CORE WORKSHOP

Coordination: DPEP (Divisão para a Pesquisa e Exploração de Petróleo)*

Presentation: J.M. Martins (DPEP) and C. Moita (DPEP)

Location: LNEG (Laboratório Nacional de Energia e Geologia)**- Rock Archive

Schedule: Tuesday 28th September 2010, Afternoon (14-17h)

The Core Workshop will start with a brief presentation of Lusitanian Basin´s stratigraphy and its potential petroleum systems. This Workshop will address two main subjects:

i) Lithostratigraphic overview

Main geological formations (*sensu* WITT, 1977), representative of the Lusitanian Basin, will be showed in some of the well cores which resulted from hydrocarbon exploration; the succession of siliciclastic and carbonate facies reflects the evolution of the basin, with different source rocks and reservoirs.

ii) Jurassic Petroleum System

Torres Vedras region - Southern Lusitanian Basin - with numerous seeps and shallow wells with oil/gas shows reported, has been a target for hydrocarbon exploration since late 1940´s. The cores to be displayed, from wells drilled in this region, will show the existence of a petroleum system where source, reservoir and seal rocks can be observed.

Fig.1 - Cores from the Fracares wells drilled in the Torres Vedras region, showing strong oil impregnation in Montejunto formation limestones.

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** National Energy and Geology Laboratory

Session 1: Lithostratigraphic overview

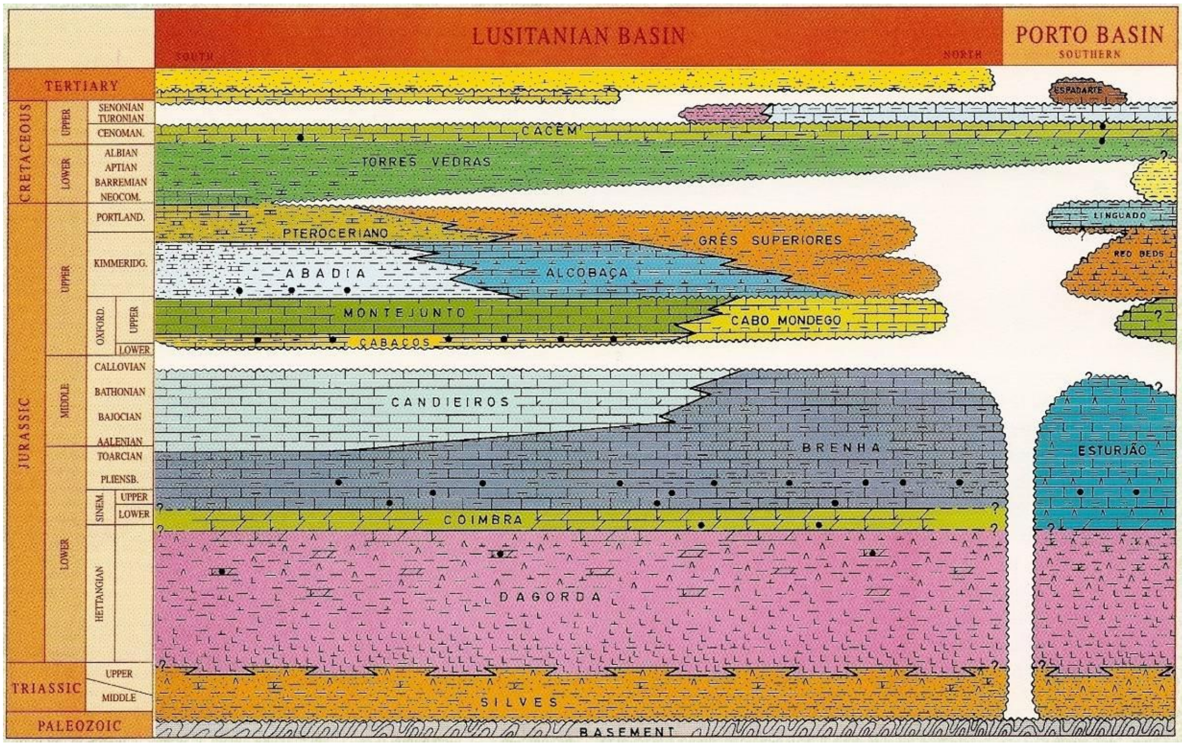

Figure 2: Simplified lithostratigraphic synopsis of the Lusitanian Basin/Porto basins, adapted from WITT (1977) and followed in the Core Workshop.

Opening of the Lusitanian basin began in the Late Triassic. Lusitanian rifting marked the western boundary of the Iberian Meseta. During this Syn-rift period, an irregular and dynamic topography, of blocks limited by normal faults related with the reactivation of the basement main tectonic features, was formed. The filling of the basin started with the deposition of terrestrial red beds (**Silves formation**), consisting of shales, coarse sandstones and conglomerates, mainly of alluvial-fluvial nature, with variable thickness over the basin. Locally, in outcrop, black shales are present at the top of the Silves and may represent the initial marine incursion into the rift system, before the abortion of the rifting, with no oceanic crust formation.

The **Dagorda formation** is a sequence of marginal marine, evaporitic and dolomitic sediments, wich reflect the gradual opening up of the basin to an open marine environment. This formation culminates in transgressive, hypersaline, restricted marine sequence formed on the margins of the proto-Atlantic. It has a littoral character (lagoon and tidal flats), in a dry and hot climate, similar to actual Sabhka environment. Except for a generally thinner salt development in the southern part of the basin, the dolomites and evaporites of this series seem to have been deposited in fault-bounded sub-basins, attaining thicknesses in excess of 2 km. This thickness was favoured by strong subsidence conditions and by the halokinetic processes due to the activation of basement fractures.

The **Coimbra formation** is represented by dolomites at the base and limestones towards the top. The depositional environment is recorded to show an upward change from lagoonal/tidal flat to shallow carbonate shelf/restricted open marine carbonate shelf. Porous, sandy limestones in the Peniche area seem to indicate a clastic influx from a western horst system. This formation represents the first opening of the basin to the open sea, with the installation of a low energy homoclinal carbonate ramp (AZERÊDO et al, 2003). A very shallow sea spread over most of the Lusitanian Basin and deposited the regionally uniform carbonates of this formation (WITT, 1977).

The **Brenha formation** was deposited in a deep-water marine shelf environment and its facies are recorded to have their thickest development in a central belt parallel to the present-day coastline. In this area the facies are represented by variably bituminous shales and impure, fine-grained lime mudstones deposited under predominantly euxinic conditions during the late Sinemurian-early Pliensbachian. This formation is laterally equivalent to the shallow-water carbonates of the **Candeeiros formation**. The interfingering of these two formations, starting in Aalenian-Bajocian times, is attributed to a relative sea-level regression and to a high rate of carbonate deposition. With time, the shallow water facies become more developed in the E/SE part of the basin (Candeeiros facies), while there is a retraction of the more deeper marine facies (Brenha facies) to the W/NW.

With relative tectonic stability, low rate homogeneous subsidence, dominant tendency of sea level raise, subtropical climate and a low grade topographic substrate, the carbonate ramp depositional system that was initiated on Early Jurassic evolved into a high energy carbonate ramp with its most maximum expression during Bathonian times (AZERÊDO *et al.*, 2003).

The deposition of the Candeeiros carbonates, mainly of high energy, represents an inner ramp environment (AZERÊDO, 1993; MARTINS, 2007). Facies belts include well-defined upper shoreface, foreshore, backshore and tidal flat/lagoon sub-environments. The stacked, high-energy grainstones and subordinate lime mudstone prograded westward during the late Bajocian and Bathonian. Stacking and vertical accretion of facies is suggested to have resulted from high rates of *in situ* sediment production, suficcient to accomodate the effects of shoreface erosion and washover during sea level rise. Although less frequent than in overlying formations, some biostrome/reefal facies were also formed.

The Middle Jurassic-Upper Jurassic transition is marked by the occurrence of a basin wide regression and led to the emergence of major parts of the Lusitanian Basin. This regression is marked by an important unconformity which covers, in respect to the Ammonite record, the interval uppermost Callovian-lower Oxfordian but it is wider and started, in some places, at upper Bathonian times.

The **Cabaços formation** represents the first post-hiatus Upper Jurassic deposits and the reactivation of carbonate deposition. Later, renewed rifting in the Upper Jurassic, changed the depositional environment, allowing clastic sediments to overlay and bypass the carbonate ramp. Cabaços formation comprises lacustrine carbonates with anhydrite, organic-rich shales and bituminous lime mudstones and marginal-marine limestones (brackish to restricted, shallow-marine environment).

The transgressive **Montejunto formation** contains in the lower part mainly shallow marine to brackish lagoonal carbonates. The upper part grades from open marine shelf limestone into deeper shelf ammonite-bearing limestone. Laterally the ammonite-facies grades into a reef and coral limestone facies in the Montejunto-Torres Vedras area. Further northward, restricted shallow marine limestones predominate.

With the onset of the Kimmeridgian, the Lusitanian Basin received a strong supply of clastics. This has probably been the result of rejuvenated basement tectonics which increased the relief in the source area of the Iberian Meseta and, to a lesser degree, also in the high basement area to the west of the present offshore. The primary marine facies of this clastic wedge is the **Abadia formation**. The Abadia fm south of Torres Vedras-Montejunto area is characterized by proximal turbidites. In the Arruda sub-basin, more than 2.200 meters of arkosic gravels were deposited in a submarine fan system sourced from the east. These sediments form the Castanheira member of the Abadia formation.

Towards the south and southwest the clastic supply diminished and at the same time the marine influence increased (Alcobaça formation). Marine conditions continued south of the latitude of Peniche where the Alcobaça formation grades laterally into the Abadia formation.

The main rifting phase commenced in the Late Jurassic (Oxfordian), latter leading to the separation of the Iberian Peninsula and North America in the Lower Cretaceous.

The Upper Jurassic shows dramatic thickness variation due to the differentiation of the Lusitanian Basin into a number of rapidly-subsiding sub-basins, particularly during the late Oxfordian and early Kimmeridgian. Sub-basins developed both as half-grabens (Turcifal and Arruda) and salt-withdrawal structures (Bombarral-Alcobaça). These sub-basins had distinct depositional histories.

During Tithonian (Portlandian) times prevailed the same general situation, marine sediments in the south and terrestrial deposits in the north, with the deposition of coarser terrestrial clastics – **Grés Superiores** – reaching now much further to the south than before. South of Peniche, the Grés Superiores formation grades into shallow shelf clastics and carbonates – “Pteroceriano” – and is overlain by mainly shallow shelf carbonates.

Eventually marine carbonate sedimentation continued only in the Sintra area without any break from the Upper Jurassic to the Lower Cretaceous. Everywhere else, Upper Jurassic and Lower Cretaceous sediments are separated by a major unconformity.

The separation of North America and Europe from Iberia ocurred in the early Cretaceous and resulted in major unconformities at Neocomian and intra-Aptian levels. These unconformities increase in magnitude towards the eastern margin of the Lusitanian Basin and indicate that boundary faults were active during Lower Cretaceous deposition. The deposition of new Cretaceous clastic sediments succeeded a major phase of diapiric remobilization at the end of the Upper Jurassic.

The following deposited sequences represent the post-rift phase of the Upper Jurassic rifting episode: the Valangian to Lower Aptian sequence and the Upper Aptian to Turonian sequence exhibit similar facies distribution, show relatively little thickness variation and cover much of the basin. In both sequences, fluvial clastics are suggested to characterize the northern parts of the basin (Torres Vedras fm); southward, these sediments grade into marine marls and rudist limestones (Cacém fm).

The **Torres Vedras formation** was formed in mixed environments, with the fluvial/deltaic facies more developed than the interlayered marine to marsh limestones.

During Cenomanian time, a very shallow sea spread again over most of the Lusitanian Basin depositing the regionally very consistent limestones of the **Cacém formation**. The upper part of the Cacém formation has, again, a regressive facies that includes some rudist build-ups.

During Senonian, the area south of Cabo Mondego emerged. However, to the north, an Upper Cretaceous basin developed, which was sequencially filled with terrestrial clastics – **Gândara formation** -, marine marls and limestones – Carapau formation – and very shallow marine clastics and dolomites - Dourada formation.

The Atlantic margin appears to have remained a passive sag zone through much of the Upper Cretaceous-Early Tertiary.

During the Oligocene, only sporadic terrestrial sedimentation – **Benfica formation** – occurred in the onshore part of the Lusitanian Basin, while in the western and northern offshore only a thin sequence of very shallow marine carbonates grading to coastal and terrestrial clastics – Espadarte formation – was deposited.

The Neogene is represented by a thin sequence of mainly terrestrial clastics – Moreia formation.

The earliest phase of inversion appears to be late Campanian-Maastrichtian in age and is related to the onset of compression due to the changing movement of Iberia relative to Europe and Africa. The most recent phase of basin inversion occurred in the Late Miocene. The collision of Africa with the Iberian Plate created the Rift-Betic mountain belt across southern Spain-North Africa and resulted in a compressive tectonic regime across much of south-central Portugal.

BASEMENT

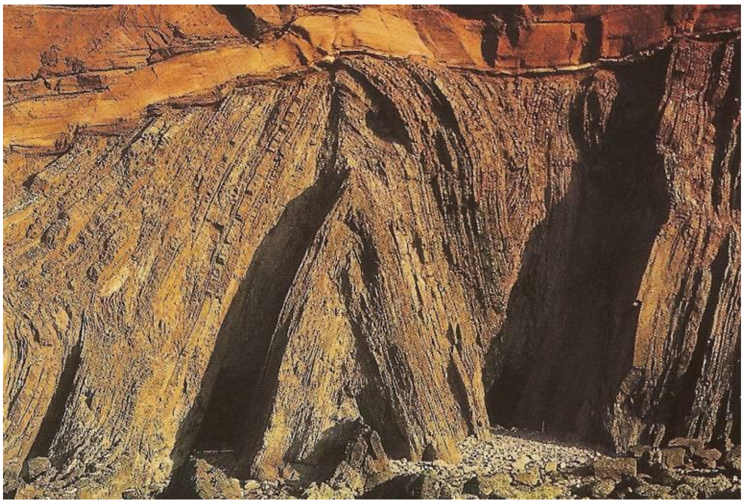

Figure 3: Late Triassic continental sandstones lying unconformably on Upper Carboniferous marine basement shales & graywackes of the South Portuguese Zone.

Figure 4: 5A-1 well quartzite cores.

Figure 5 & 6: 17C-1 well granite cores.

Figure 7 & 8: Sobral-1 well shists cores.

***Source Rock quality**: the black carbonaceous shales of Silurian age are rich in organic carbon, as well as the marine shales of Carboniferous age. Their maturity is variable, having generally high degree of maturity. They may constitute potential source rocks for gas. Some Silurian black shales have measurements of Ro eq. between 1.75% and 3.5% and the Marine Carboniferous shales of 3.5%. In some dark metasediments of the Praia do Murração, of Visean age, the mean Ro eq. value is 1.7%.*

SILVES FORMATION

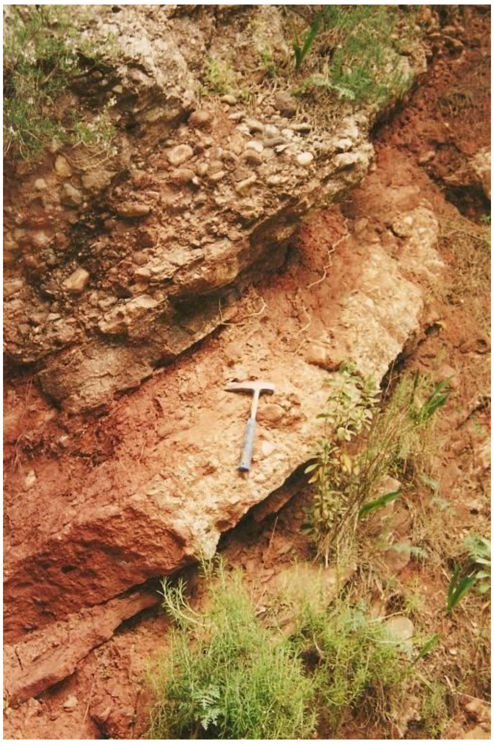

Figure 9: Silves Fm conglomerates at the Serra de S. Luis, near Coimbra**.**

Figs. 10 & 11: Silves Fm thin sandstones cores in Pe-1 well.

***Age**: Triassic-Hettangian.*

***Position**: this formation overlies unconformably rocks of Paleozoic age. At the central portion of the basin, the major upper part of the sequence consists of shale overlain by Dagorda evaporites, which can be considered to be a lateral equivalent of the upper Silves Fm outcropping in the east.*

***Reservoir quality**: this formation is sandy-conglomeratic at the eastern basin margin. In westerly direction, towards the center of the basin, grain sizes diminish. Porosity is variable, in general low to medium. Locally up to 20%. It may be considered a reservoir rock for the potential source-rocks of the Paleozoic.*

DAGORDA FORMATION

Figure 12: Dagorda fm at A-da-Gorda quarry, showing black marls.

Figs. 13 & 14: Dagorda fm rock salt in NM-1 well.

***Age**: UpperTriassic-Hettangian.*

***Lithology**: shale, variegated marl, marly limestone, dolomitic limestone, gypsum and rock salt.*

***Position**: in some wells this formation underlies conformably the Coimbra formation and overlies conformably the Silves formation.*

***Source Rock**: dark grey to black shales within the evaporitic sequence in the center of the salt province. These shales qualify as marginal oil to gas source rock: locally fair to good TOC (up to 3.2%), locally fair to good S2 (19 kg HC/ton.rock), organic matter of type II with HI negligible to medium (up to 390 mg HC/g TOC), net thicknesses variable from 0 to 120 m and SPI always lower than 0.5 ton. HC/sq.m. (BEICIP, 1996).*

COIMBRA FORMATION

Fig. 15: Coimbra & Brenha formations Sinemurian/Pliensbachian paper-shales at Água de Madeiros, near São Pedro de Muel.

***Age**: Sinemurian.*

***Lithology**: consists of sideritic dolomitic limestones, dolomitic limestones, marls, gypsum & bedded, compact limestones.*

***Position**: in some wells these shallow shelf carbonates overly conformably the Dagorda Formation and generally underly conformably the Brenha Formation.*

***Reservoir Rock quality**: this formation consists mainly of tight, partly mud supported limestones and dolomitic limestones with porosities of less than 5%. Vacuolar and fractured sections exist within the formation .*

***Source Rock quality:** In the center of the Lusitanian Basin, shale beds within the Coimbra Formation constitute potential source rock. In the northern part of the Lusitanian Basin they have fair to good petroleum potential (1.1 to 60 kg HC/ton. rock), small thickness (5 to 25 m), variable maturity from 0.7% to 2% Ro eq. (oil zone to gas zone) and poor to good TOC (up to 3,6%).*

Figs. 16, 17 & 18: Coimbra fm porous dolomitic limestones in SM-1 well cores.

BRENHA FORMATION

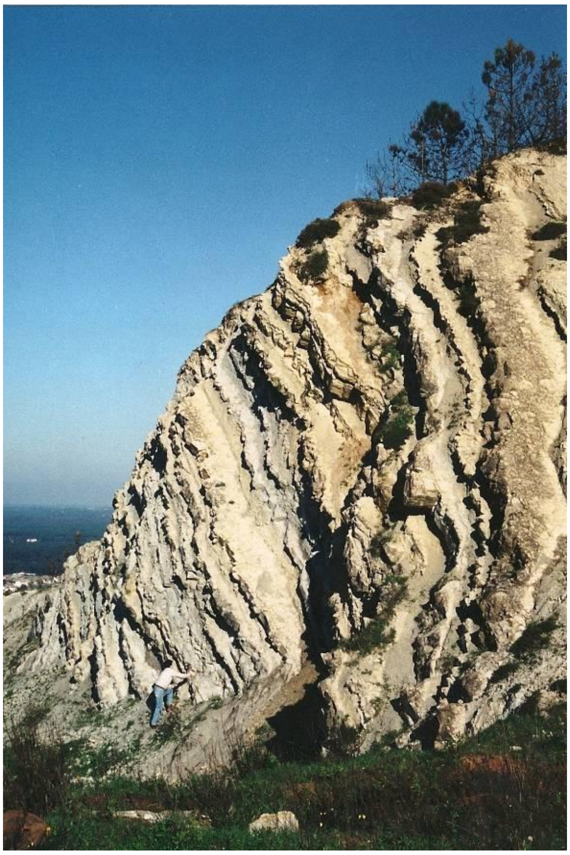

Figure 19: Brenha formation outcrop at Brenha.

Figs. 20 & 21: Brenha formation shaly limestones in MRW-9 well cores.

***Age**: Upper Sinemurian-Callovian*

***Lithology**: dark grey and grey lime mudstones grading to and interbedded with calcareous shales.*

***Position**: overlies conformably the Coimbra formation and underlies unconformably the Cabaços & Cabo Mondego formations. In the eastern part of the Lusitanian Basin, this formation grades into the shallow marine Candeeiros formation.*

***Source Rock quality**: the argillaceous lower part of the Brenha formation is a well-documented oil source rock with recorded TOC content up to 18%. In the northern part of the Lusitanian Basin the TOC content is fair to rich (2,5 to 10%) and the initial petroleum potential is fair to very rich (10 to 45 kg HC/ton. rock). It has a thickness of 140 to 190 m and a maturity ranging from 0.7% to 2% Ro eq. (oil zone to gas zone). The organic matter is of type II combined with some type III (BEICIP, 1996.*

CANDEEIROS FORMATION

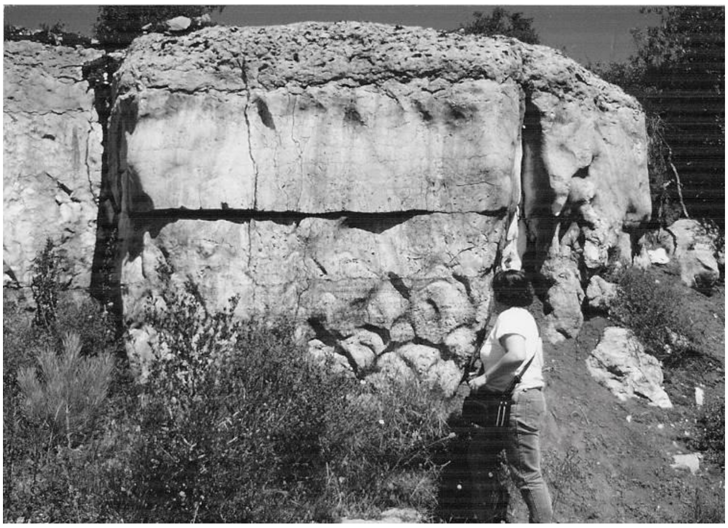

Figure 22: Shallowing upwards peritidal cycles in Sicó area.

Figs. 23 & 24: Candeeiros fm micritic limestones in well Bf-1 cores and porous bio-intraclastic packstones in Br-1 well cores.

***Age**: Middle Jurassic (Aalenian-Callovian).*

***Lithology**: oolitic, skeletal and pelletoidal limestones, interbedded dolomites; lime mud, oncoidal & birdeyes limestones and subaerial exposure carbonates.*

***Position**: In the western part of the Lusitanian Basin, this formation grades into the deeper marine Brenha formation. It overlies/ interfingers with the Brenha formation and it underlies unconformably the Cabaços formation.*

***Potential reservoir quality:** subaerial exposure and karstification may have enhanced significantly reservoir quality as well as some reefal and high-energy facies.*

CABAÇOS FORMATION

Figure 25: marginal marine limestones with lignitic layers at Rocha Forte quarry, near Cercal.

Fig. 26 Cabaços fm bituminous limestones in well FR-3 cores.

*.**Age**: Upper Oxfordian.*

***Lithology**: limestones, rich in bivalves and bituminous limestones.*

***Position:** overlies unconformably the Candeeiros and Brenha formations and near Torres Vedras underlies conformably the Montejunto Formation.*

***Source Rock quality**: this formation is a well-documented source rock. In the south of the Lusitanian Basin has thicknesses ranging from 20 to 110 m, fair TOC content (up to 3%) and a high initial petroleum Potential (up to 87 kg HC/ton. rock).*

Fig. 27 Cabaços fm impregnated limestones in well TV-4 cores.

Fig. 28 Cabaços fm bituminous limestones in well FR-3 cores.

MONTEJUNTO FORMATION

Age*: Upper Oxfordian.*

Lithology*: grey limestone, corallic/oolitic limestone, fine grained fossiliferous limestone.*

Position*: overlies conformably the Cabaços formation and underlies the Abadia and Alcobaça formations.*

Reservoir Rock quality*: the Montejunto formation consist in general of particle supported limestones with low permeability and porosities of less than 5%. However, reefal, vugular and fractured reservoirs with oil filled fractures do exist.*

Figure 29 Montejunto fm impregnated limestones in well FR-3 cores.

Figs 30 & 31: Montejunto fm limestones in well TV-4 core and limestones showing oil filled fractures in well FR-3 cores.

ABADIA FORMATION

Figure 32: Abadia formation in Torres Vedras area outcrop.

***Age**: Kimmeridgian.*

***Lithology**: predominantly marls, with sandstones, conglomerates and limestones.*

***Position**: overlies the Montejunto formation and underlies conformably the Corálico do Amaral fm.*

***Reservoir/Source Rock quality**: good sandstone reservoirs have been reported in the Torres Vedras, Arruda dos Vinhos & Barreiro areas. Shales in the lower part of the Abadia fm represent source rock in some wells; richest in organic matter is the Cabrito member. Kerogen analysis suggest influences of terrestrial deposicional environment.*

Figure 35: Abadia formation coarse arkosic sandstones in Ar-1 well cores.

Figs 33 & 34: Abadia formation sandstones in AG-2 well cores and micaceous marls in VV-2 well cores.

CORÁLICO DO AMARAL

***Age**: Kimmeridgian.*

***Lithology**: between Alenquer and Arruda dos vinhos, a 32 meters thick section consists of light grey, marly, oolitic limestone with thin intercalations of calcareous, marly, ooidal and oncoidal quartz sandstone & coralgal biostromes.*

***Position**: overly conformably the Abadia formation and underly the Grés Superiores formation.*

Figure 36: Corálico do Amaral bio-intraclastic limestones in Ms-1 well cores.

GRÉS SUPERIORES FORMATION

***Age**: Kimmeridgian-Tithonian.*

***Lithology**: variable, from argillaceous, feldspathic, often lignitic, sandstones with conglomerate lenses to sandy, micaceous and lignitic marls.*

***Position**: overlies unconformably the Cabo Mondego fm and underlies unconformably the Torres Vedras fm. The limnic-brackish Grés Superiores fm grades southwards into the Alcobaça formation and the "Pteroceriano". Towards the west, the lower part of the formation grades into the Alcobaça formation.*

***Reservoir Rock quality**: channel sandstones within this unit constitute good reservoirs. However, their thickness and their frequency diminish rapidly from the basin margin in the north towards the Upper Jurassic paleobasin further to the south.*

Figure 37 & 38: Grés Superiores fm lignitic micaceous siltstones in Mj-1 well cores.

TORRES VEDRAS FORMATION

Figure 39: Torres Vedras formation in Torres Vedras area outcrops.

Age*: Lower Cretaceous-Cenomanian.*

Lithology*: coarse conglomeratic sandstones grading into fine grained sandstones, sandy clays and marls and intercalated limestones.*

Position*: overlies unconformably the Grés Superiores fm and underlies conformably the Cacém fm.*

Reservoir Rock quality*: the unconsolidated sands to loosely consolidated sandstones of Torres Vedras formation, capped by shales of the Cacém formation, represent one of the best potential reservoirs of this basin. Its homogeneous thickness and geographic distribution also enhances this unit as a good reservoir.*

Figure 42: Torres Vedras sandstone in MRW-9 well cores.

Figs 40 & 41: Torres Vedras formation sandstones in MRW-9 well cores.

CACÉM FORMATION

Figure 43: Cacém formation limestones, near Lisbon.

***Age**: Cenomanian-lower Turonian.*

***Lithology**: limestone, argillaceous limestone and rare dolomite with marl intercalations. Rudist build-ups at the top of this formation.*

***Position**: overlies conformably the Torres Vedras formation and underlies the Lisboa Basalt Complex.*

Figure 44: Cacém formation limestones in MRW-2G well cores.

GÂNDARA FORMATION

***Age**: Turonian-Senonian.*

***Lithology**: sandy argillaceous limestones and micaceous marls, coarse quartz sandstones, fine micaceous sandstones. **Position**: overlies conformably the Cacém formation and underlies unconformably the Moreia formation.*

Figure 45: Gândara formation limestones in MRW-8 well cores.

BENFICA FORMATION

Figure 46: Benfica formation outcrop.

***Age**: Oligocene.*

***Lithology**: variegated marl and clay, calcareous conglomerates, red marls, compact limestones.*

***Position**: overlies the Lisboa Basalt Complex (Eocene) and underlies marine sediments of Lower Miocene age.*

Figure 47: Benfica formation coarse calicified sandstones in MRW-2G well cores.

Figure 48: Benfica formation coarse calicified sandstones in MRW-2G well cores.

Jurassic Petroleum System

The Torres Vedras region (south of the Lusitanian Basin) (Fig.49), with numerous seeps and shallow wells with confirmed oil/gas shows, has been a target for hydrocarbon exploration since late 1940´s. The cores, from a well (Fracares-3) drilled in the Abadia structure (Fig. 50), show the existence of a petroleum system where source, reservoir and seal rocks can be observed.

Source-Rocks: the Upper Jurassic sequence in this area includes rich, oil prone upper Oxfordian source rocks (Fig. 51). These source rocks occur as marginal marine limestones and lacustrine bituminous limestones, both in wells and outcrops, with the latter ones better developed in the synclines. Geochemical analysis of samples from the Torres Vedras - Montalegre area revealed source rock thicknesses between 20 a 110 m, TOC values up to 3 % and maturation levels ranging from immature to overmature. These rocks, of the Cabaços formation are most probably responsible for the numerous seeps and impregnations observed in the basin and for the oil seen in many of the wells drilled in the area.

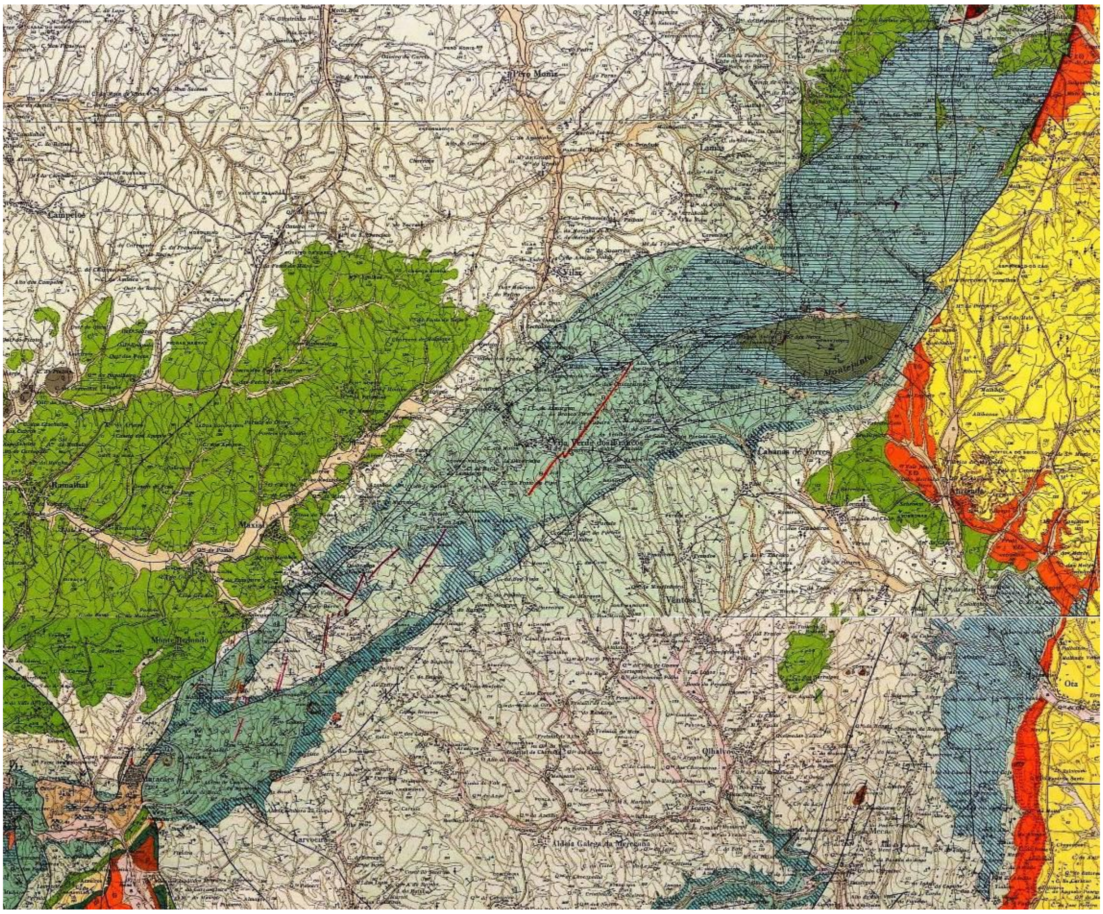

Figure 49: Torres Vedras-Montejunto Geology (composed from Carta Geológica de Portugal, 1:50.000 scale, sheets ALENQUER (30-D) and BOMBARRAL (30-B)).

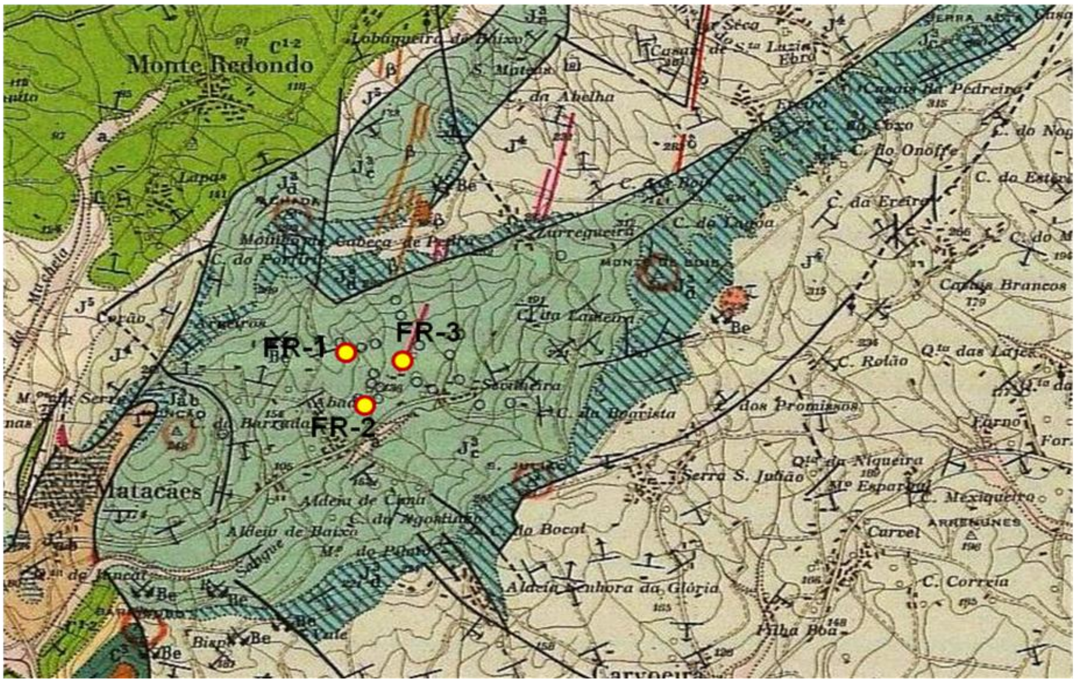

Figure 50: Abadia Structure, showing the FRACARES wells.

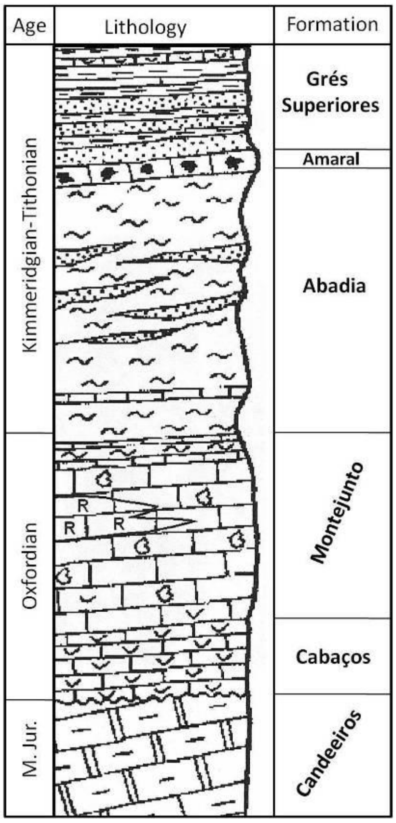

Figure 51: resumed Upper Jurassic Torres Vedras area stratigraphy.

Reservoir Rocks: fair to good reservoirs are found in the Upper Jurassic of this area in Oxfordian reef carbonates and fractured/porous limestones of the Montejunto formation and in Kimmeridgian clastics of the Abadia formation (Fig.51).

Seals: some tight limestones of the Montejunto formation and the marls and clays of the Abadia formation (Fig.51) are regarded as possible seals.

The main objective of the FRACARES project was the study of flow and of preferred flow pathways through an onshore fractured carbonate reservoir at Abadia Valley, in Torres Vedras area ("Abadia Dome") (Fig.50). Three wells were drilled and water was injected in one of the wells in order to observe returns in the other two wells.

The project involved also the acquisition, processing and interpretation of seismic data, the planning, drilling, coring, logging and imaging of 3 wells (FR-1, FR-2 & FR-3) (Fig.50) together with the geological and petrophysical analysis of well data, and the construction of fracture flow models consistent with all of the available geological, geophysical and flow data.

The project was financed under the THERMIE Programme (EU) and involved the following entities: Gabinete para a Pesquisa e Exploração de Petróleo (at the time designated GPEP), Entreprise Oil, Fault Analysis Group (FAG), Geological Sorvey of Denmark and Greenland (GEUS), Hellenic Petroleum and Instituto Geológico e Mineiro (IGM).

Figure 52: Impregnated Cabaços fm bituminous limestones in FR-3 well cores.

Figure 53: Montejunto fm limestones in FR-3 well cores.

Figure 54: Montejunto fm limestones in FR-3 well cores, showing oil impregnated fractures.

Figure 55: Abadia fm micaceous marls with siltstone/sandstones intercalations in FR-3 well cores.

Figure 56: Abadia fm oil impregnated sandstones in FR-3 well cores.

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