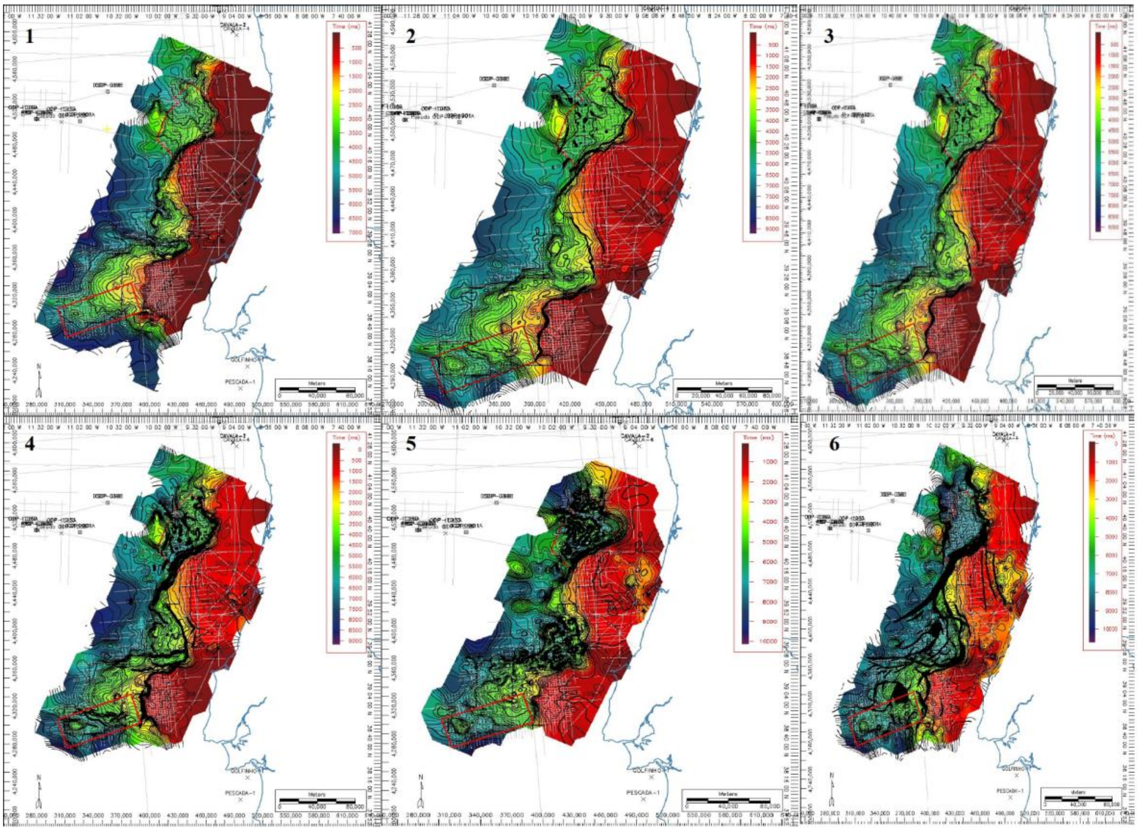


*Figure 53- Peniche Regional TWT maps:1-Base Oligocene Map; 2- Top Late Cretaceous Map; 3- Early Cretaceous map; 4- Top Late Jurassic Map; 5- Top Middle Jurassic; 6- Top Salt Map*

Top Basement has been identified in the deep-water realm as the bottom high amplitude coherent reflector. This reflector was tied to Grav-Mag data and depth estimation models presented in the previous chapter for better precision.

## Regional Depth Maps

The horizons were converted to depth using check-shot data from the wells and was produced the regional depth maps shown below (Figure 54).

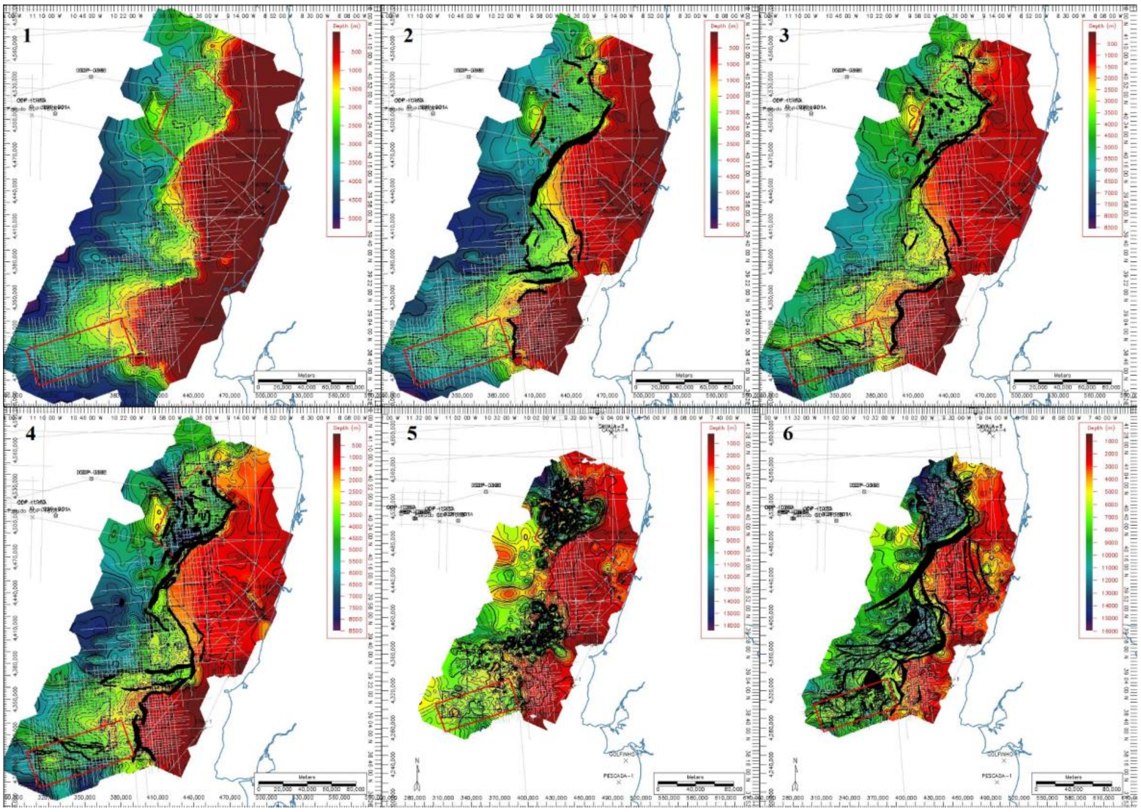


*Figure 54- Peniche Regional depth maps:1-Base Oligocene Map; 2- Top Late Cretaceous Map; 3- Early Cretaceous map; 4- Top Late Jurassic Map; 5- Top Middle Jurassic; 6- Top Salt Map*

# 3D data volumes mapping

## 3D Seismic Grids

This detailed job has started with the Acoustic Basement. This reflector is quite complex and sometimes it´s almost invisible in the seismic, hidden below the salt or just because the signal hasn´t penetrated deep enough. To compensate that fact, the seismic interpretation was combined with the gravity and magnetics grids, which have been demonstrated as a very helpful tool.

For the depth conversion (Figure 58), the velocities from 2008 2D seismic survey 46-BR (Figure 55) has been used, as there are no wells in the area to calibrate the output. This is important to be considered, the degree of uncertainty in the depth maps is high concerning the numerical depth absolute values. Despite this fact, the resulting depth maps are in good accordance with the geological model.

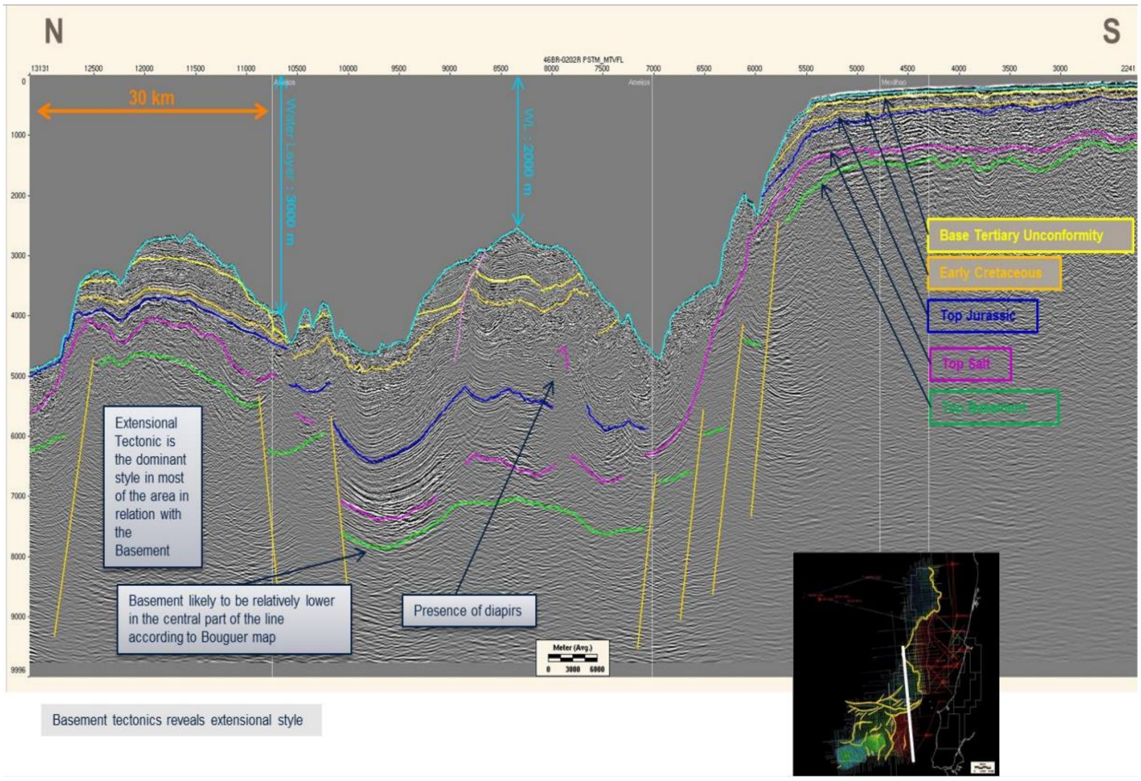


*Figure 55- shows the main regional horizons that are being interpreted throughout the whole basin.*

It is important to remind that Peniche Basin corresponds to a very complex and underexplored area, where several issues surge:

- Well calibration. No information is available inside the 3D area, and the tie to the nearby platform wells is almost impossible as no continuous reflections can be followed due to the sharp platform edge termination.
- The southeast-northwest incision, clearly active for several million years, cuts the sequence preventing to continue the interpretation of the upper Mesozoic and Cenozoic section from the southern to the northern part of the survey.

- Jurassic Carbonatic Section. The presence of a high impedance section on top of the salt bodies masks the Triassic salt interpretation, and thus the depth processing.
- Basin edge. The steep fault pattern that form the basin edges, and the important water column differences complicates the processing, and the interpretation of the basin borders.
- Basement. No clear basement reflection is observed. Gravity and Magnetometry helped to stablish the basement nature and depth. A series of interpretation horizons have been established, mainly based on depositional sequence analysis. An effort has been made to relate the observed seismic surfaces to regional knowledge and available well information. The horizon naming (Figure 56) is an attempt to correlate them to the main geological boundaries in the area, but no fixed ages can be established to these interpreted surfaces.

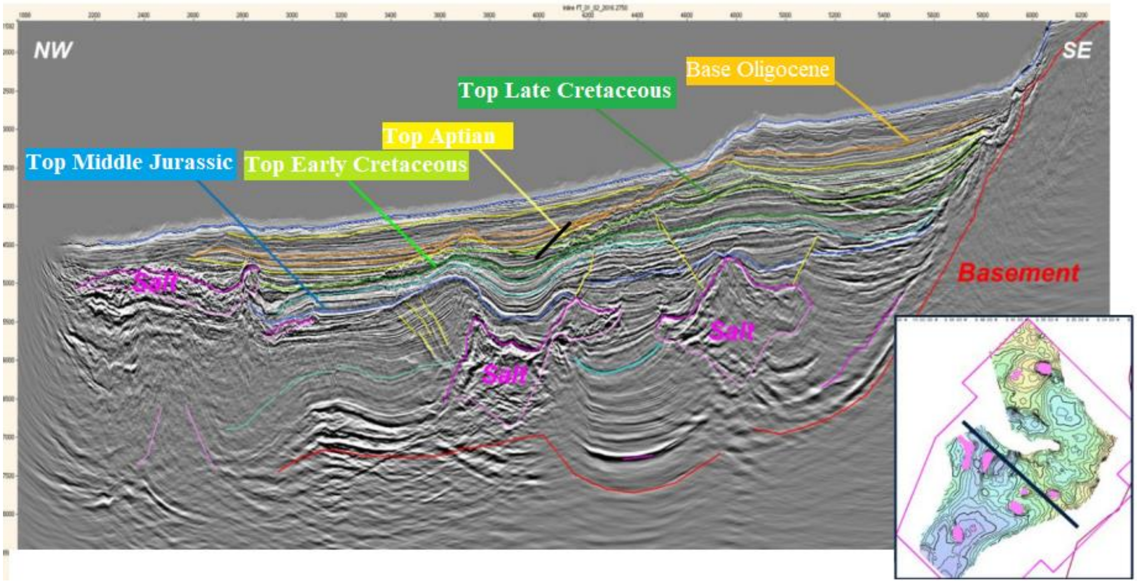


*Figure 56-Main interpretation horizons definition (PSTM, inline 2750)*

## Camarão 3D TWT Maps

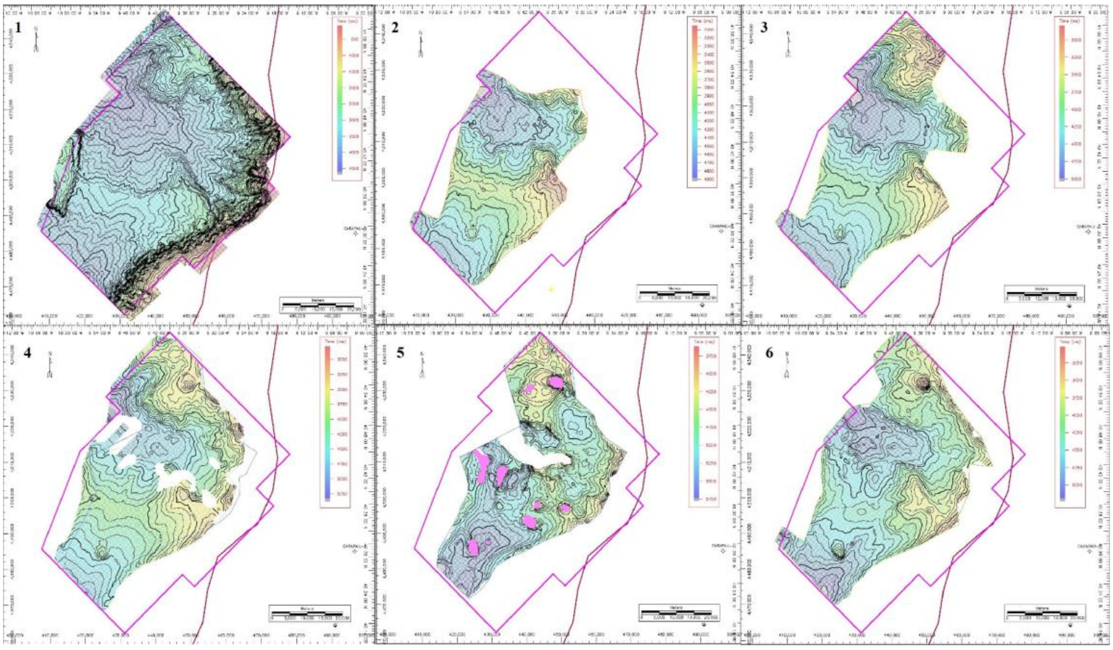


*Figure 57- 3D volume Camarão interpreted TWT maps 1-Base Oligocene Map; 2- Top Late Cretaceous Map; 3- Early Cretaceous map; 4- Top Late Jurassic Map; 5- Top Salt Map; 6- Top Middle Jurassic*

## Camarão 3D Depth Maps

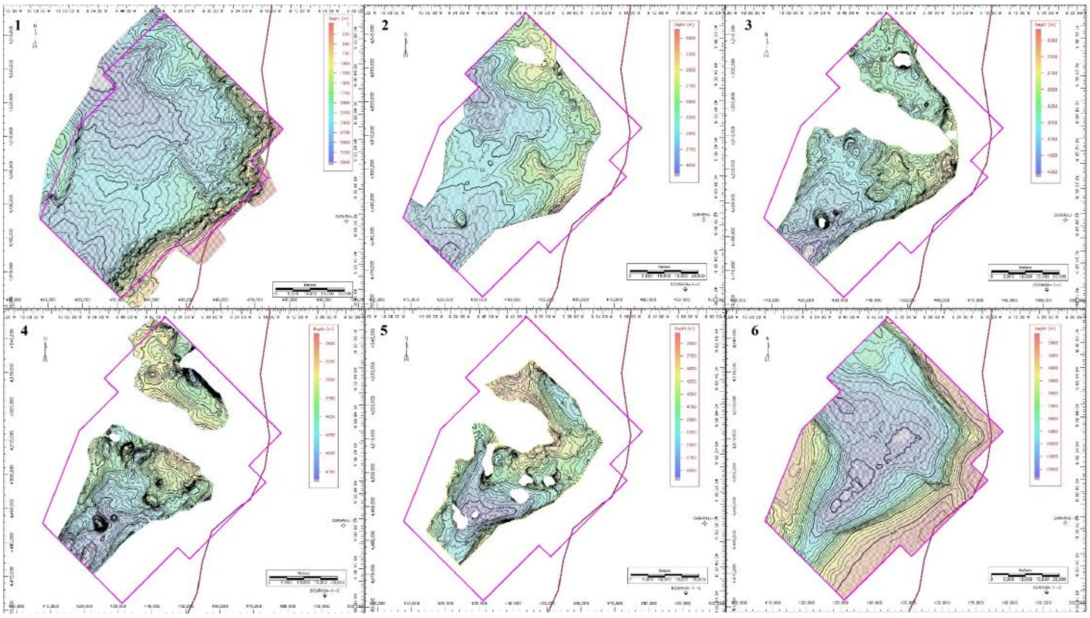


*Figure 58- 3D volume Camarão interpreted depth maps 1-Base Oligocene Map; 2- Top Late Cretaceous Map; 3- Early Cretaceous map; 4- Top Late Jurassic Map; 5- Top Salt Map; 6- Top Middle Jurassic*

# Seismic interpretation Concluding remarks

Eight horizons have been interpreted to provide a structural framework along the basin, based on variable quality seismic data with an uneven line spacing of 10 km to 150 km. Confidence in age interpretation is higher in the north, where published papers support the interpretation in the deep water away from well ties.

Regional seismic interpretation enables for the mapping of key horizons such as Oligocene, Albian, Aptian, Top Jurassic. Mid-Jurassic, Salt boundaries, pre-salt, Triassic and Basement. Salt tectonics imprint several attractive un-explored plays of the basin.

Key reflectors were interpreted above and beneath the original Triassic salt-rich unit, the Dagorda Fm. Faults and fractures affected the structuring of Peniche Basin, both the large Nazare Fault to the south and the northern Aveiro Fault are linked to major tectonic events and have been clearly identified on seismic, gravity and magnetics.

The Late Triassic rift is overlain by a Jurassic sag capped by a Callovian unconformity. Above it, the Late Jurassic/Early Cretaceous rift is filled by clastics progradation under the Late Aptian break-up unconformity (Figure 57). Salt diapirs rose through fractures and deformed the Mesozoic sequences. These events and the structural fabric imprint from several episodes of tectonic inversions, Campanian, Late Eocene and Late Miocene, are identifiable on seismic leading to an overall comprehensive interpretation of structuring and the role of salt tectonics in the deepwater realm of the basin.

# CHAPTER 3 – LEADS IDENTIFICATION

## Seismic mapping 3D Leads

From Petrobras (2008) 3D survey trough seismic interpretation was identified four structural Leads (Figure 59).

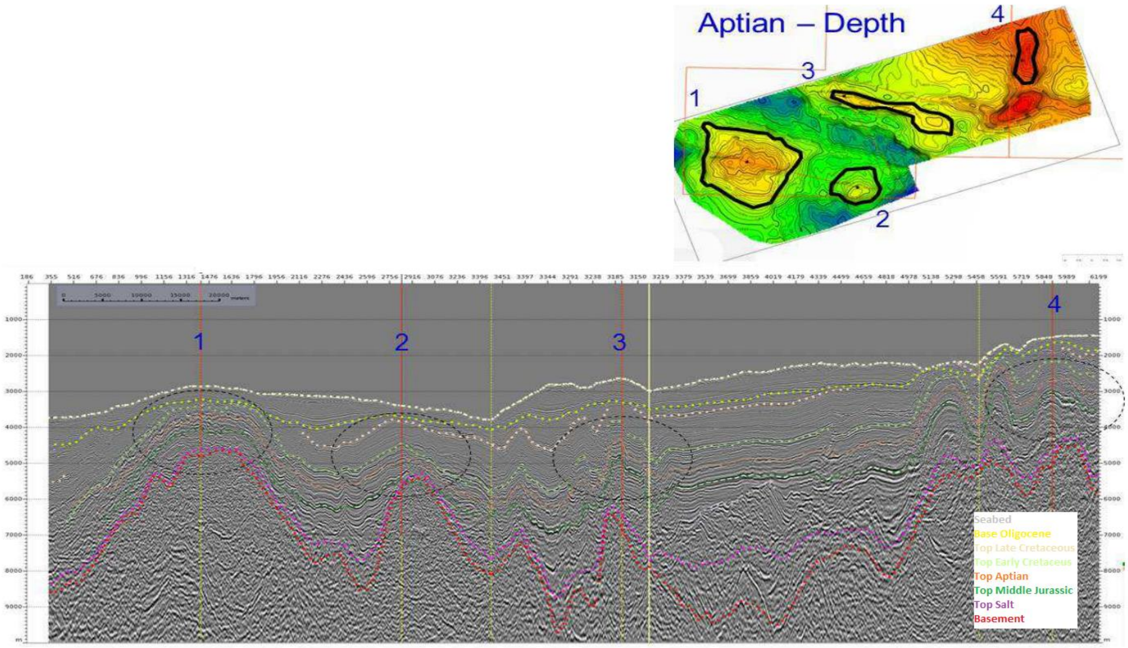


*Figure 59- Leads covered by 3D Seismic Data **1**- Lead 1; **2**-Lead 2; **3**;Lead 3 and **4**- Lead 4*

## Lead 1

The lead 1 (Figure 60) comprises a 224 km$_2$ (Number 1 on the Figure 59) anticline with a well-defined four-way closure. The structure is a Miocene inversion of a Jurassic – Cretaceous depocenter and the maximum vertical height is 700 meters. The water depth in the structure apex is about 2835 meters.

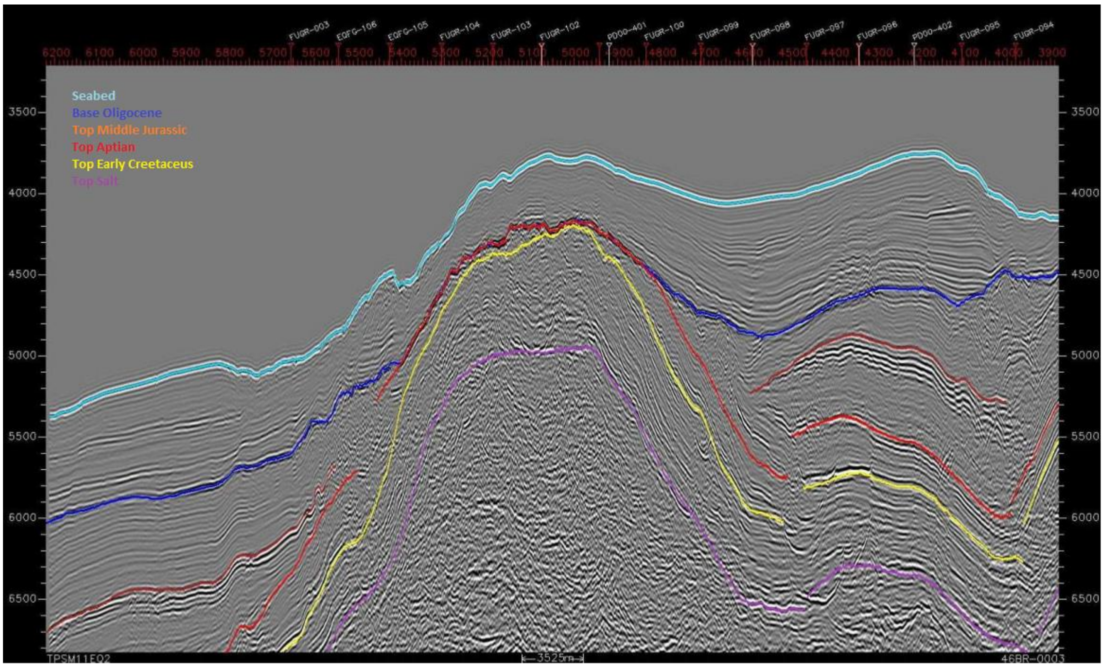


Figure 60- TWT section showing Lead 1

## Lead 2

The lead 2 comprises a 65 km2 anticline with a well-defined four-way closure. The structure is a Miocene inversion of a Jurassic – Cretaceous depocenter and the maximum vertical height is 450 meters. The water depth in the structure apex is about 3255 meters. (Figure 61)

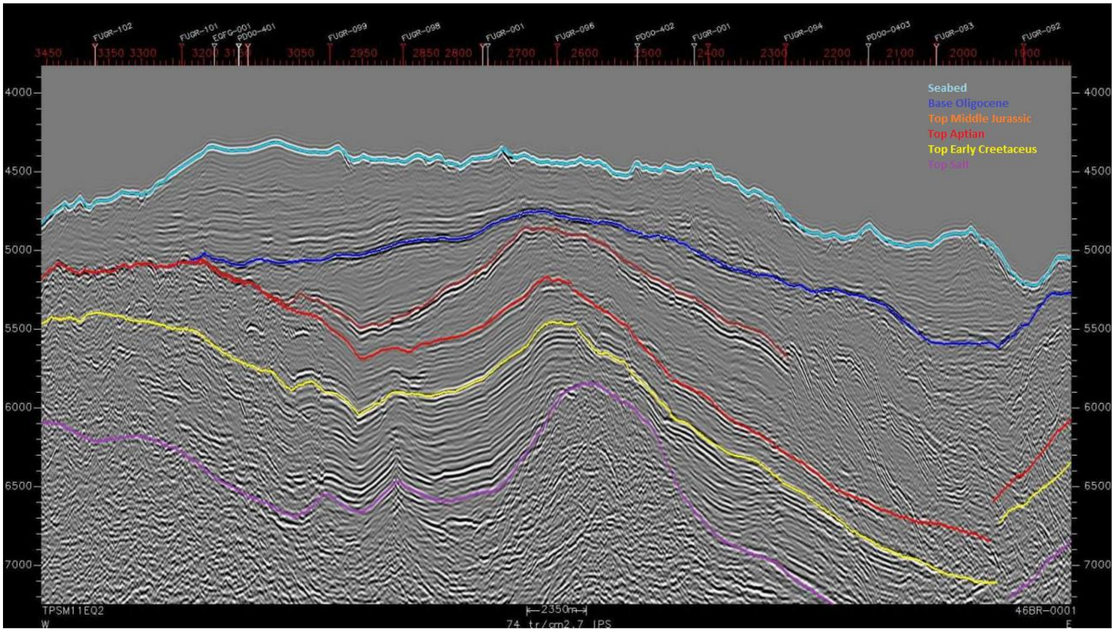


Figure 61- TWT Section showing the Lead 2

## Lead 3

The lead 3 comprises a 26 km2 anticline with a well-defined four-way closure. The structure is a Miocene inversion of a Jurassic – Cretaceous depocenter and the maximum vertical height is 400 meters. The water depth in the structure apex is about 1410 meters. (Figure 62)

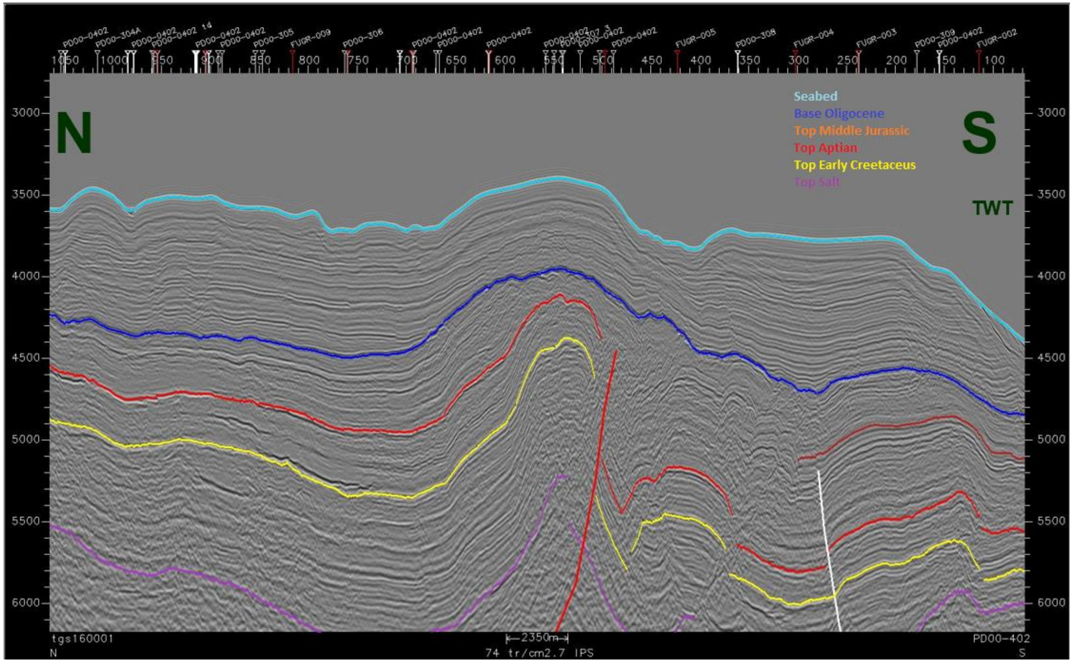


Figure 62- TWT Section showing the Lead 3

## Lead 4

The lead 4 comprises a 55 km2 anticline with a well-defined four-way closure. The structure is a Miocene inversion of a Jurassic – Cretaceous depocenter and the maximum vertical height is 450 meters. The water depth in the structure apex is about 1510 meters. (Figure 63)

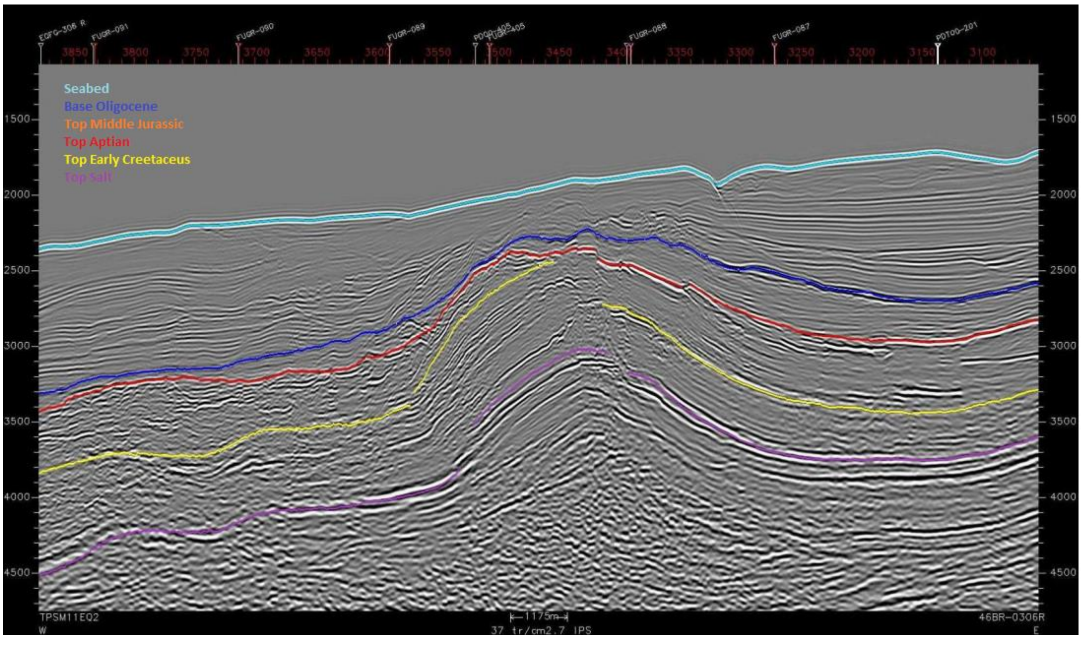


Figure 63- TWT Section showing the Lead 4

# PROSPECTIVITY AND HYDROCARBONS POTENTIAL OF PENICHE BASIN

The geophysics outlining Peniche Basin links its geology framework to the newly acquired geophysics data. Faults and fractures derived from the major tectonic events affecting the structuring of Peniche Basin identified on seismic, gravity and magnetics. Key reflectors representing the sedimentary deposition of siliciclastics and carbonates are clearly expressed on seismic records leading to the mapping of Leads above and beneath the original Triassic salt-rich unit, the Dagorda Fm. The Late Triassic rift is overlain by a Jurassic sag capped by a Callovian unconformity. Above it, the Late Jurassic/Early Cretaceous rift is filled by clastics progradation under the Late Aptian break-up unconformity. Salt diapirs rose through fractures and deformed the Mesozoic sequences. These events and the structural fabric imprint from several episodes of tectonic inversions, Campanian, Late Eocene and Late Miocene, are identifiable on seismic leading to an overall comprehensive interpretation of structuring and the role of salt tectonics in the Deepwater realm of the basin.

Deepwater Leads&prospects are encountered at more than 1,500 meters of water depth, these are well defined structural anticlines with four-way dip closures shaped recently by late Miocene tectonic inversion of the Jurassic-Cretaceous depocenters. These features are readily recognized by the geophysics data.

# CONCLUSIONS

Peniche Basin developed in the Atlantic Margin offshore Portugal along the western edge of the Iberia margin. This un-explored basin has attracted considerable interest due to its hydrocarbon potential and prospectivity. The basin formed as a rifted, non-volcanic, Atlantic continental margin type, trending on an N-S orientation that is roughly parallel to the Portuguese coastline between Lisbon and Aveiro. Its stratigraphy is genetically linked to the onshore Lusitanian Basin, these twin basins correspond to the inner (Lusitanian) and outer (Peniche) continental margin segments of West Iberia.

Data interpretation leads to consider that there are several active petroleum systems in the Peniche Basin and that the petroleum generated and trapped in this basin is at least comparable in volumes to what is generated in the Lusitanian Basin

Lower Cretaceous and older source rocks should potentially be mature for hydrocarbon generation these in the deeper portions of the rift basin, whereas in the Upper Cretaceous there might be Turonian-Cenomanian source rocks that also could yield mature oil generation along the Estremadura Spur.

Reservoir stratigraphy may comprise Cretaceous turbidites formed on basin floor fans and thick lower Cretaceous deltaic sequences these are readily recognizable on seismic. In the Jurassic succession there are sandstone reservoirs and in the Lower Jurassic porous carbonates may have developed. Regional seals shales and marls cap most of the structural traps. Several DHI's are recognized on seismic data, these are bright-spots amplitudes and flat-spot amplitudes that may indicate fluid content.

This geophysics interpretation of Peniche Basin was made from newly acquired and processed seismic reflection records and tied to gravity and magnetics interpretation. The key seismic reflectors representing interfaces along the sedimentary deposition of siliciclastics and carbonates are clearly expressed on the seismic records leading hence to the mapping of petroleum leads.

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# APPENDIX 1 – Grav-Mag Grids

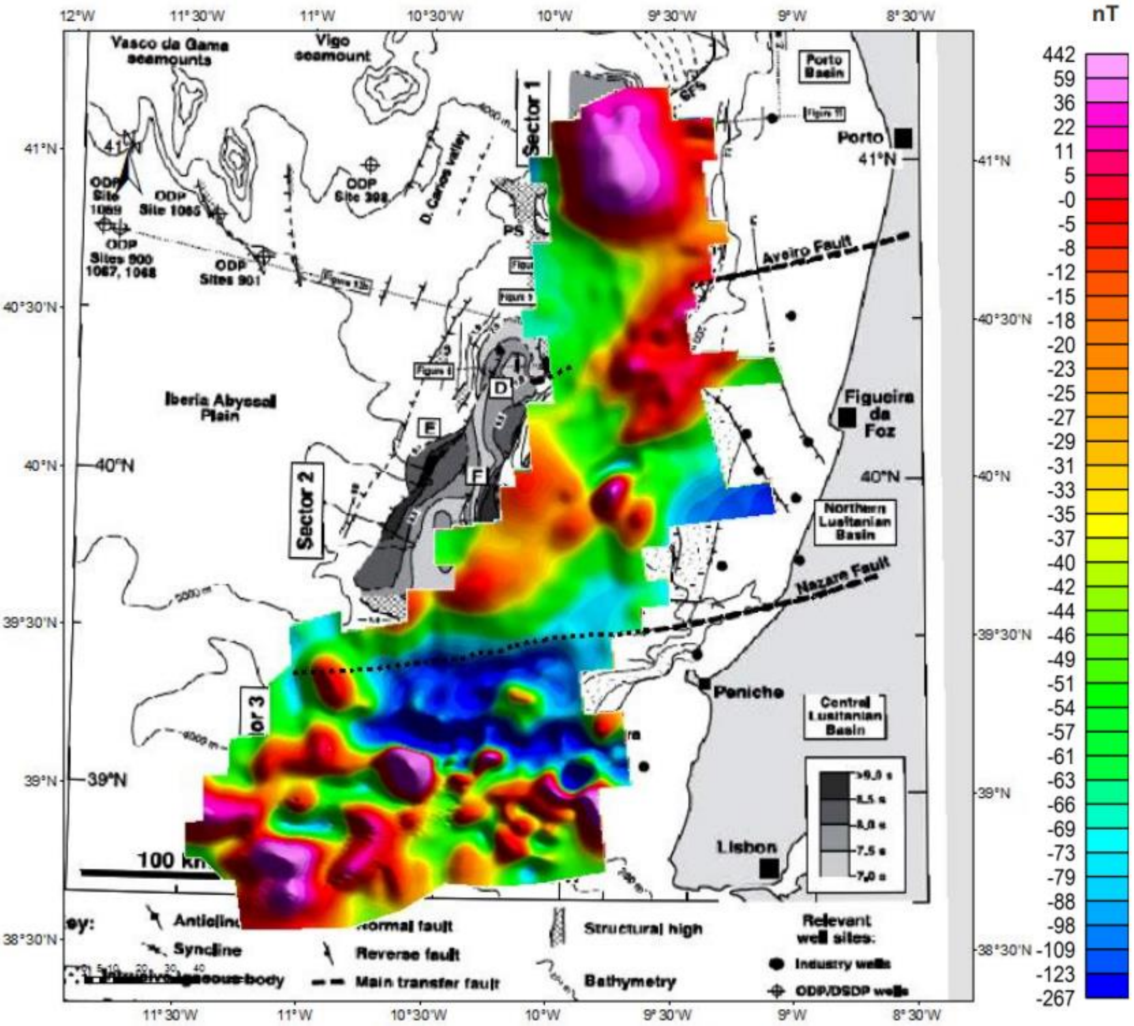

*Figure 64- The aim of this display is to show the structural map with gravity data.*

# 50 km RTP Residual

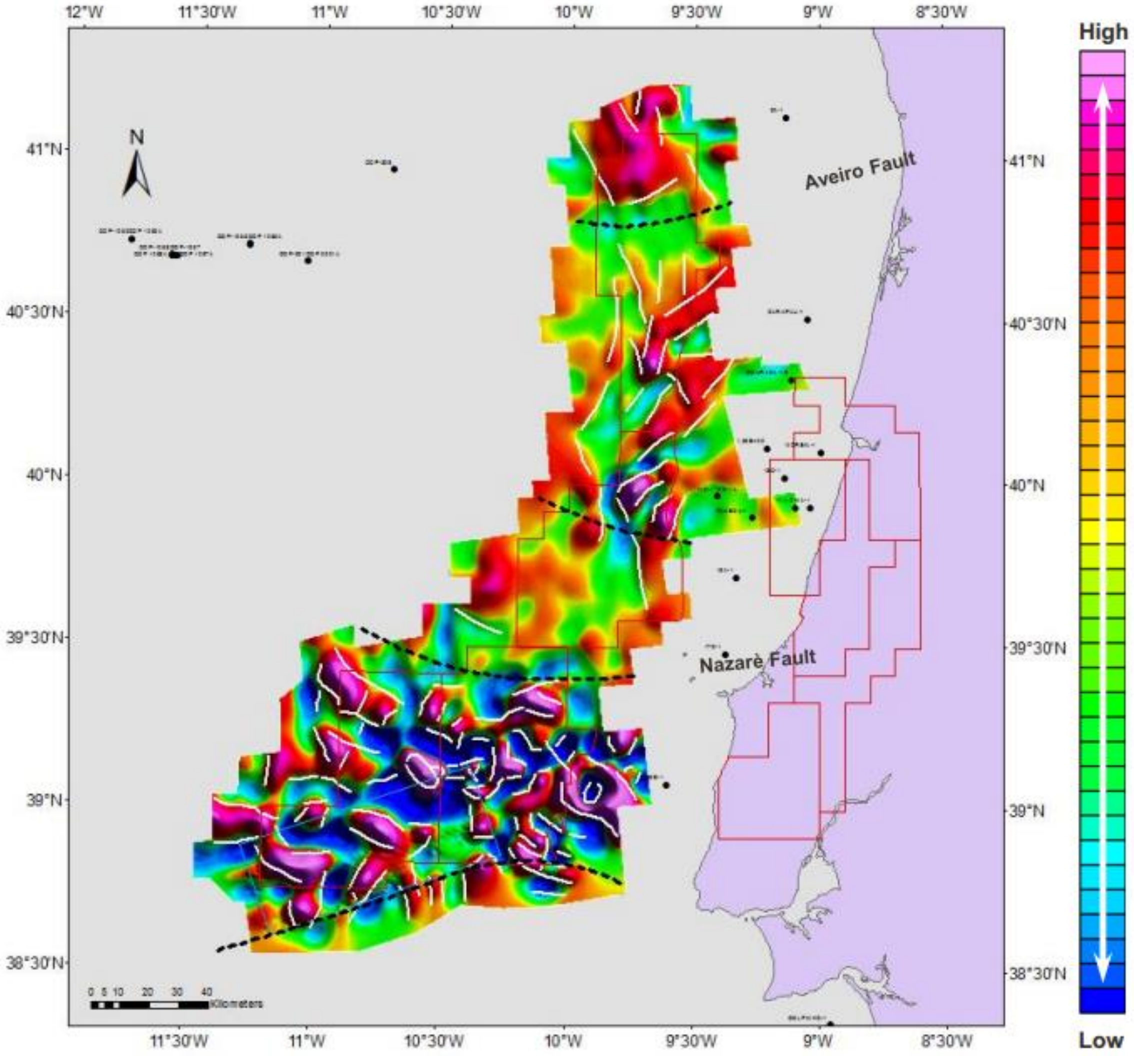

*Figure 65- 50km RTP Residual of Peniche basin from Repsol Annual Exploration Activity Report - Lineaments have been mostly picked by looking at the total horizontal gradient magnitude transformation except for a few minor faults. The mapped lineaments are very coherent with the previously shown enhanced maps and subsequent structural interpretation.*

## Horizontal gradient of RTP

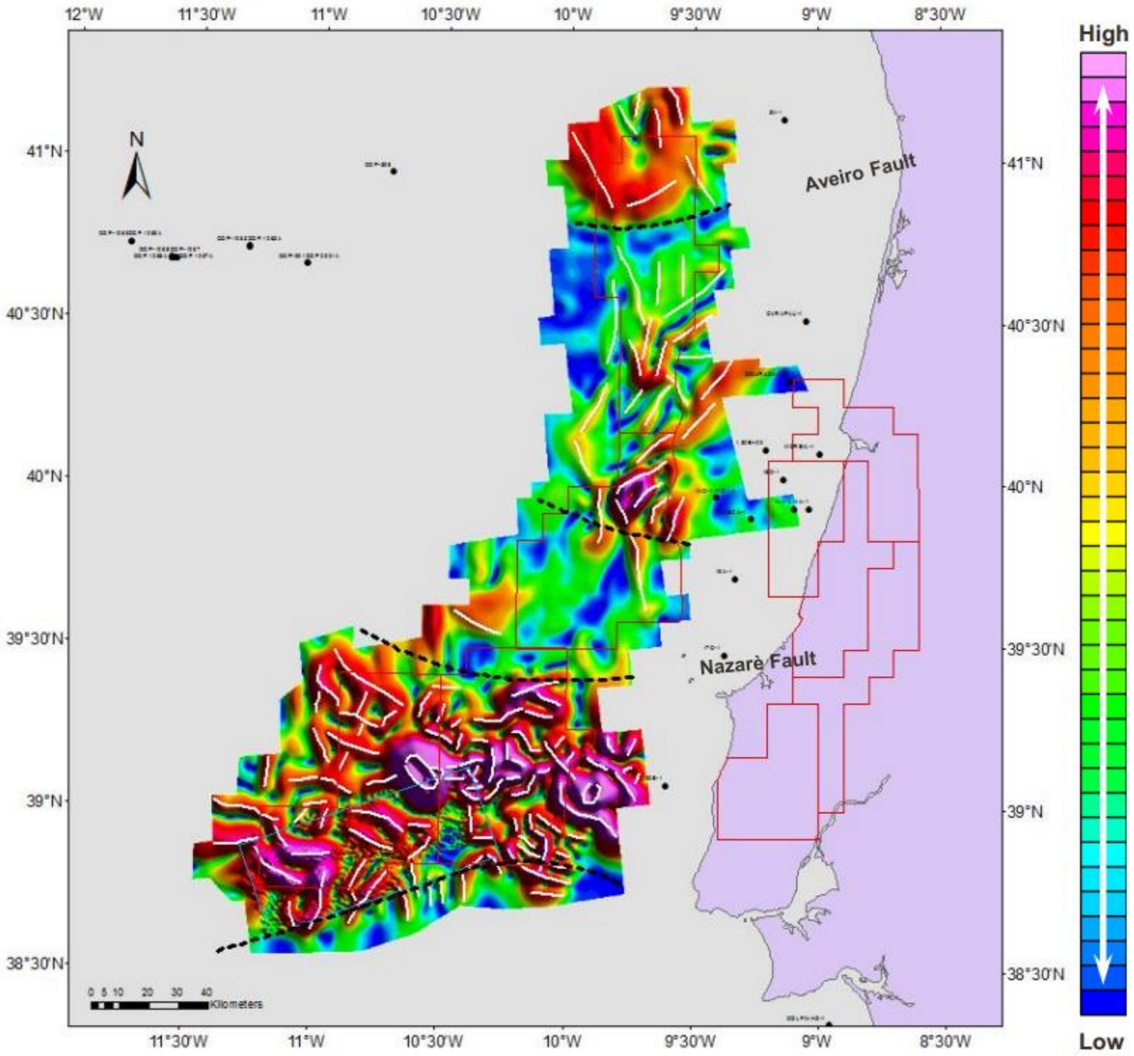

*Figure 66- Horizontal Gradient of RTP magnetics of Peniche basin from Repsol Annual Exploration Activity Report - Total horizontal gradient is used to sharpen up anomalies to highlight the edges of magnetic anomalies. Maxima locate over the edges of the source of the magnetic anomalies, highlighting structural lineaments and edges of tilted blocks or horst structures. A host of methods can be applied to pick the lineaments from this enhancement or others, however ACLAS method (Cascone et al., 2012) is able to compare more than one to achieve the most objective result.*

## Normalized Bouguer Gravity Residual

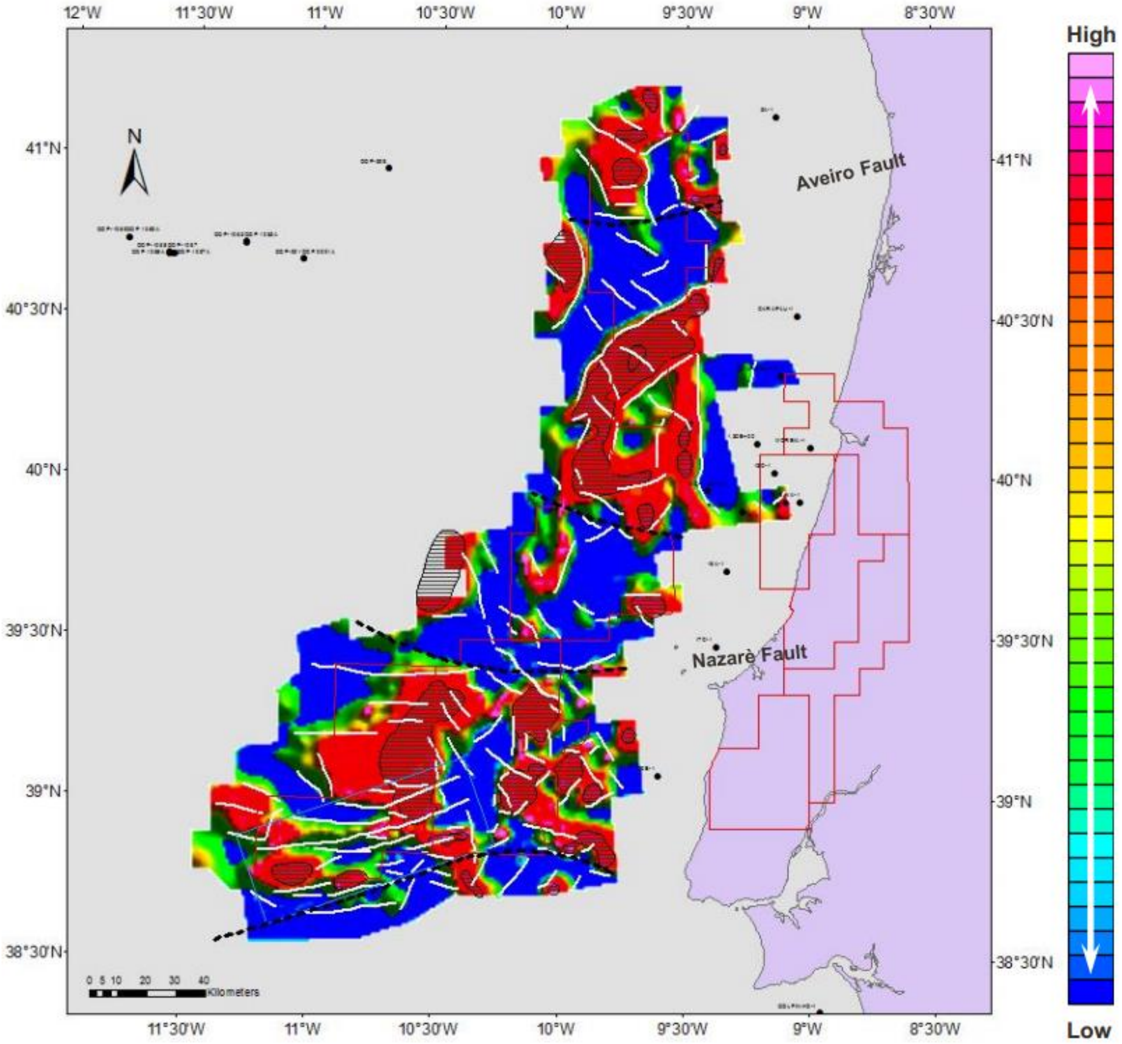

*Figure 67- Normalized Bouguer Gravity Residual of Peniche basin from Repsol Annual Exploration Activity Report - Lineaments have been mostly picked by looking at the total horizontal gradient magnitude transformation except for a few minor faults. The mapped lineaments are very coherent with the previously shown enhanced maps and subsequent structural interpretation.*

## Normalized Bouguer Gravity Residual

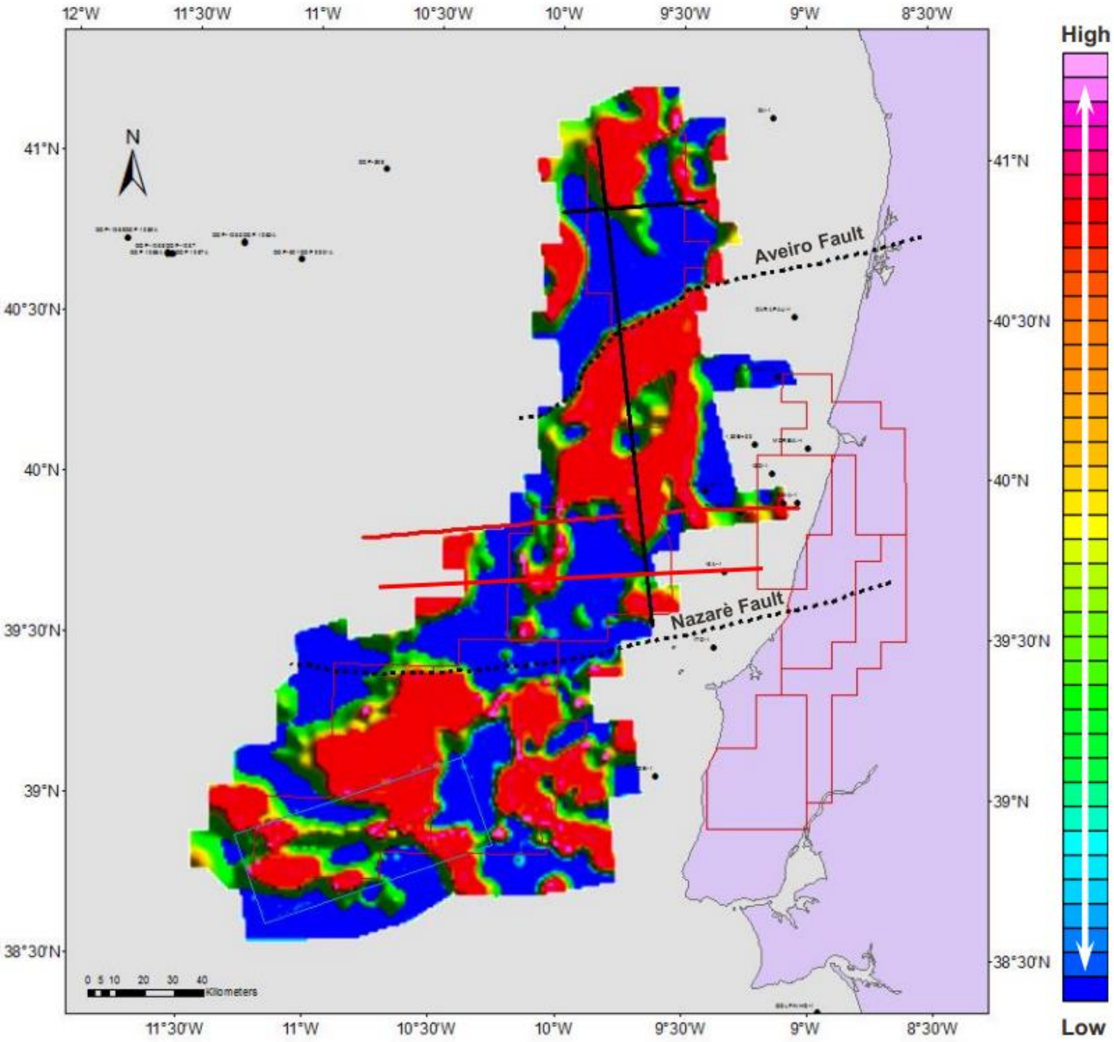

*Figure 68- Normalized Bouguer Gravity Residual of Peniche basin from Repsol Annual Exploration Activity Report - This is a normalized high pass residual showing areas of relative structural high displayed below in red colours. Again, there is an obvious correlation with the tectonic features of the Peniche Basin.*

## Normalized Bouguer Gravity Residual

This is a normalized high pass residual showing areas of relative structural high (red colours) enhancing, sharpening, the resolution of data.

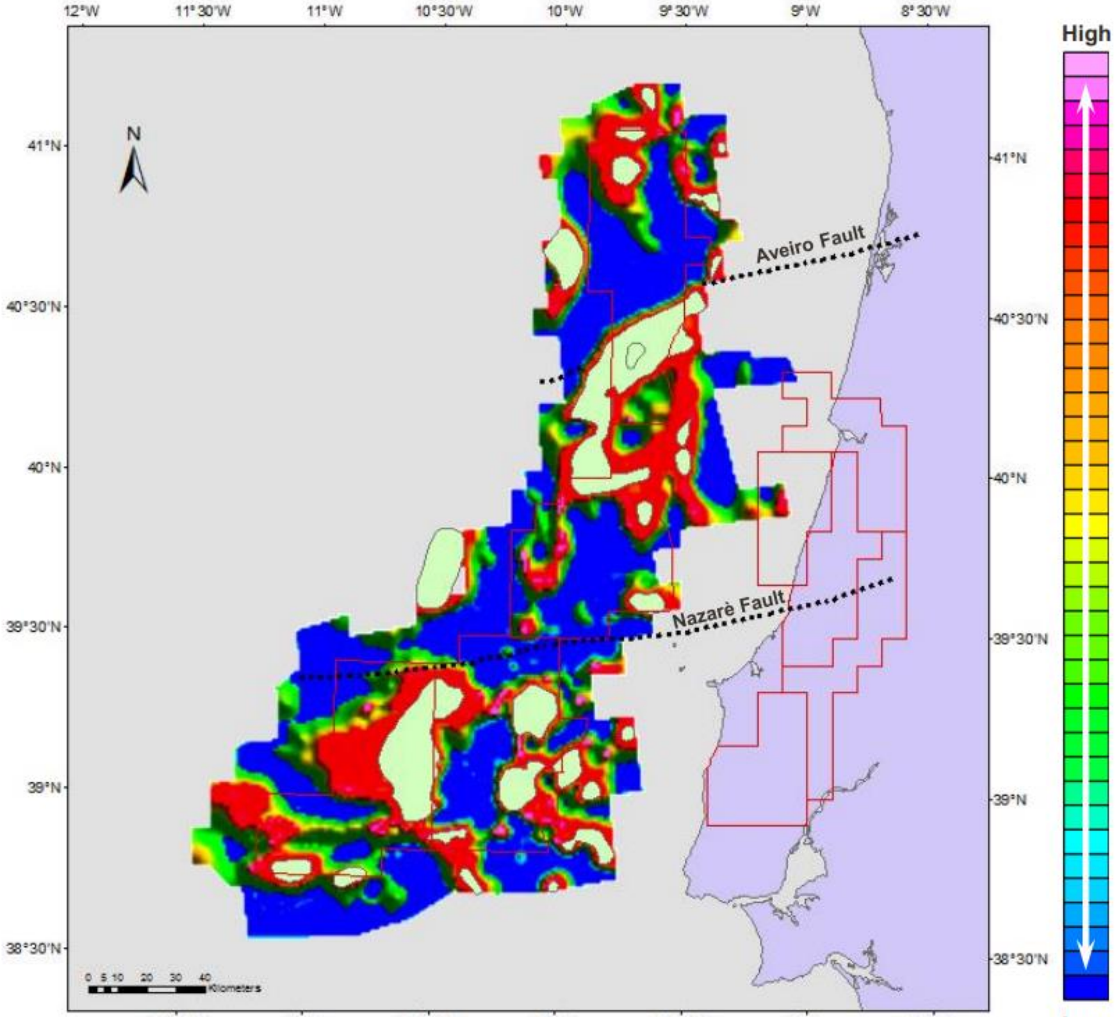

*Figure 69- Normalized Bouguer Gravity Residual - Polygons highlight major gravity anomalies location*

# APPENDIX 2 – 2 D regional Seismic Grids

## Regional Two-Way-Time Maps

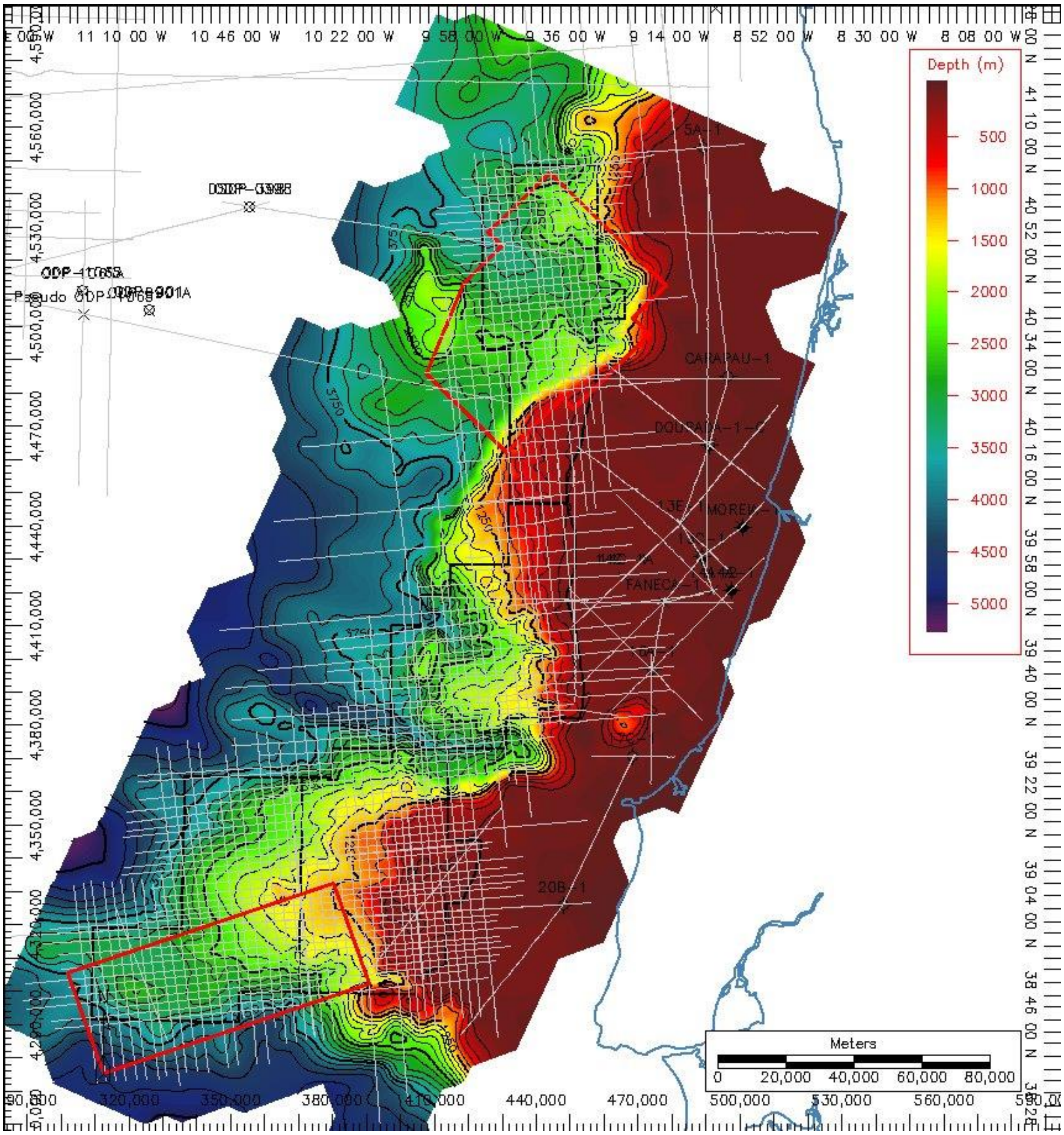

Figure 70- Peniche Regional Seabed TWT Map

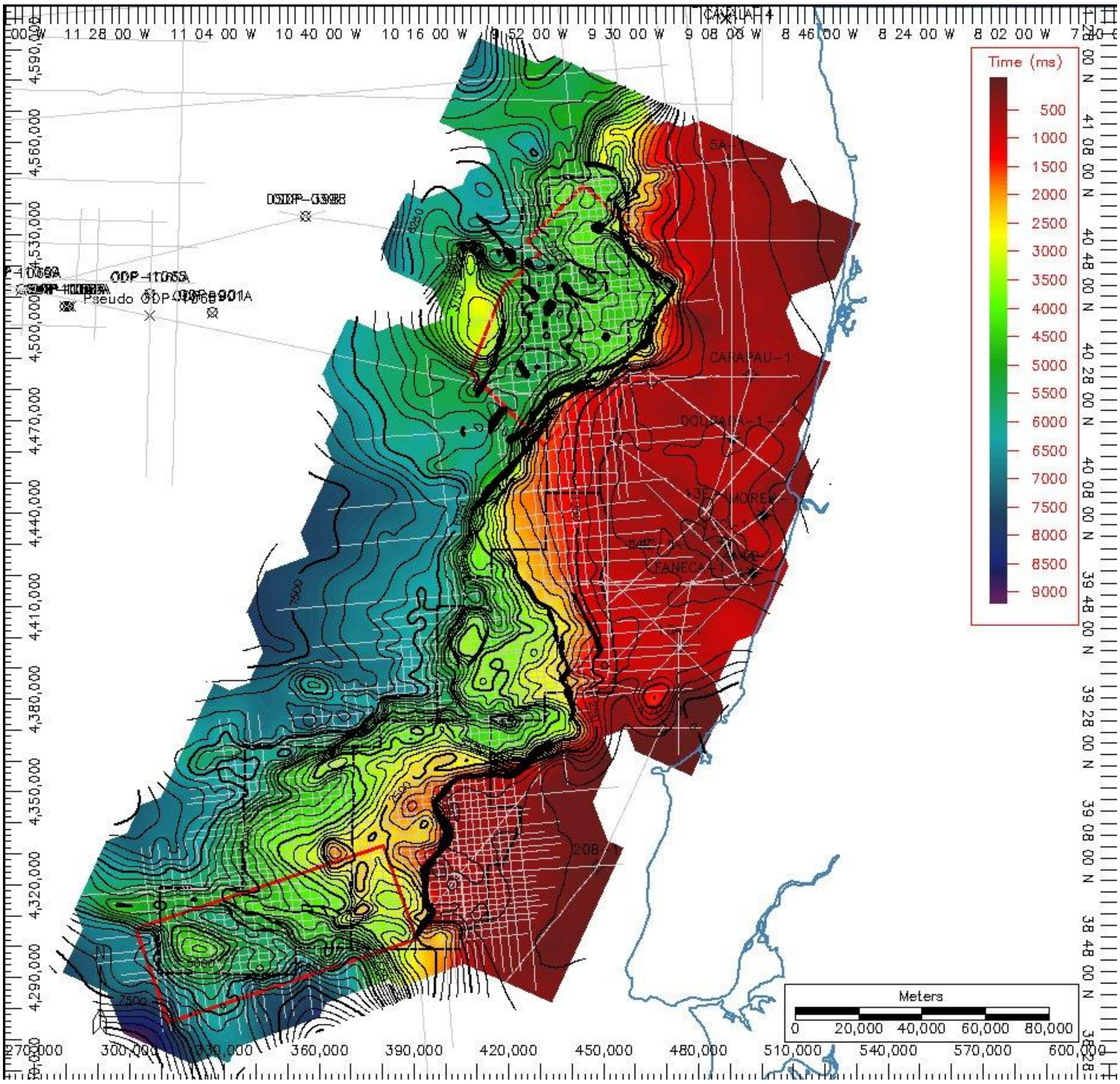

Figure 71- Peniche Regional Base Oligocene TWT Map

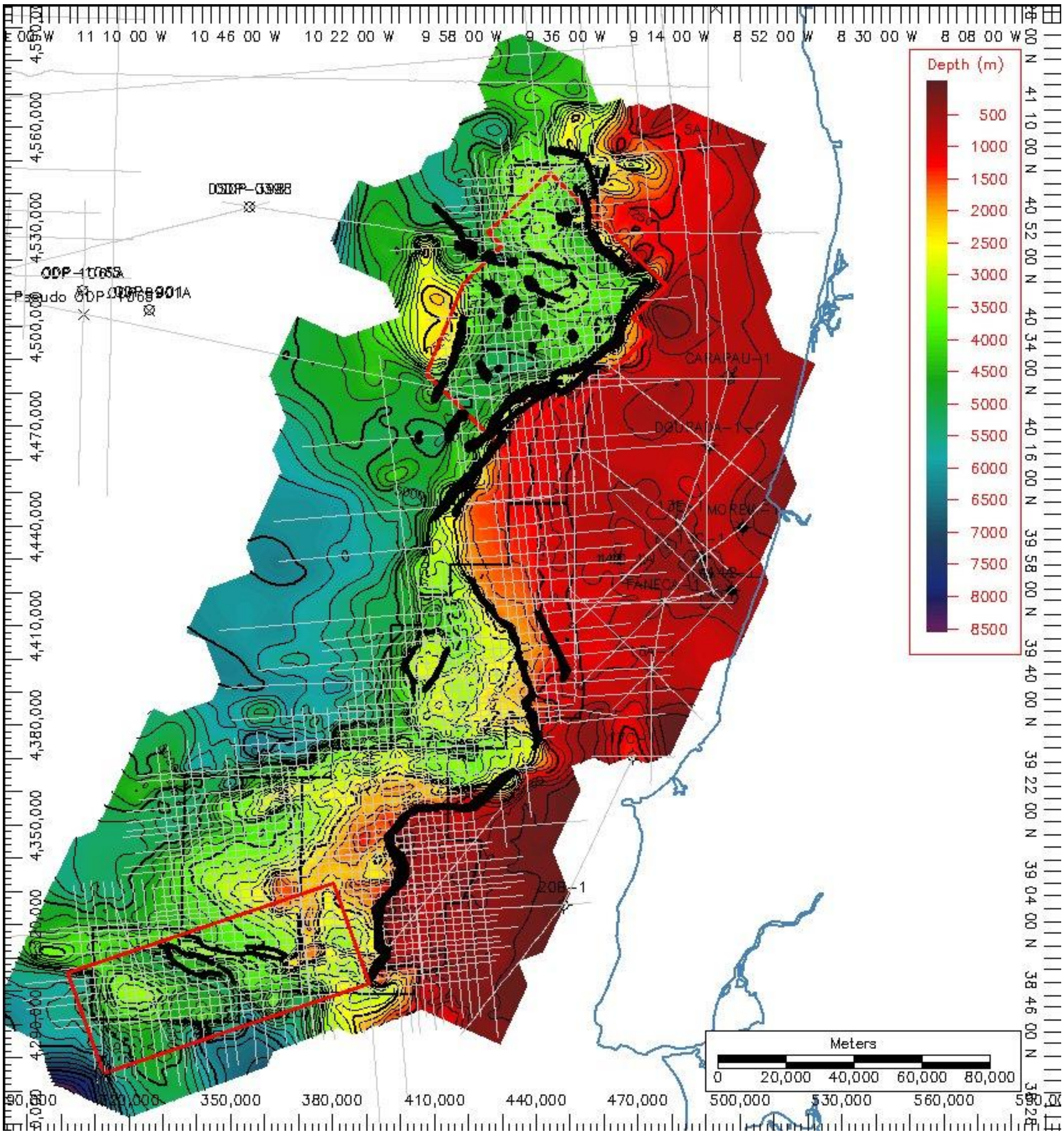

*Figure 72- Peniche Regional Top Early Cretaceous TWT Map*

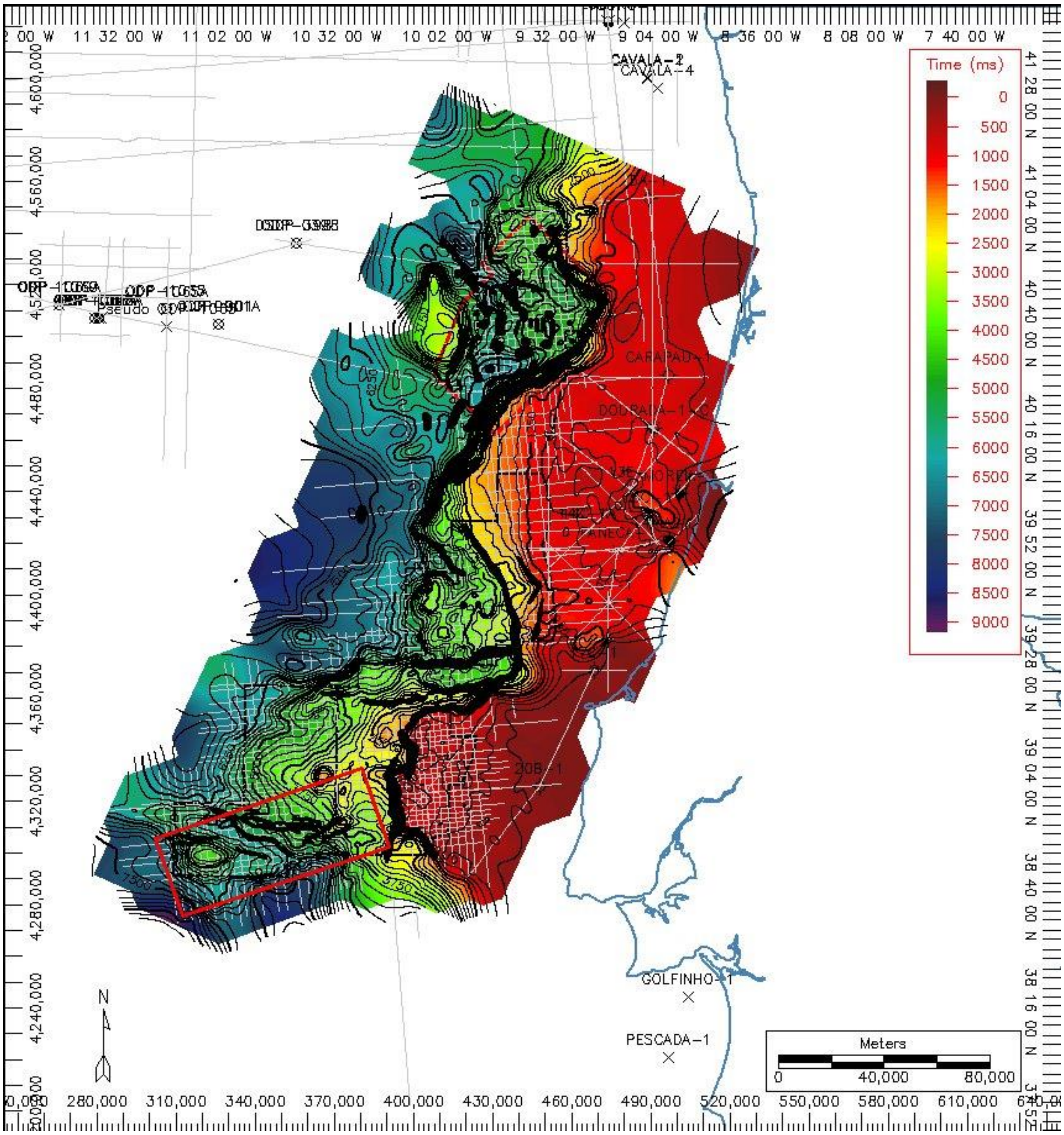

Figure 73- Peniche Regional Top Jurassic TWT Map

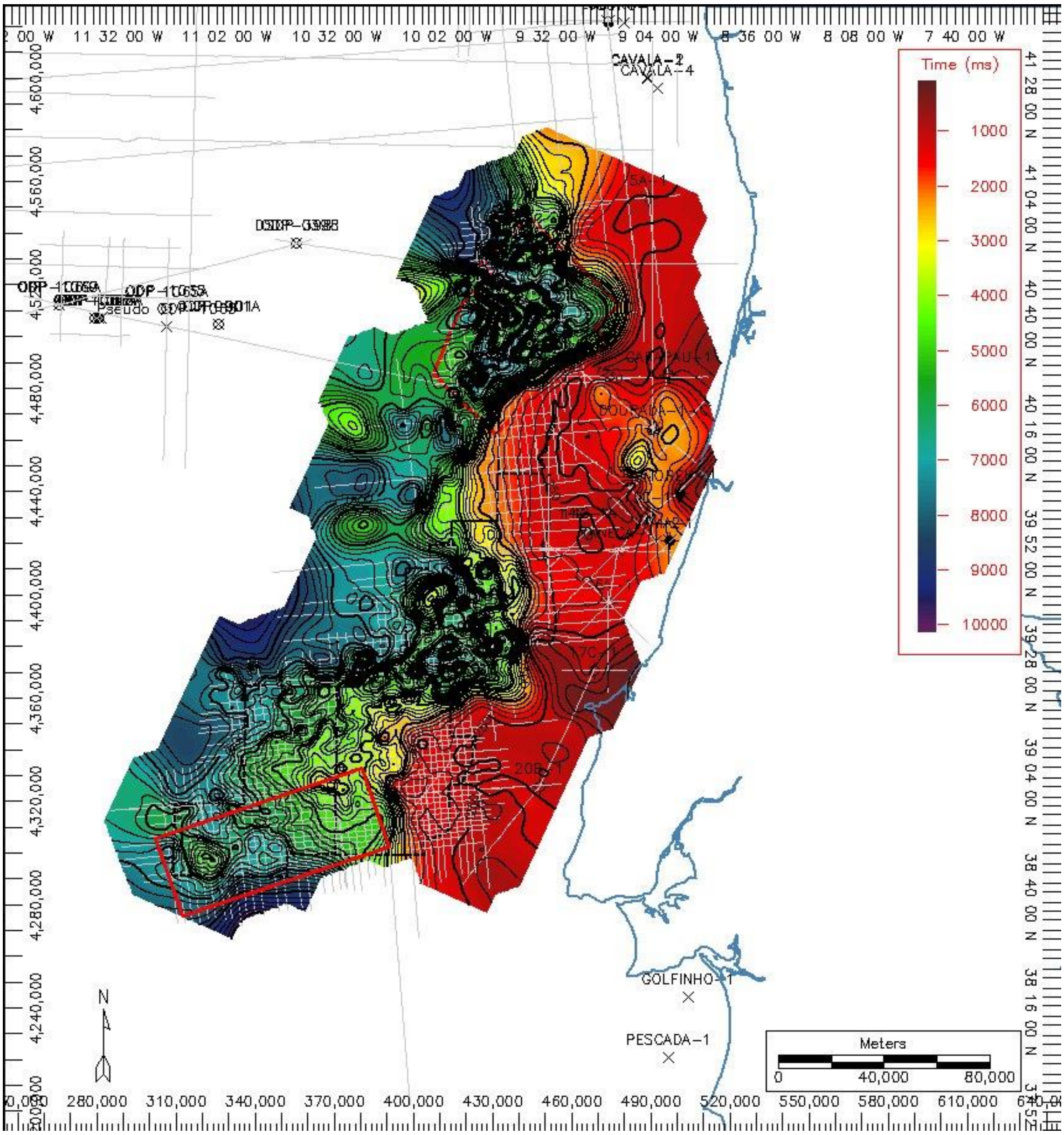

*Figure 74- Peniche Regional Top Salt TWT Map*

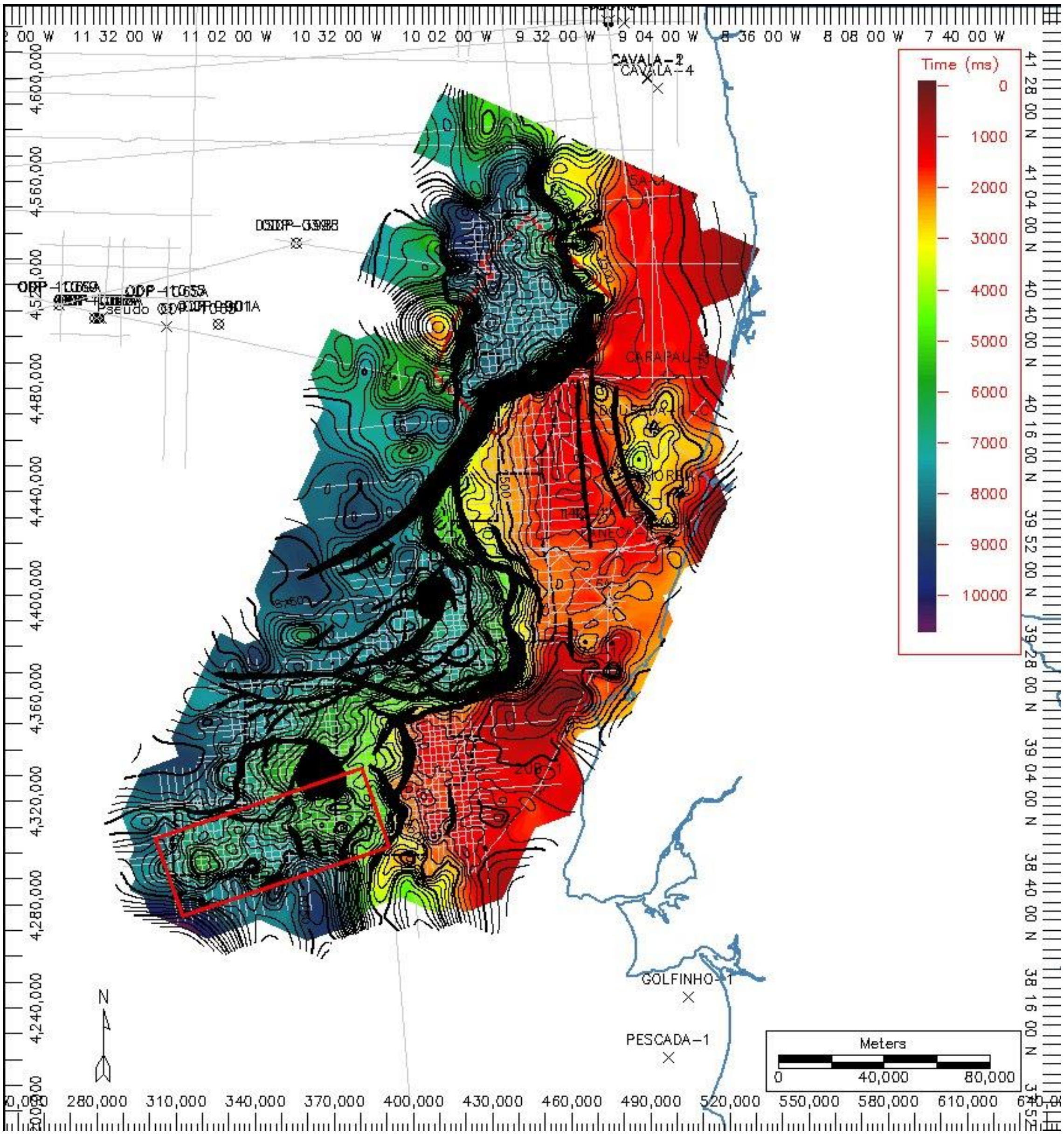

Figure 75- Regional Top Basement TWT Map

# Regional Depth Maps

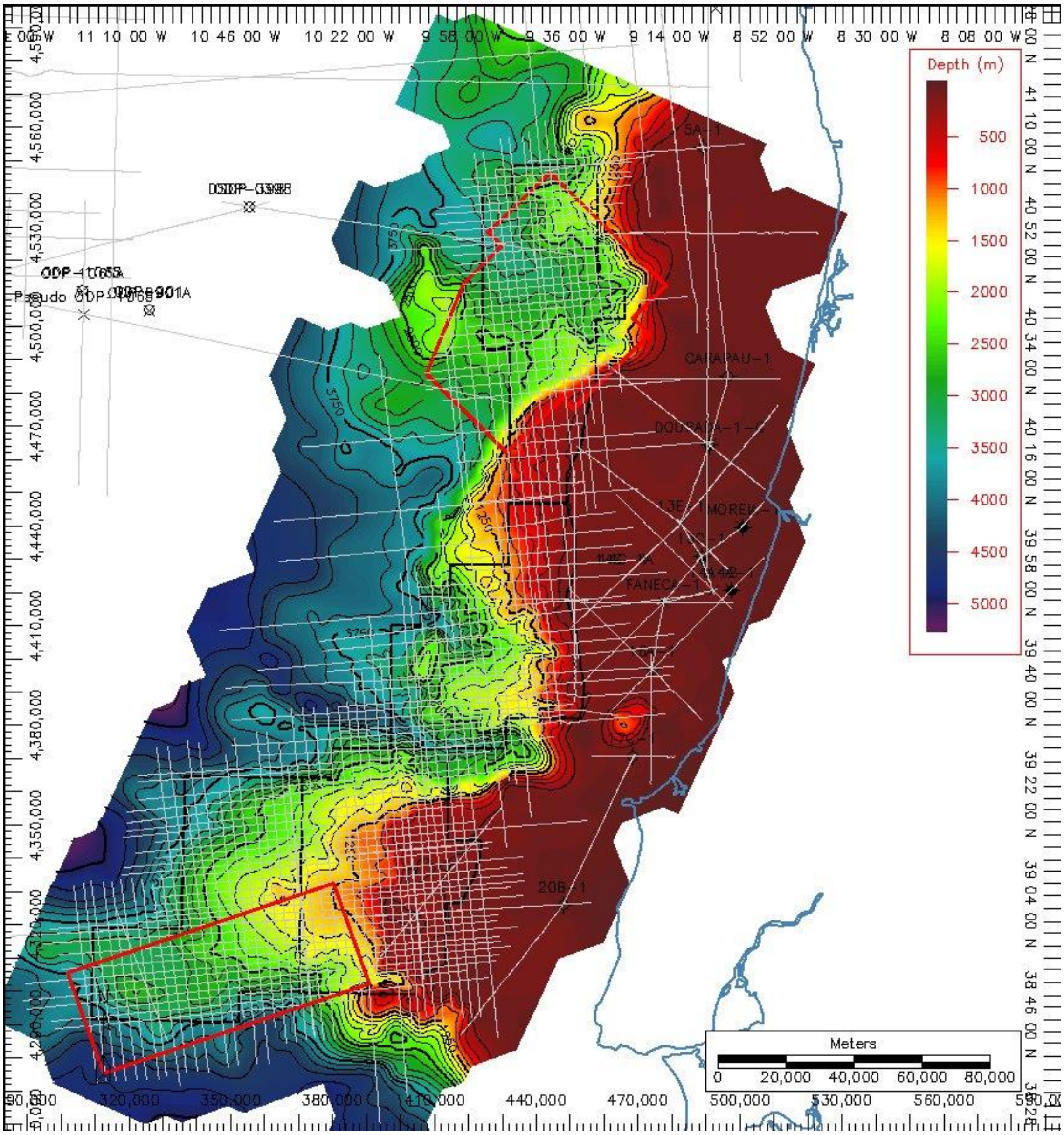

Figure 76- Peniche Regional Seabed Depth Map

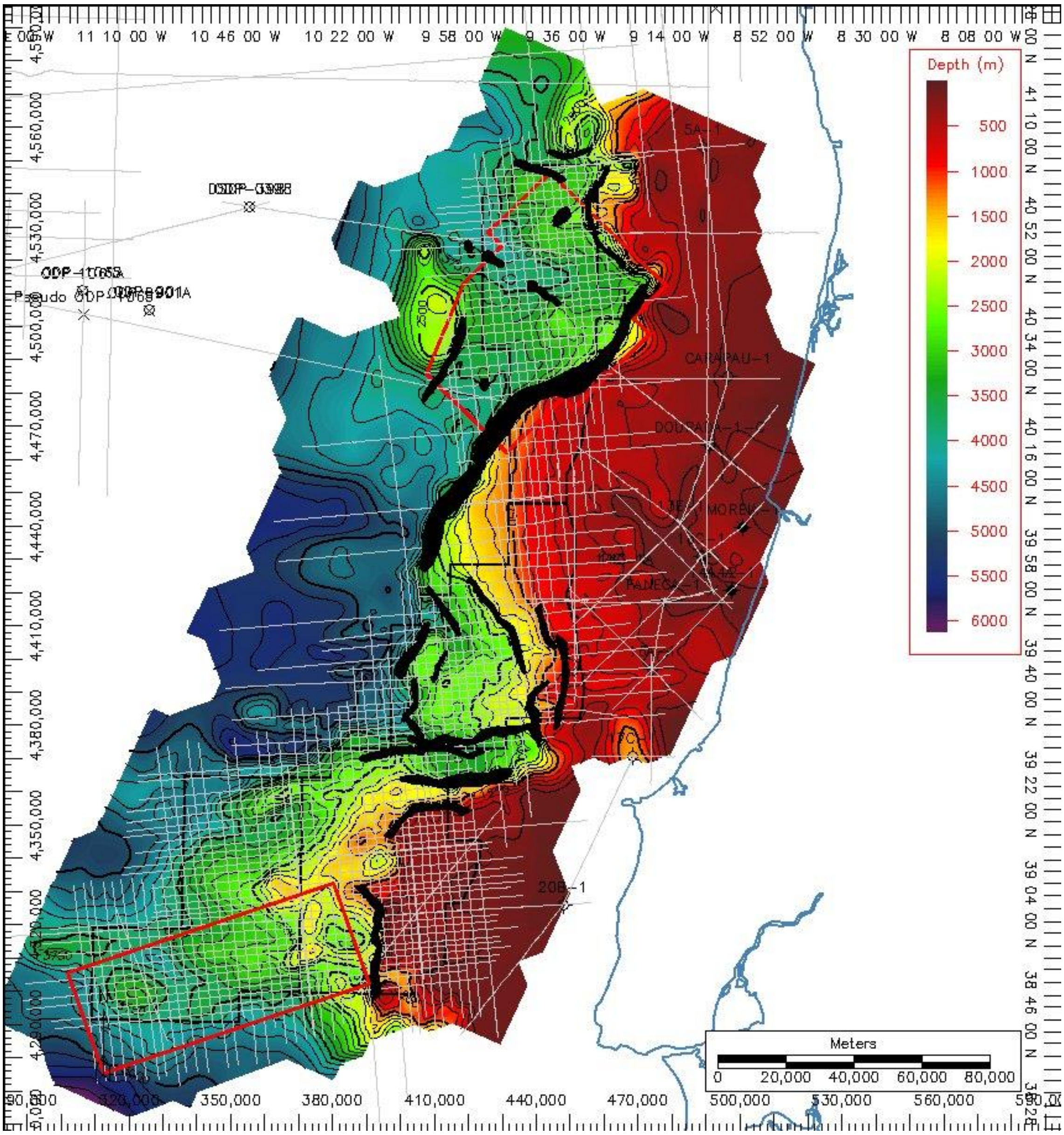

Figure 77- Peniche Regional Base Oligocene Depth Map

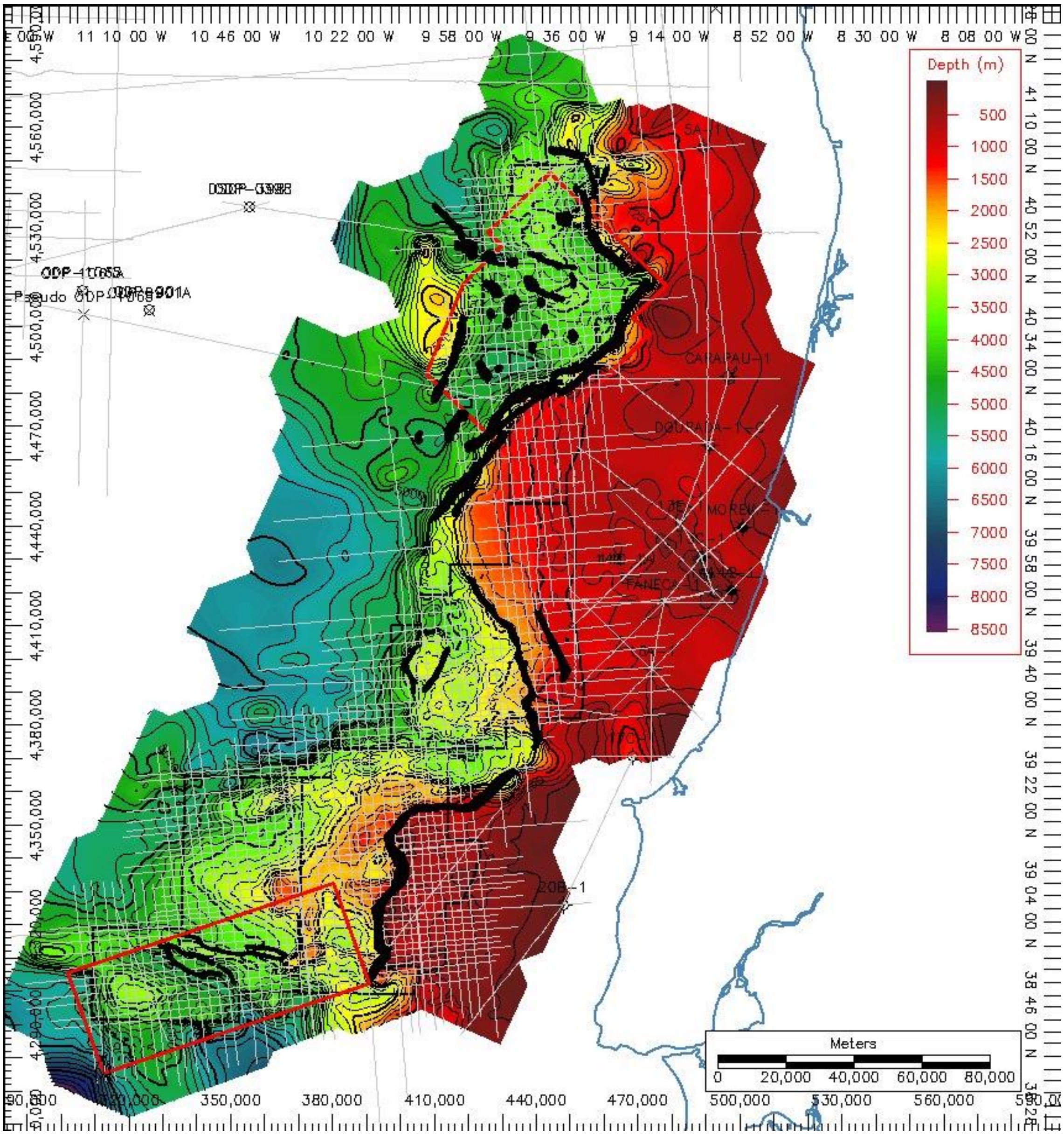

Figure 78- Peniche Regional Top Early Cretaceous Depth Map

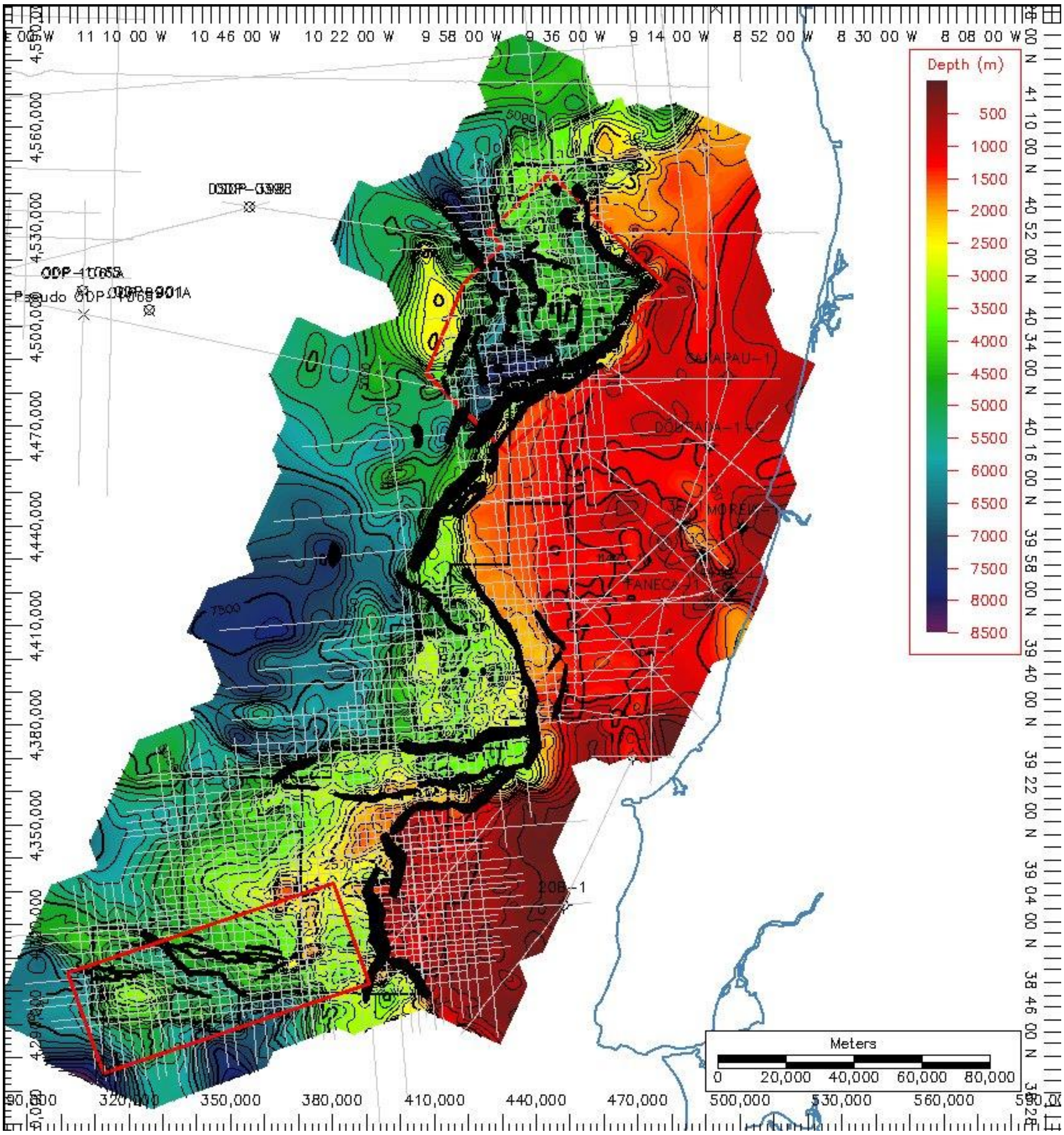

Figure 79- Peniche Regional Top Jurassic Depth Map

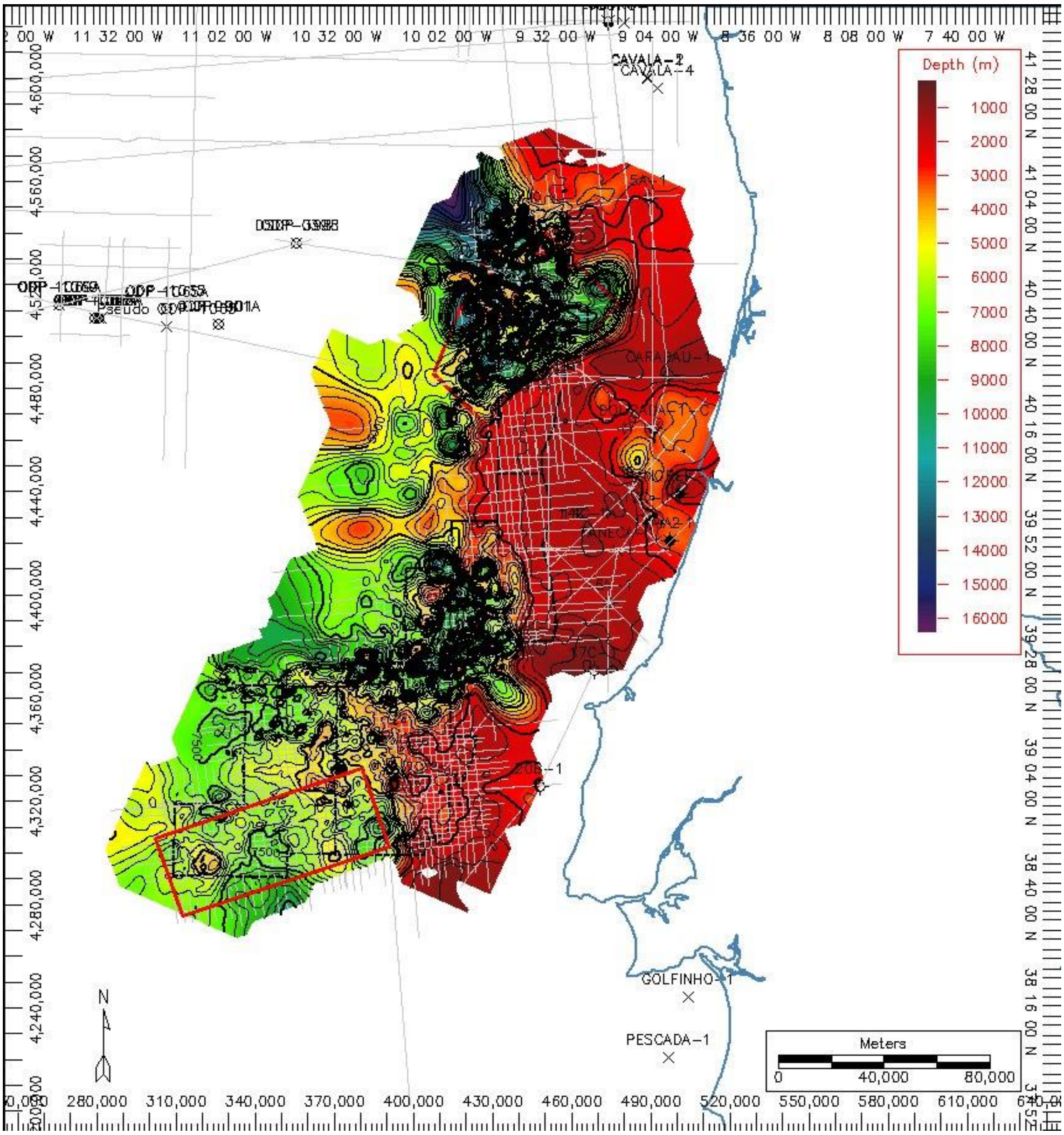

Figure 80- Peniche Regional Top Salt Depth Map

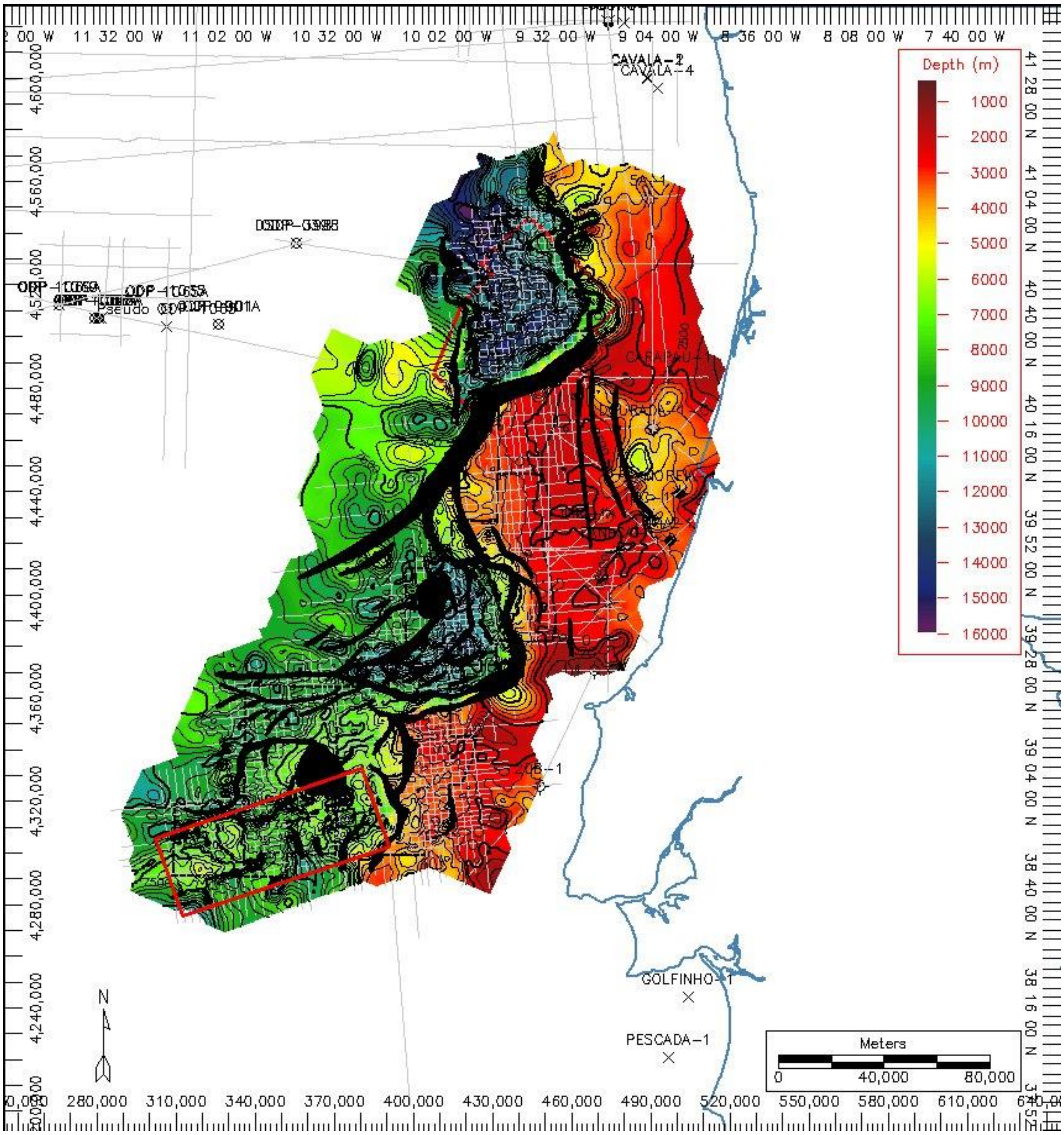

*Figure 81- Peniche Regional Basement Depth Map*

# APPENDIX 3 – 3 D Seismic Grids

## Camarão Time maps:

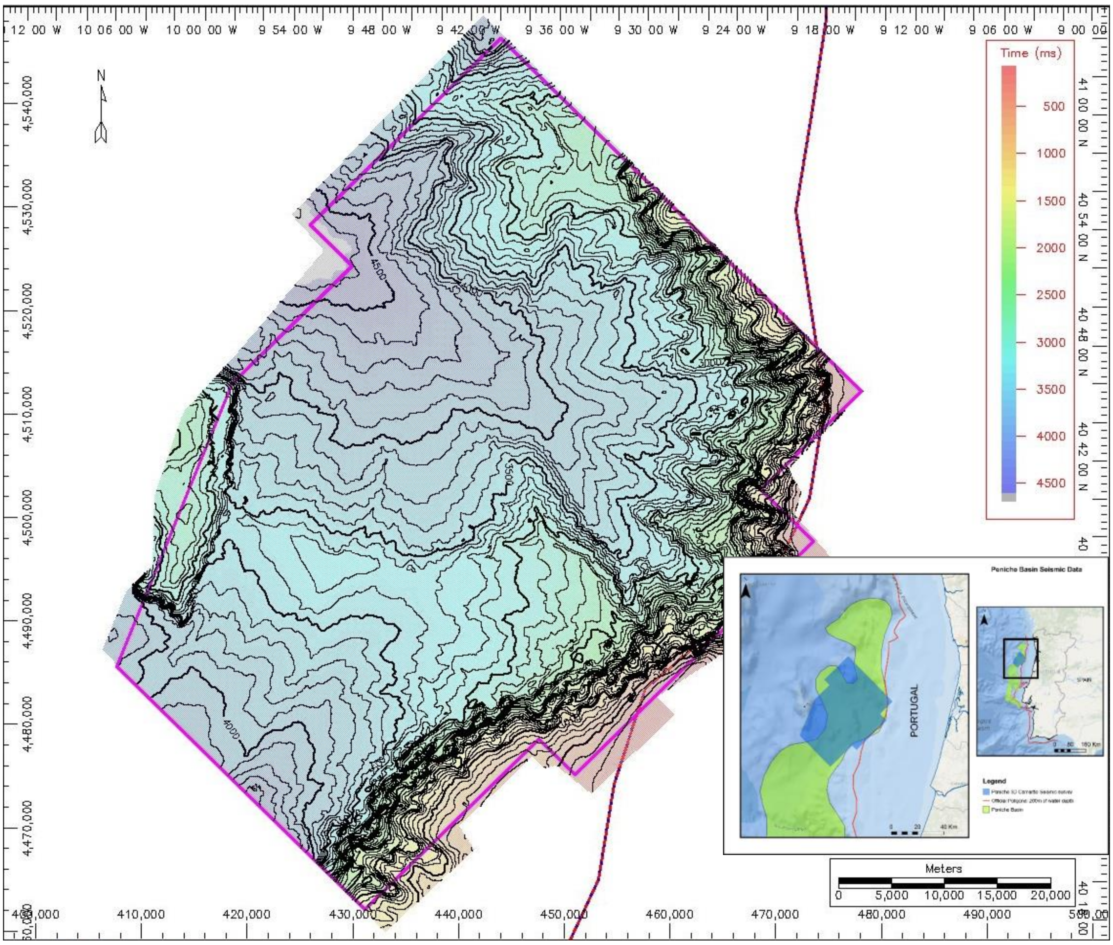

Figure 82- 3D volume Camarão interpreted TWT seabed map

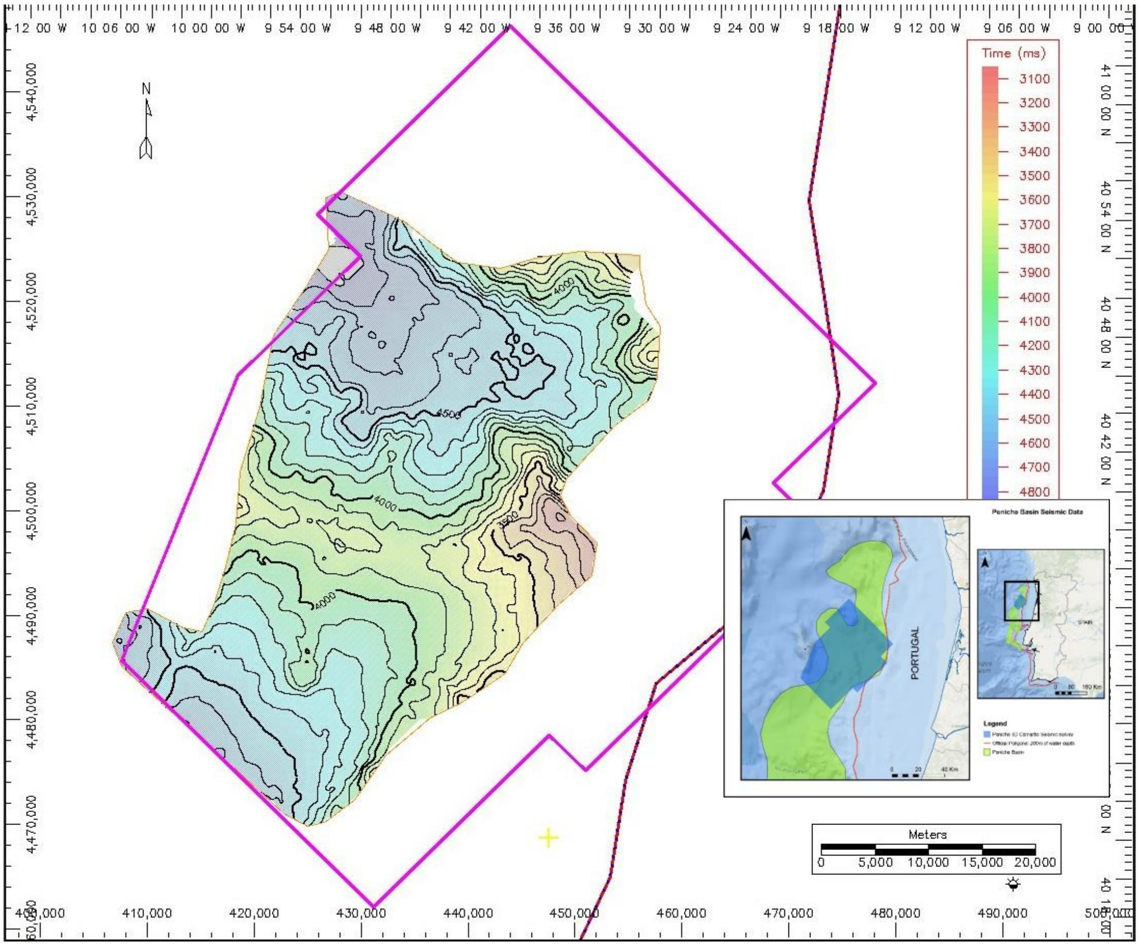

Figure 83- 3D volume Camarão interpreted TWT Base Oligocene

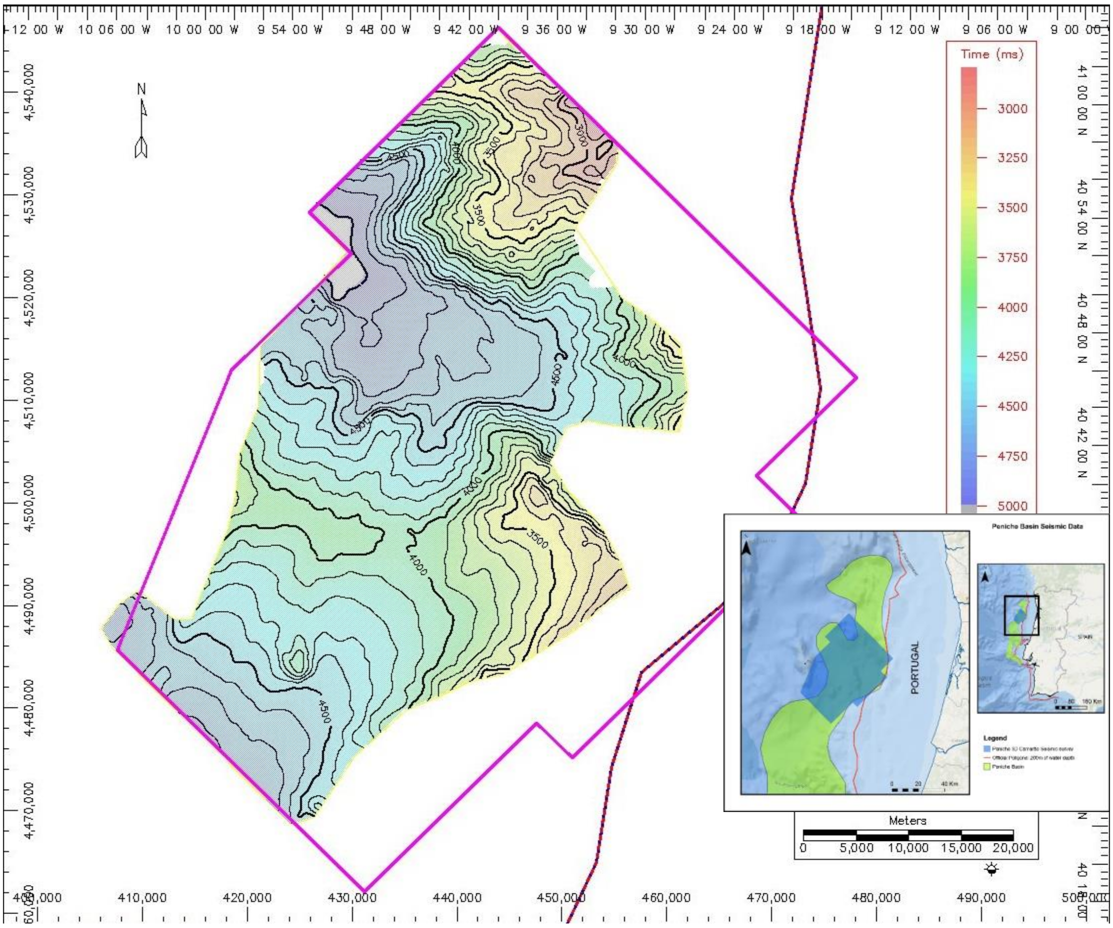

Figure 84- 3D volume Camarão interpreted Top Early Cretaceous

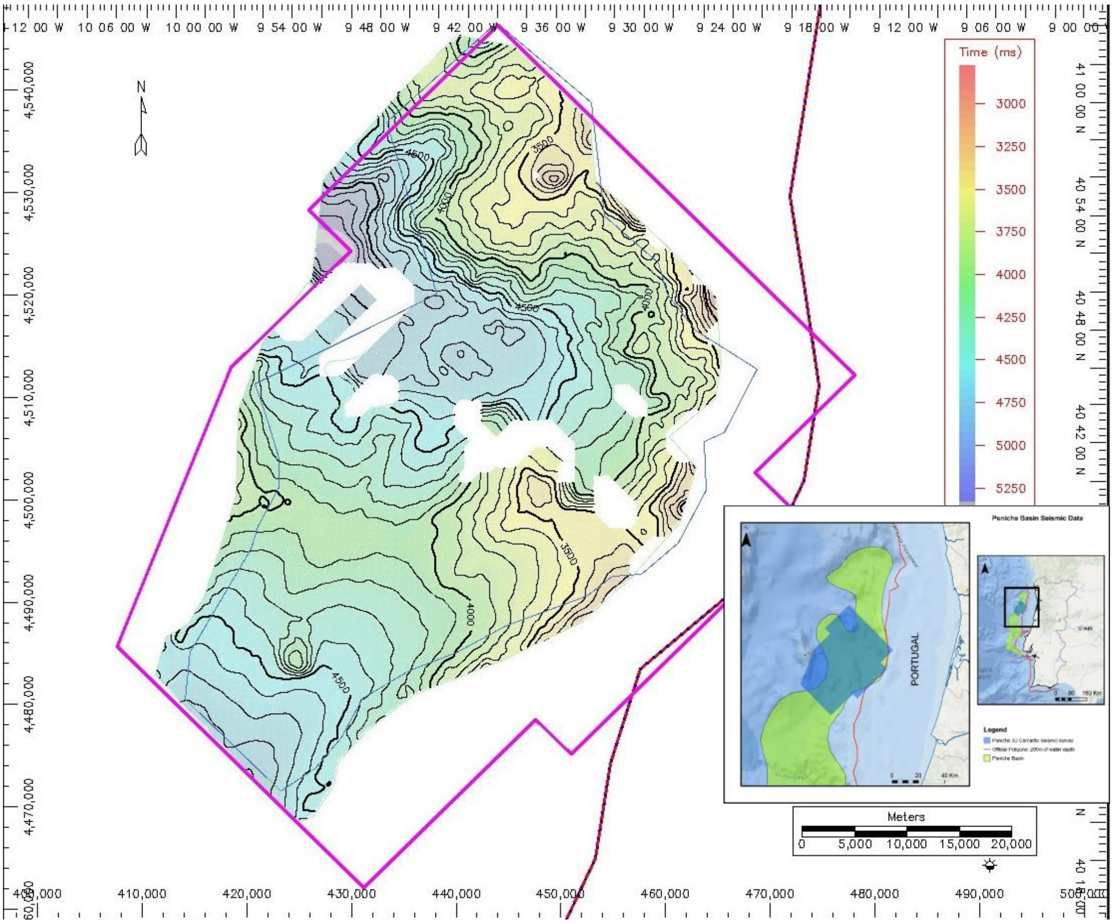

Figure 85- 3D volume Camarão interpreted TWT Late Cretaceous map

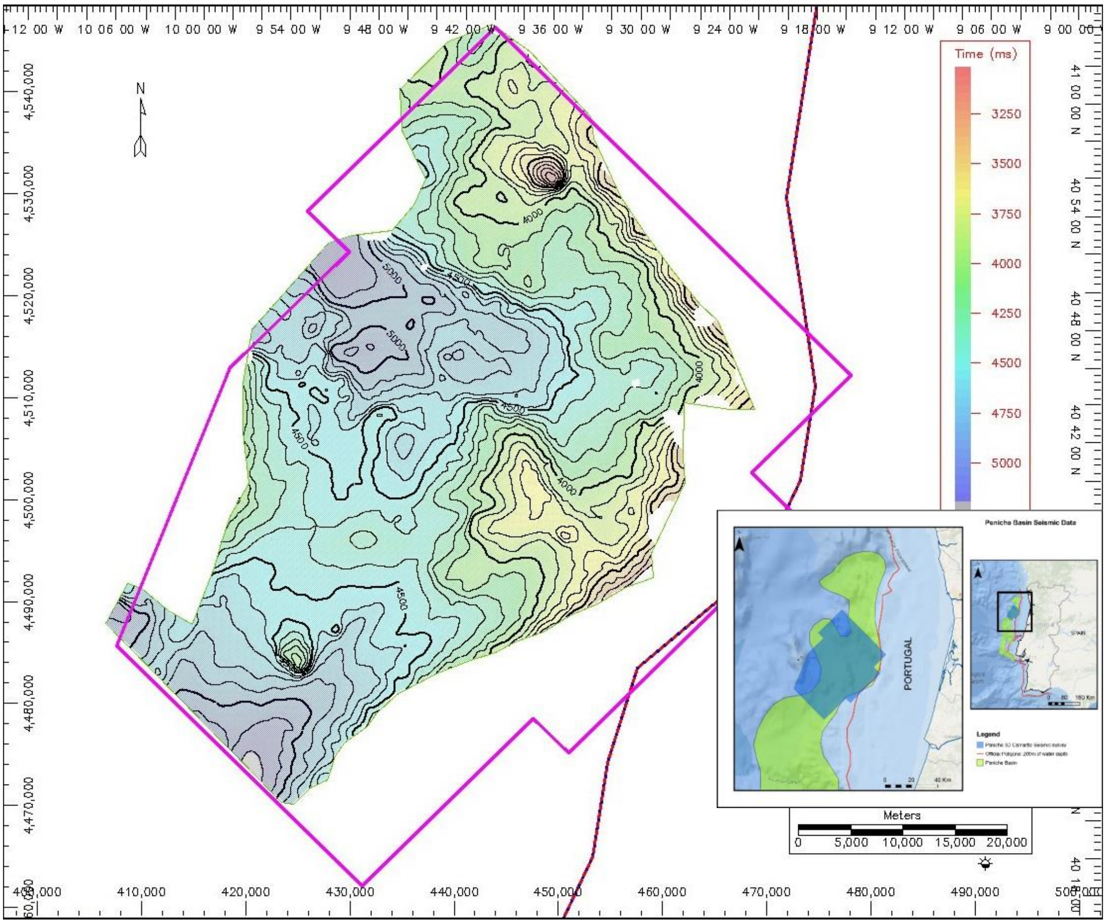

*Figure 86- 3D volume Camarão interpreted TWT Top Jurassic map*

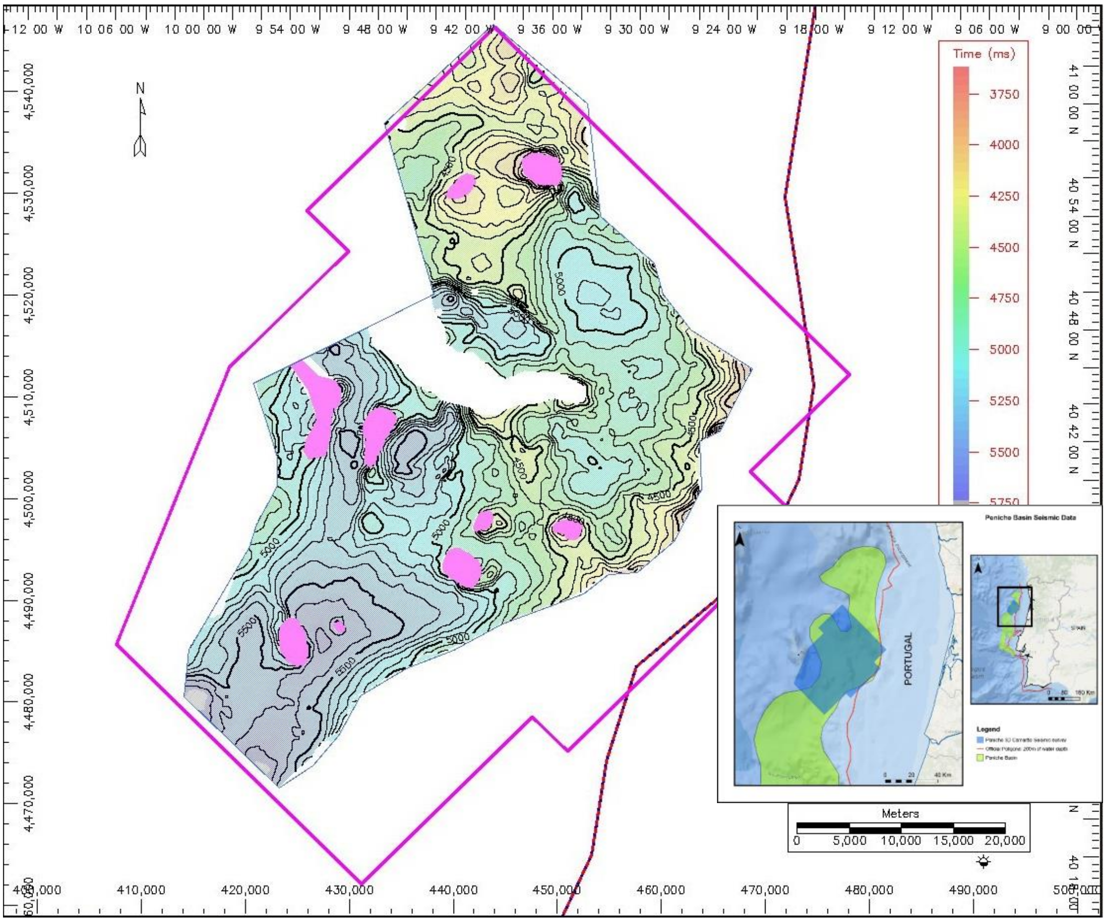

Figure 87- 3D volume Camarão interpreted TWT Top salt map

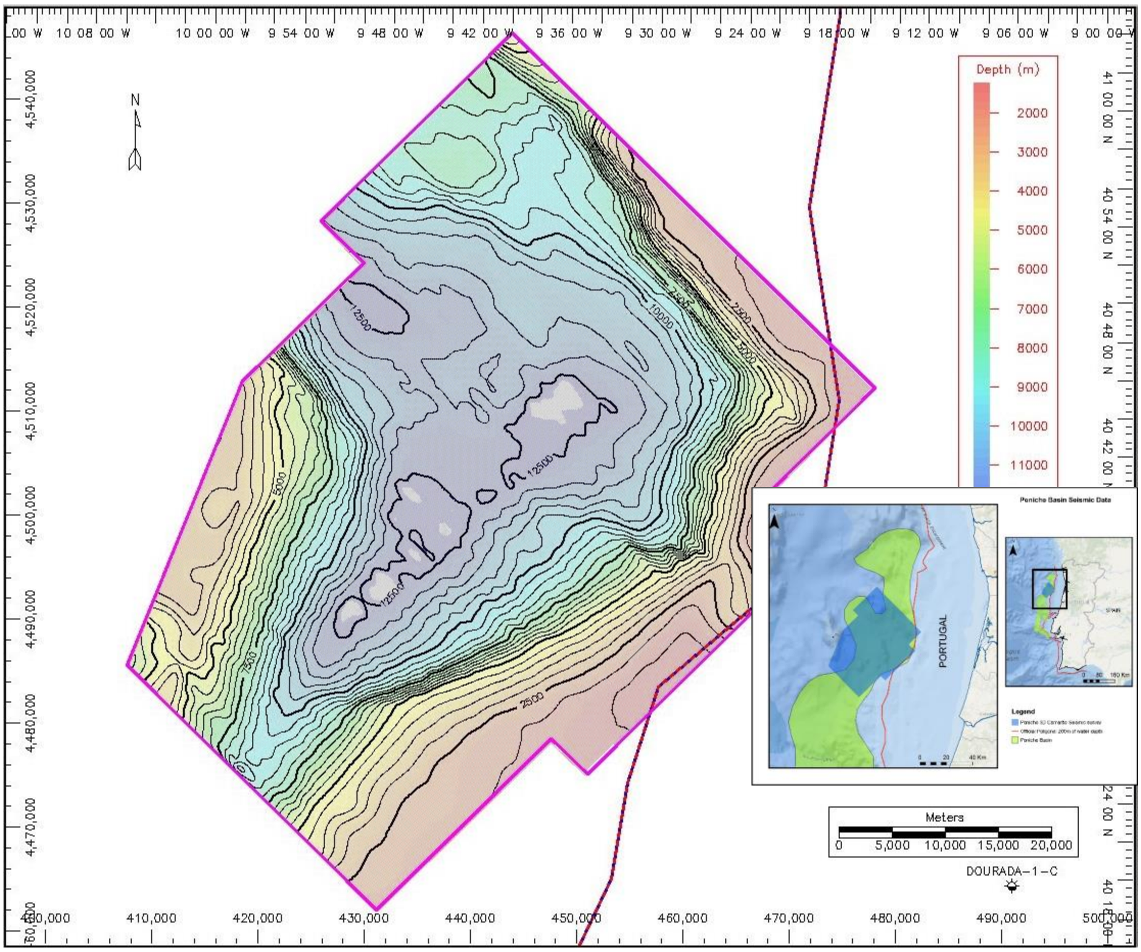

Figure 88- Figure 86- 3D volume Camarão interpreted TWT Top Basement map

# Camarao 3D Depth Maps

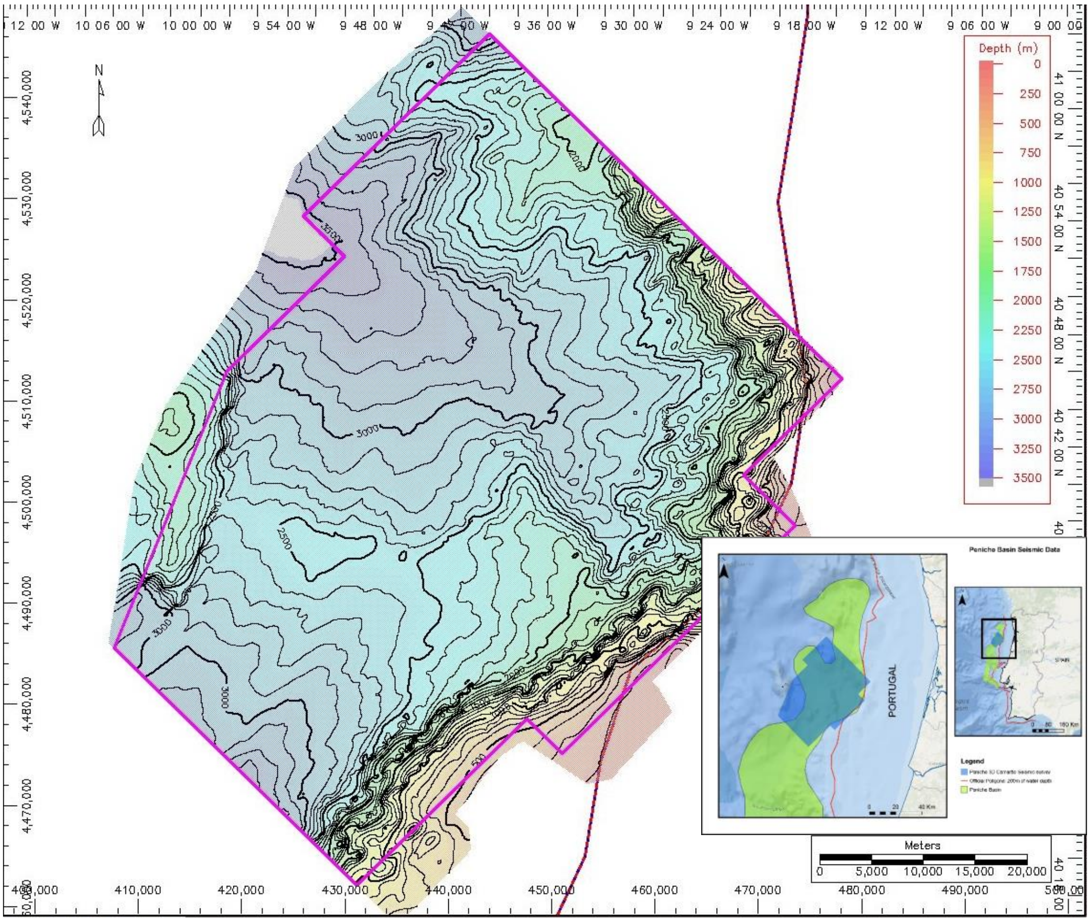

Figure 89-3D volume Camarão interpreted Depth seabed map

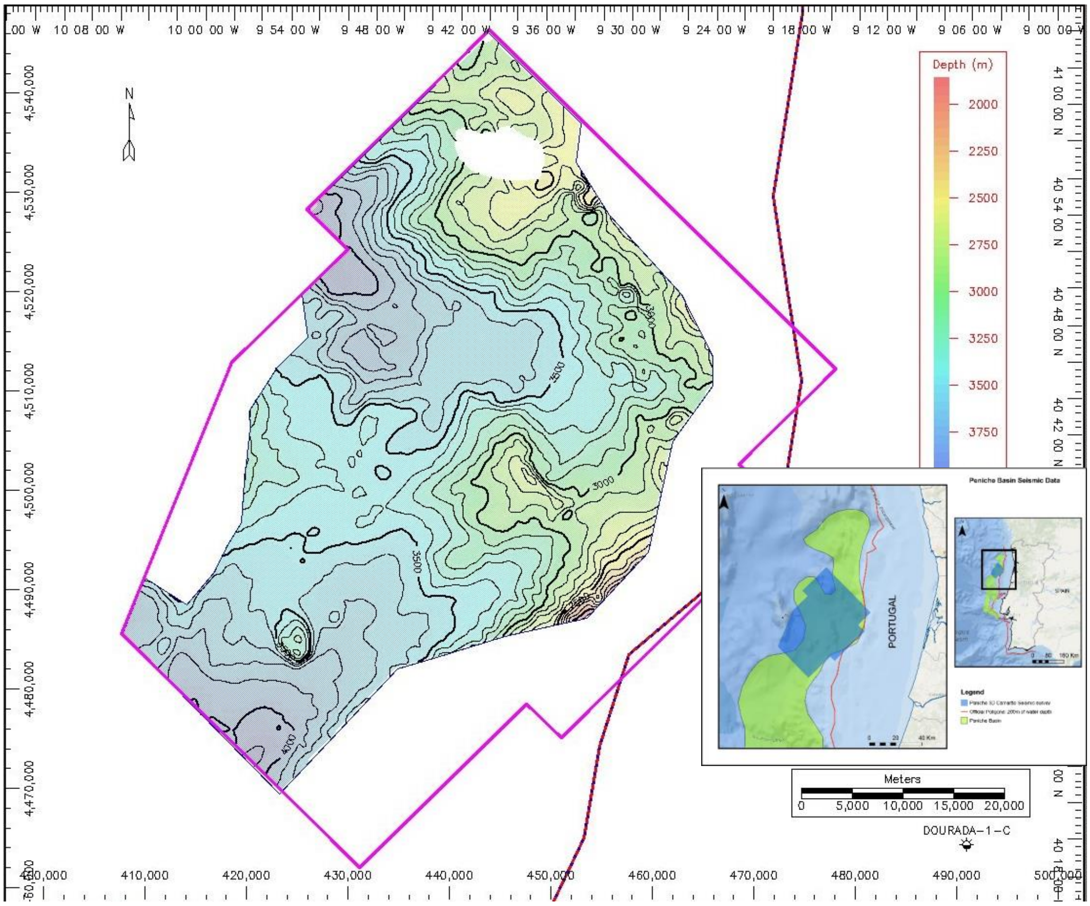

Figure 90- 3D volume Camarão interpreted Depth Base Oligocene map

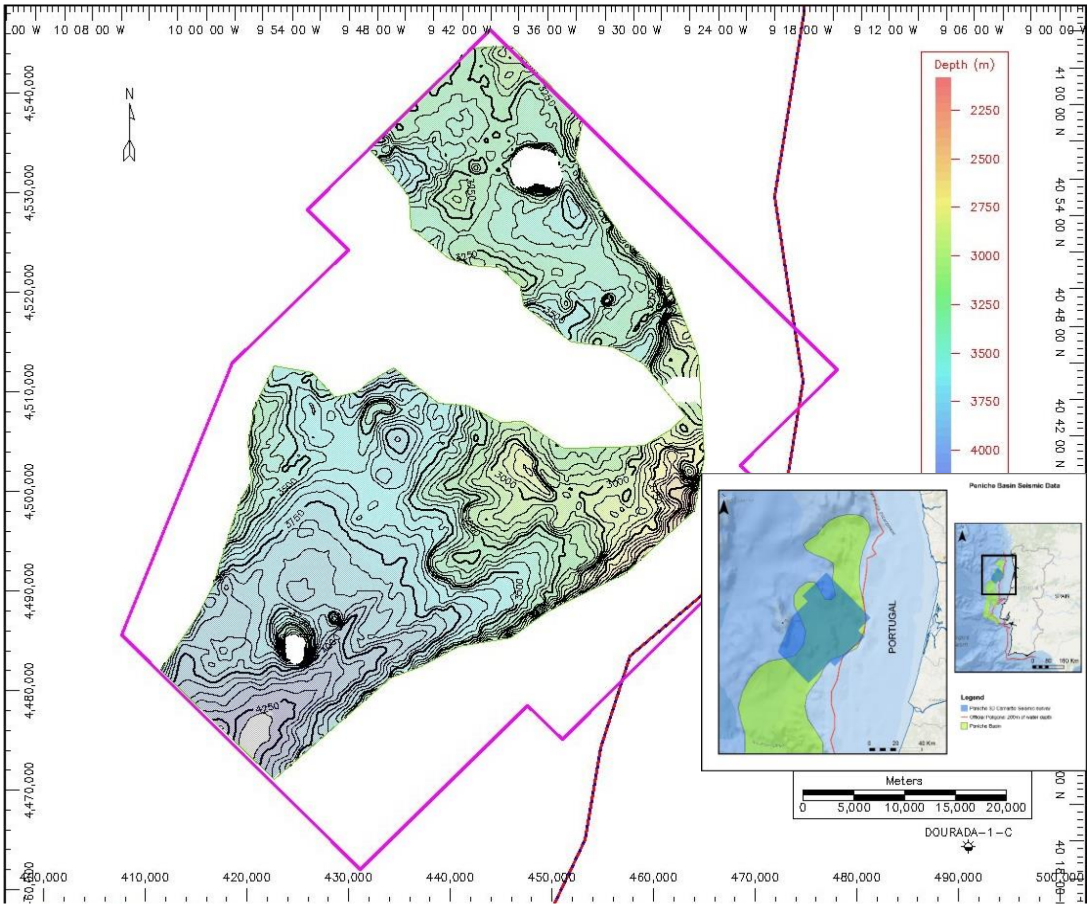

Figure 91-3D volume Camarão interpreted Depth Top Early Cretaceous map

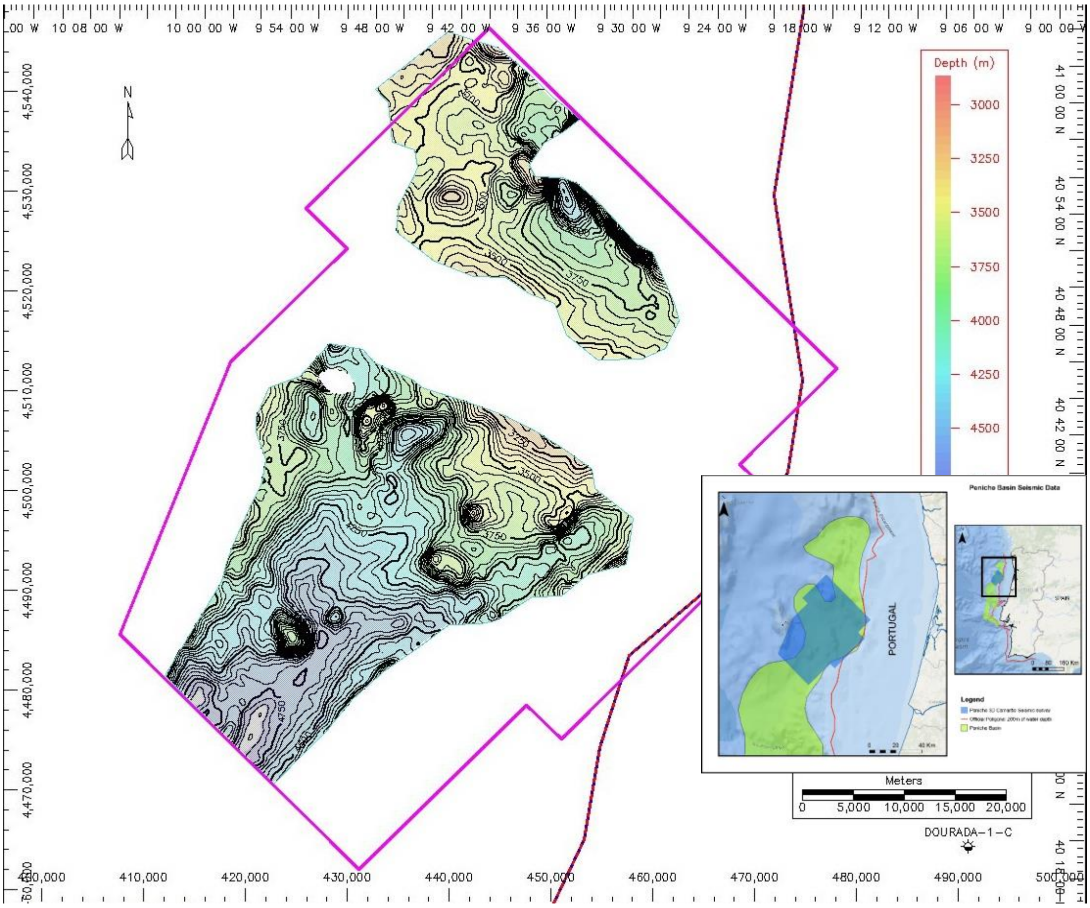

*Figure 92-3D volume Camarão interpreted Depth Top Jurassic map*

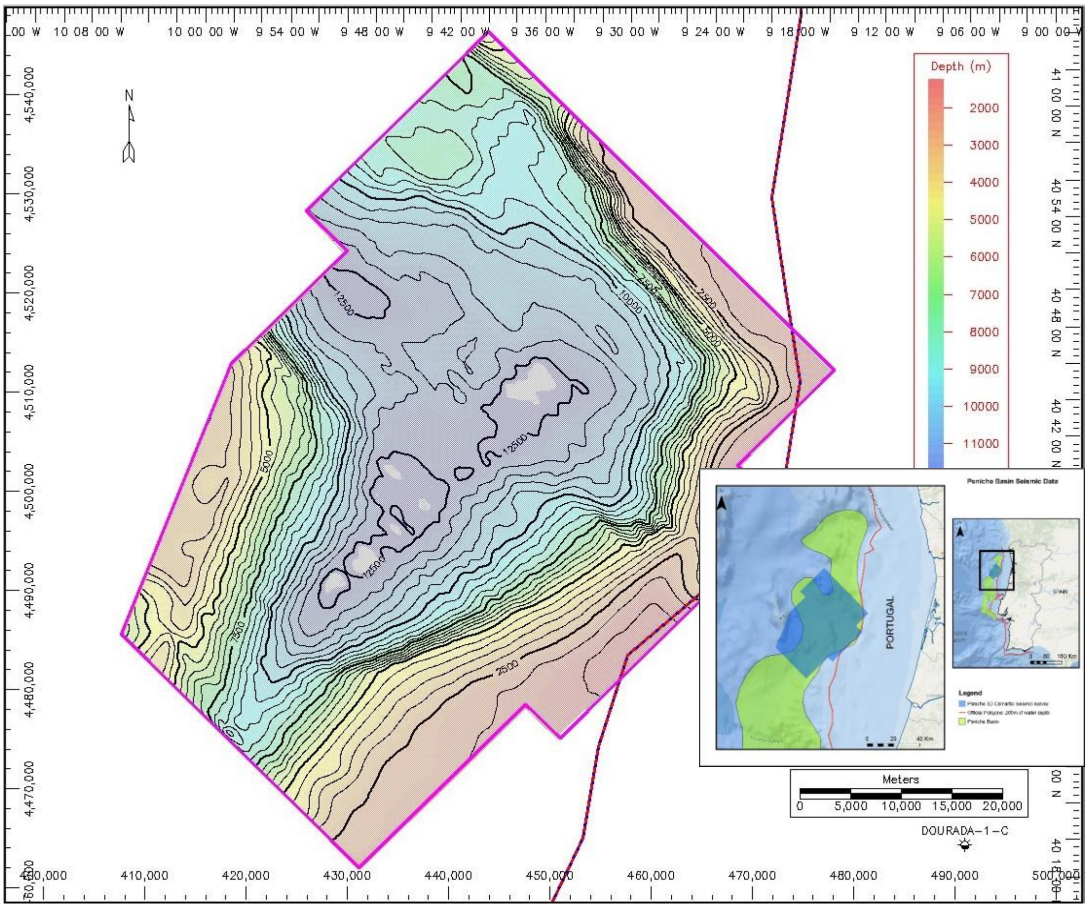

Figure 93-3D volume Camarão interpreted Depth Basement map