Journal of the Nigerian Association of Mathematical Physics
Volume 29, (March, 2015), pp 363 – 374

Shale gas potential of the Silurian Tanezzuft Hot Shale, Ghadames Basin

Edegbai, A.J. and Igbinigie, N.S

Department of Geology, Faculty of Physical Sciences, University of Benin, Benin-City, Nigeria.

Abstract

The Ghadames Basin is a Large Multi-cycle basin encompassing parts of Libya, Algeria and Tunisia. Its complex Basin history can be summarized into 3- phases: the Pre-Hercynian phase (Basin initiation), Hercynian (large scale sediment exhumation) and Post-Hercynian (change in depositional axis towards the Northwest). This basin plays host to two world class source rocks: Silurian Tanezzuft Hot Shale and the Devonian Aouinet Ouinine Formation.

This study aims to assess the lithology and geochemical properties of Silurian Tanezzuft Shale with a view to evaluating its shale gas potential. This evaluation was done using organic richness, maturity and HI data from 37 wells. Back calculation of organic richness and hydrogen index was carried out and results indicate it has good source quality with type II kerogen.

Initial organic richness and Thermal maturity maps were generated, and they show increasing trend towards the NW flank of the basin. Application of Cut-offs of 2.0wt% TOC and 1.0%R_o and subsequent merging of the maps reveal a sweet spot in the NW flank of the basin. Basin modelling in the sweet spot area reveals the current thermal maturity (wet – dry gas stage) of the Tanezzuft gas shale was attained in the Palaeocene. Adsorption model generated suggests great potential for thermogenic gas adsorption and retention exist in the Tanezzuft Hot Shale. Furthermore, the Tanezzuft Hot Shale compares favourably with similar aged established shale gas plays (i.e. Utica and Marcellus shale plays) in the US.

Keywords: Shale gas, Ghadames basin, Hot shale, thermogenic gas, sweet spot.

1.0 Introduction

Self containing petroleum systems (i.e. source, reservoir and seal all inclusive) like Shale gas plays form continuous accumulation that is being successfully exploited commercially in the US. This is largely driven by government policy, technology and rising natural gas price [1]. Currently, natural gas production from shale gas plays in the US stands at over 46% [1]. The future outlook of natural gas production from shale gas systems in the US is very bright. This, coupled with rising gas price is driving exploration in shale gas basins around the world, notably, Europe, China, North Africa and the Middle East thus making Shale gas systems an important energy resource for the future.

The Ghadames Basin is a Large Multi cycle Basin in North Africa encompassing parts of Algeria, Libya and Tunisia.

Exploration efforts over the years targeted conventional hydrocarbon resources. These efforts have been very successful and in recent times huge oil and gas discoveries have been made in the Algerian part of the basin. This is attributable to good quality seismic imaging [2]. Current estimate of proven hydrocarbon resources is put at 32BBOE [3].

Shale gas exploration is still in its early stages in the basin. In recent times, the Tunisian end of the basin has been on the spotlight [4, 5]. The estimated in place volumes of gas currently stands between 80 – 120 TCF with recovery factor of 10-15% [5].

The Basin plays host to two 'world class' source rocks (the Silurian Tanezzuft Shales and the Devonian Aouinet Ouinine Formation) [3] which are potential targets for shale gas exploration.

This study is aimed at evaluating the shale gas potential of the Silurian Tanezzuft Shales via established geology and geochemical guidelines with a view to improving the hydrocarbon prospectivity of the basin.

The study aims to answer the following research questions, viz:

- Does the Tanezzuft gas shale have sufficient organic richness (TOC)?
- What Kerogen type is present in the gas shale?

Corresponding author: Edegbai, A.J., E-mail: joel.edegbai@yahoo.com, Tel.: +2348137114844

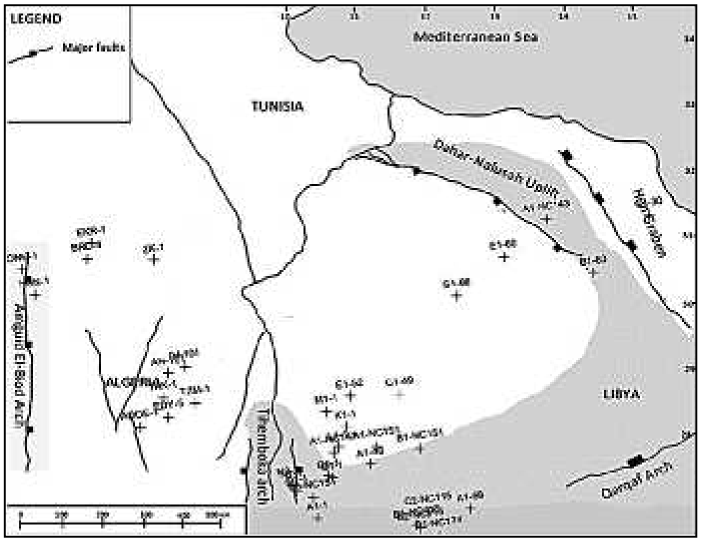

Fig 1: Ghadames Basin [6]

- What is the thermal maturity history / distribution, and has the Tanezzuft gas shale reached the right thermal Maturity?
- Are there any similarities between the geochemical and lithological characteristics of the Tanezzuft and established shale plays in the US?

2.0 Literature Review

The Ghadames Basin is a Large (about 350,000km^2) Multi cycle Basin (intracratonic sag basin at present day) in North Africa encompassing parts of Algeria, Libya and Tunisia [7]. Its main boundaries are: the Dahar – Naffussah, Qarqaf uplift and Hogar shield, Amguid – El Biod Arch, Sirte basin, north, south, east and west respectively [6, 7] *(Fig. 1).*

Basin initiation/subsidence began in the Paleozoic and it has been modified via several tectonic episodes viz: the Taconic event (Early Ordovician), Caledonian event (Late Silurian-Early Devonian), Hercynian event (Late Carboniferous - Permian), Neocomian event, Austrian event (Aptian), and the Alpine event (Eocene-Oligocene) [6, 7] characterized by depocentre shift, widespread uplift and sediment exhumation as it evolved through time [2, 7]. Thus, the present day Basin morphology and structural style is an expression of multiple tectonic episodes which it has suffered during the course of its evolution [2].

Sedimentation began in the Cambro-Ordovician spanning through to Pliocene with variable sediment fill comprising terrigenous sediments, glaciogenic sediments, marine carbonates and evaporites. In its deepest parts the Ghadames Basin has an infill of sediments up to about 8000m [3].

Tanezzuft Shale

Large scale flooding of the basin during the Silurian transgressive episode consequent upon the melting of ice in a passive margin tectonic setting brought about the widespread deposition of organic rich radioactive marine shales - the Tanezzuft Formation [7-9]. Its geographical distribution was controlled primarily by the Sahara metacraton [3].

The Tanezzuft Shale occurs as grey – green and red laminated shales, commonly with interbeds of fine sand and silt. It is gypsiferous and has a high organic richness [10]. It is a Type 2 kerogen 'world class' source rock described by [8] as a 'double hot shale': a lower hot shale (most prospective source interval) between 20m-50m thick, organic richness (TOC) up to 17% and hydrogen index (HI) hovering between 250MgHc/g -450MgHc/g which is more widespread in its distribution [11], and an upper hot shale with qualities similar to the lower hot shales but more restricted in its distribution, separated by poor quality shales of similar composition. The Tanezzuft Shale is reputed to have generated over 80% of all the hydrocarbons in the Paleozoic Basin [9].

The best source rock quality occurs at the deepest part of the Paleozoic depocentre [9], whilst thermal maturity progresses towards south and west [10, 11]. This trend may be complicated in areas where anomalous geothermal gradients due to regional fault structures exist [10].

Its overall thickness varies from Less than 200m to over 500m, and tapers southwards, due to truncation by the Hercynian unconformity [9].

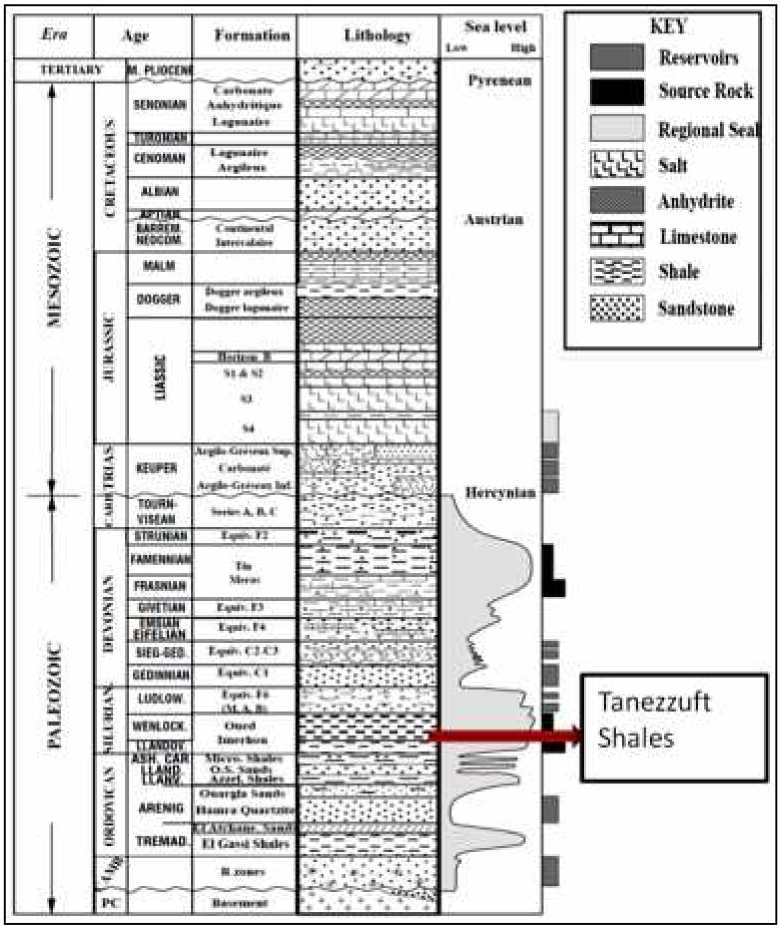

Fig 2: Ghadames Basin Stratigraphy [12]

3.0 Methodology

The workflow shown in Fig.3. was adopted for this study. The data set available for this study include: organic richness (TOC data), Maturity data, and hydrogen index (HI) data for 37 wells.

Basin Screening

To ascertain to shale gas potential for a basin, potential gas shales must be screened using established geological and geochemical criteria [13 - 15]. The main criteria used in this study for Basin screening include:

- **Kerogen type**

Four (4) main types of kerogen have been described as shown in Table 1.

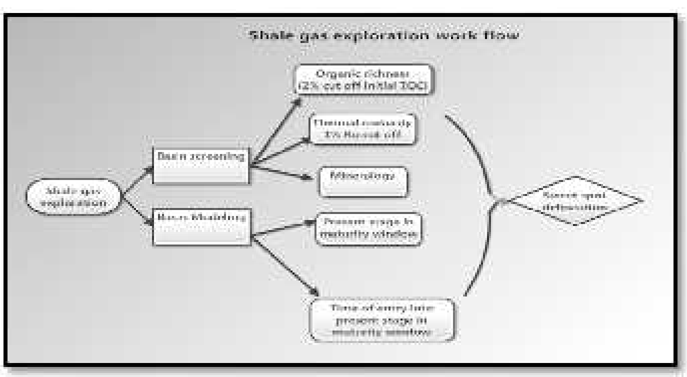

Fig 3: Shale gas exploration work flow

Table 1: Kerogen types [16]

Kerogen Type	Depositional Environment	Organic Precursors	Hydrogen Product
I	Lacustrine	Algae	Liquids
II	Marine Reducing Conditions	Marine Algae, Pollens, Spores, Leaf waxes, Fossil Resins	Liquids
III	Marine, Oxidizing conditions	Terrestrial-Derived Woody Materials	Gas
IV	Marine, Oxidizing conditions	Reworked Organic Debris, Highly Oxidized Material	None

Of the aforementioned, oil prone Type I/ II Kerogen gas shales with potential for thermogenic gas generation (especially Type II Kerogen Transgressive marine gas shales) are the most sought after [13]. [7- 9, 11,13] tagged the Tanezzuft shale as Type II Kerogen Transgressive marine shale.

- **Organic richness**

The organic richness (i.e. quantity and quality) of any gas shale is directly proportional to its source rock potential [17] and consequently determines how much carbon, oxygen and hydrogen atoms is available for petroleum generation [10]. As a result, gas shales with high organic richness have the best hydrocarbon potential. As gas shale pass through the various stages of petroleum generation (consequent upon increased burial, time, temperature and pressure), its level of organic richness diminishes [19]. Thus, for Shale gas potential evaluation it is common practice to convert present day organic richness (which can be significantly lower) to initial organic richness [17].

Table 2: Initial TOC conversion formula [19]

$$TOC_{initial} = TOC_{measured} / [1-(F\Delta C)]$$

$$F = \text{Extent of HC generation} = HI_{initial} - HI_{measured} / HI_{initial}$$

$$\Delta C = \text{Maximum TOC loss for kerogen type}$$

Type 1 = 65%; Type 2 = 50%; Type 3 = 20%

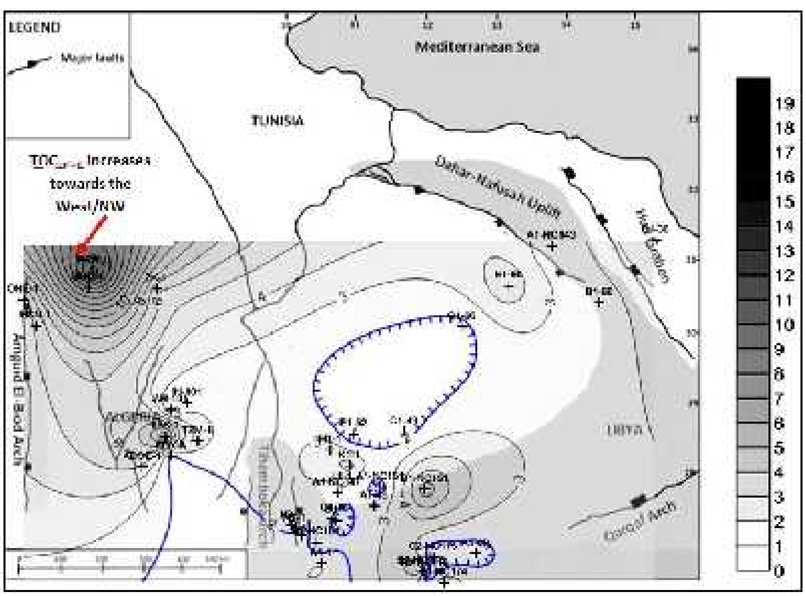

Fig. 4: Tanezzuft Shale initial TOC map (*with 2.0wt% cut-off*) showing an increase towards the West/NW

TOC data from 37 well was used to evaluate the organic richness of the Tanezzuft shale. Back calculation to its initial TOC was carried out using the formula by [19] *(Table 2);* consequently, an organic richness map for the Tanezzuft shale was generated *(Fig.4)*.The initial TOC increases towards the West/NW of the basin thus indicating better source potential in this area and by extension, better prospectively.

Maturity

The amount of heat and the exposure time within the oil window of any gas shale determine its thermal maturity. There are different stages of thermal maturity as shown in table 4. Generally, for shale gas exploration 1% R_o is taken as the minimum thermal maturity cut-off [17].

Tmax data from 37 wells which was subsequently converted to Vitrinite reflectance values (R_o equivalent) was used for this study. The conversion formula used is shown in Table 3.

Table 3: Tmax to $R_{o\ equivalent\ conversion}$ [18]

$R_{o\ equivalent}$ = 0.0180 * Tmax – 7.16 (Jarvie et al., 2001)

Thermal maturity map of the Tanezzuft gas shale was generated, and a cut-off of 1.0% Ro was applied and areas with sufficient thermal maturity for shale gas development were identified.

The trend of thermal maturity of the Tanezzuft Shale as shown in the thermal maturity map *(Fig. 5)* again shows an increase in the W/NW direction. This is in consonance with the findings of [11]. The likely reasons for this trend may be as a result of thickness of the overburden (since the depocentre shifted towards the West and Northwest in the Mesozoic [2, 7], high heat flows associated with regional faults [11] and magmatic activities as a result of the Hercynian tectonics [9].

Table 4: Thermal maturity levels [19]

	Maturation			Generation		
Stage of Thermal Maturity for oil	Ro (%)	Tmax ^{0}C	Thermal Alteration Index (TAI)	Bitumen/TOC	Bitumen (Mg/g rock)	Production Index $[S_1/(S_1+S_2)]$
Immature	0.2-0.6	<435	1.5-2.6	<0.5	<50	<0.1
Mature						
Early	0.6-0.65	435-445	2.6-2.7	0.5-1.0	50-100	0.10-0.15
Peak	0.65-0.9	445-450	2.7-2.9	1.5-2.5	150-250	0.25-0.40
Late	0.9-1.35	450-470	2.9-3.3	------	-----	>0.40
Post mature	>1.35	>470	>3.3	------	------	-----

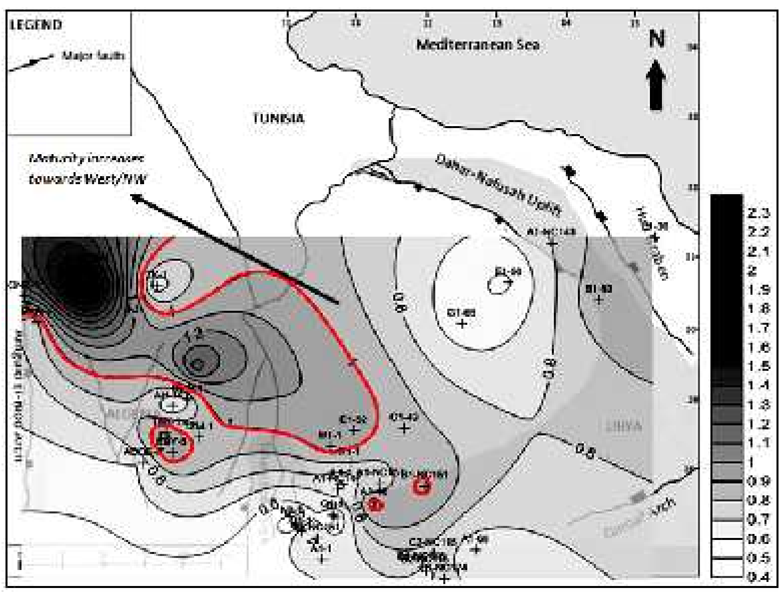

Fig. 5: Tanezzuft Shale Thermal maturity distribution map *(with 1% Ro cut- off)* showing a West/NW increase in maturity

- **Mineralogy**

It is a well known fact that the mineral mix of gas shales has a great influence on its petrophysical properties and hardness/brittle index and thus its fracking potential. Gas shales with good fracking potential commonly have non clay proportion of greater than 40% (i.e. calcite, quartz and feldspar) [15]. Furthermore an understanding of the mineral mix/distribution of gas shales is very important in shale reservoir characterization/modelling [18].
No mineralogy data was available for this study. However, the stratigraphy of the Tanezzuft gas shale suggests it has a favourable mineral mix. Furthermore, the Tanezzuft gas shale has been observed to show similar mineral mix with the Barnet shale [4, 5] in the Tunisian flank *(Table. 7).*

4.0 'Sweet spot' Delineation

The initial TOC and thermal maturity maps were merged, and a major 'sweet spot' was identified in the N/NW *(Fig. 6).*
The **key uncertainty** associated with the identified sweet spot area is the non availability of mineralogy data as earlier stated.
It is worthy of mention that the Tanezzuft shale has favourable thickness and burial depth *(Figs 10 and 11; Tables 6 and 7*). Although, these parameters where not amongst the key criteria used in the Basin screening, the thickness and depth of burial of the gas shales is useful to note during the evaluation of shale gas plays. Attractive shale gas plays generally have thicknesses 30m while depth of burial is generally between 1000m and 4000m [14]. The shallower it is, the cheaper the well.

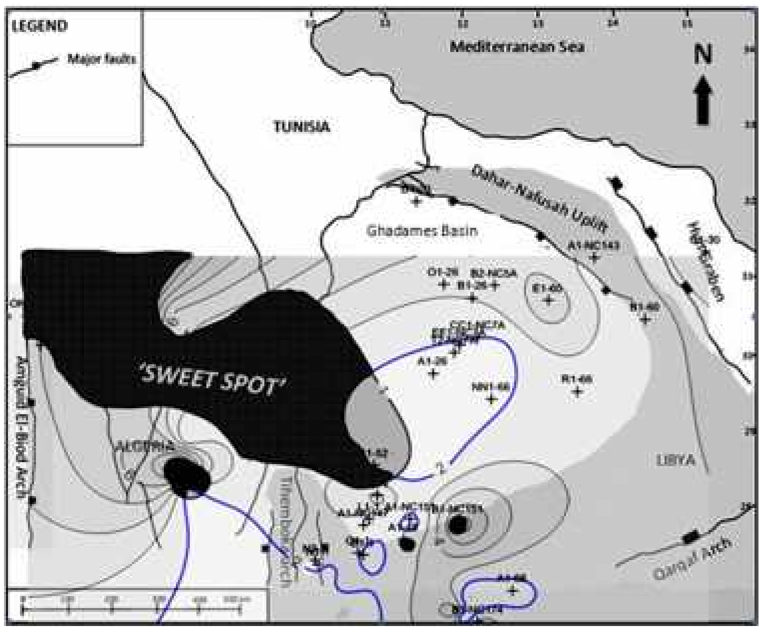

Fig. 6: 'Sweet spot' areas of the Tanezzuft Shale (after merging initial TOC map with Thermal Maturity map)

5.0 Basin Modelling

- **Burial / Maturity history**

1D Basin modelling was carried out in this study with a view to understanding the burial history and thermal maturity history of the Tanezzuft Shale. Input data include geophysical, geological and geochemical data: basin tectonic history/stratigraphy, vitrinite reflectance data, organic richness data, temperature history from wells BRD-4 and ONE-1 and basin heat flow history.
A forward modelling approach was used and the output was calibrated against observed VR data from the two wells using BasinMod software.

- **Critical input parameters**
  - Heat flow

As earlier stated, the Ghadames Basin is a multi-cycle basin, and as such, a linear heat flow model cannot be used to describe its thermal maturity history/distribution. For this study, a transient heat flow model by [6] was adopted, as it had a good calibration with Vitrinite reflectance data (R_o) observed from the wells BRD-4 and ONE-1 *(Fig. 11)*

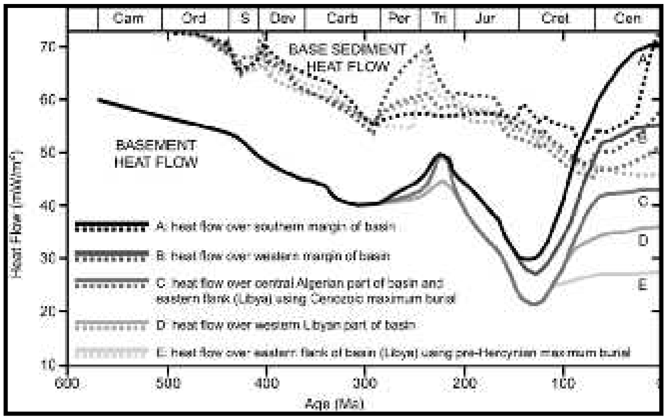

Fig.7: Heat flow model used for basin modelling [6]

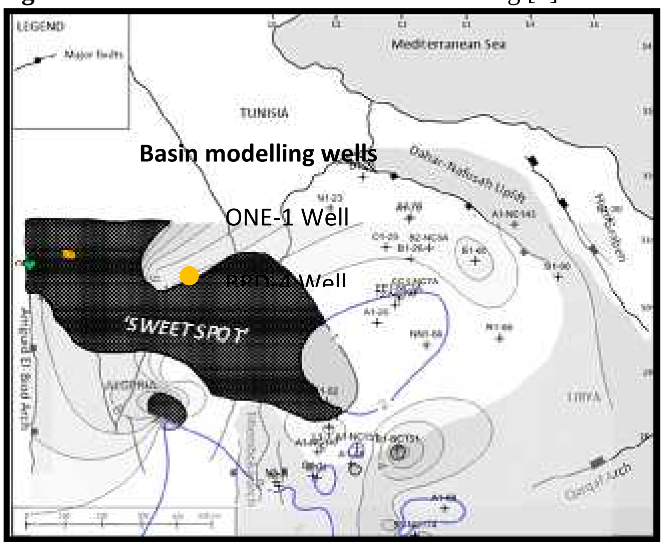

Fig. 8: Tanezzuft Shale sweet spot areas with wells for Basin modelling

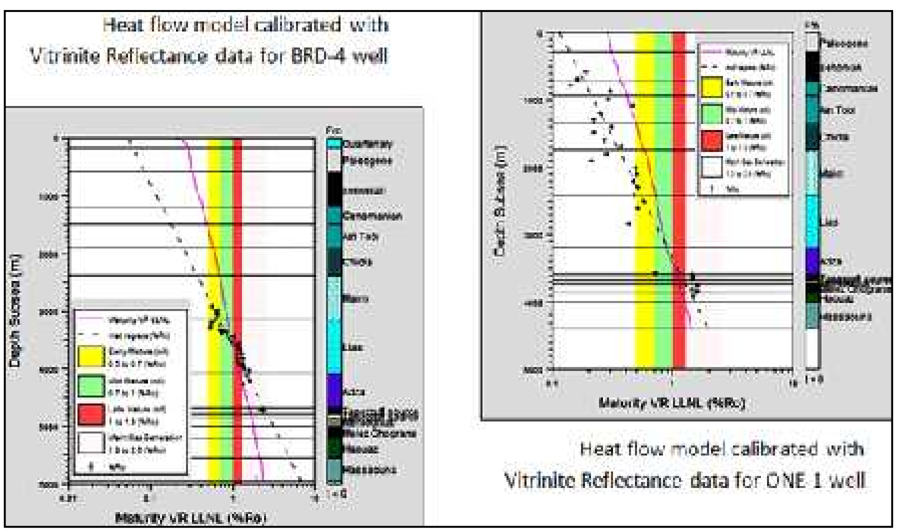

Fig. 9: Heat flow model calibrated with Vitrinite Reflectance for wells ONE-1 and BRD-4

- Amount of sediments exhumed during uplift/erosion

Estimating the amount of sediments exhumed in a multi-cycle basin like the Ghadames basin is very important if one is to understand its Burial history and estimate the time of hydrocarbon generation/expulsion from the Silurian Tanezzuft gas shale. For this study, reasonable estimates of the amount of sediment exhumed during uplifts associated with the Hercynian tectonic episode, Austrian tectonics and the Alpine tectonics was obtained from [3, 6].

Table 5: estimates for exhumed overburden after [3, 6]

Event	Begin Age (Mya)	Eroded thickness (m)
Alpine	36.7	100
Austrian	120	600
Hercynian	292	3600

- **Basin modelling results (BRD-4)**

Burial history plot *(Fig. 10)* reveals that petroleum generation took place in two phases. This is consonance with findings by [2, 7]. The Tanezzuft gas shale first entered the oil window in Mid Devonian/Early Carboniferous. Its continued generation/ progression to the gas window stopped due to widespread uplift/sediment erosion associated with the Hercynian tectonic episode. Petroleum generation resumed in the Jurassic. Alpine and Austrian tectonic events were of little importance in the Western Ghadames as revealed by the Burial history plot (this is also in consonance with [6]. Pre-Hercynian maximum burial was reached in the Carboniferous, while post-Hercynian maximum burial was attained in the Palaeocene. Furthermore, the burial history plot also reveals that the Tanezzuft gas shale entered the main gas generation window in Mid. to Late Palaeocene (i.e. when it attained maximum burial).

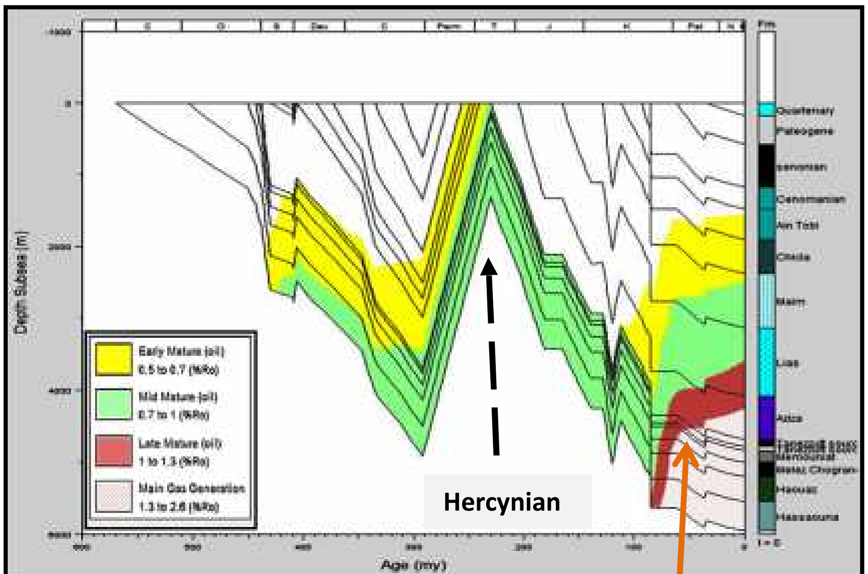

Fig. 10: BRD-4 Burial history plot

- **Implications for shale gas development**

A great potential exist for thermogenic gas adsorption and retention in this basin. The fact that the Tanezzuft gas shale attained its maximum burial/maturity level in the Palaeocene, and since then it has suffered little from the Alpine tectonic event makes it very attractive.

6.0 Basin modelling results (ONE-1)

The result *(Fig. 11)* also show reveals dual petroleum generation stages. The Tanezzuft gas shale first entered the oil window in Early Carboniferous. Its continued generation/ progression to the gas window stopped due to widespread uplift/sediment erosion associated with the Hercynian tectonic episode. Petroleum generation resumed in the Mid Cretaceous. Alpine and Austrian tectonic events were also of little importance in this area as revealed by the Burial history plot.

Pre-Hercynian maximum burial was reached in the Late Carboniferous/ Early Permian, while post-Hercynian maximum burial was attained in the Palaeocene. Furthermore, the burial history plot also reveals that the Tanezzuft gas shale entered the wet gas generation window in Mid Palaeocene (i.e. when it attained maximum burial post Hercynian tectonic event).

- **Implications for shale gas development**

There is significant potential for thermogenic gas adsorption and retention *(Fig. 11).* The fact that the Tanezzuft gas shale attained its maximum burial/maturity level in the Palaeocene, and small volume of sediment was exhumed due to Alpine tectonic event makes it very attractive.

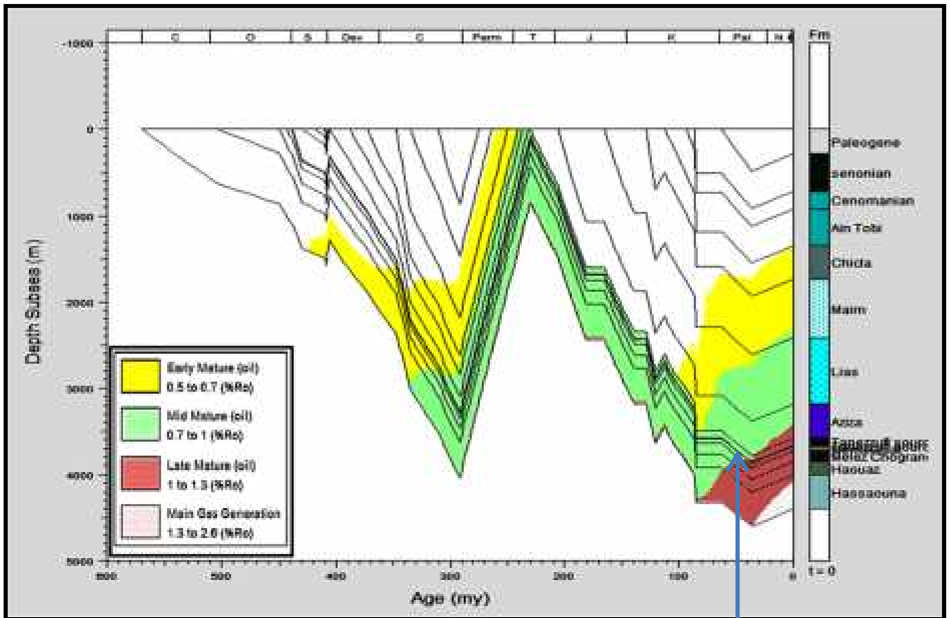

Fig. 11: ONE-1 Burial history plot

Tanezzuft entering wet gas generation window in Palaeocene

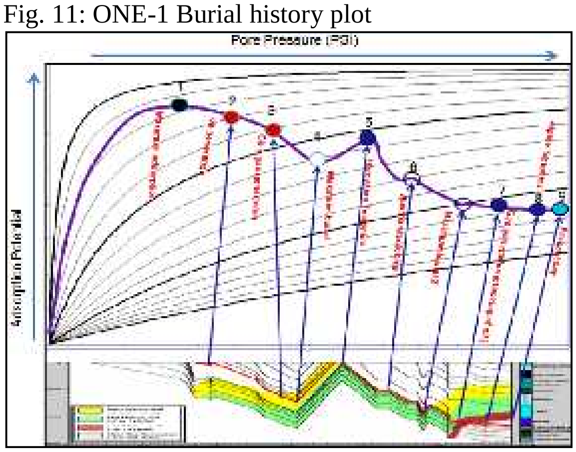

Fig. 12: ONE-1 Adsorption potential model

7.0 Comparison with established shale gas plays

Table 6: Comparison of the Tanezzuft (sweet spot) with other US shales

Parameter	Target Range	Utica	Marcellus	Tanezzuft('sweet spot')
Age	-	Middle – Late Ordovician	Middle Devonian	Silurian
TOC	>2%	0.5 – 3.0	2.5-5.5	0.5 - 17
Thermal maturity (% Ro)	>1.0%	0.3 - >1.0%	0.6 – 3.0%	0.5 – 2.2
Non clay content (%)	40 – 80%	50%	19 - 565	No data yet
Kerogen Type	I/II	II	II	II
Thickness (m)	>30	>15	>8	>30
Depth (m)	<4000	<4000	<4000	3500 - >5000

Table 7: Comparison of the Tanezzuft Hot shale (Tunisia) with other US shales [5]

Parameter	**Target Range**	**Wood ford**	**Barnett**	**Fayatte ville**	**Tanezzuft (Tunisia area)**
TOC	2 - 10%	3 - 10	3 - 8	3 - 8	3 – 15 (av. 6)
Thermal maturity (% Ro)	1.1 – 3.0%	1.1 - 3.0%	1.2 – 2.0%	1.2 – 4.0	0.7 – 2.2
Quartz content	30 – 80%	60 – 80 %	40 – 60%	40 – 60%	Up to 35%
Gas filled ϕ, %	2 – 8%	3 – 6.5	3 – 5.5%	3 – 5.5%	1 - 6
Thickness (m)	>30	30 - 65	60 - 150	15 - 100	20 - 50
YM, MMpsi	>3		4-6		-
Depth (m)	1000 - 3000	1800 - 3600	1800 - 2700	450 -2000	2500 - 4000
Pres. Grad. Psi/ft	Over press.	.52	.52	.43	-
BCF/Section		40 - 120	50 - 200	55 - 65	-
Frac. Barriers	Yes	Yes	Yes/No	Yes	Yes

The above comparison tables *(Tables 6 and 7)*, show that the Tanezzuft gas shale compares favourably with established shale gas plays in the US.

8.0 Additional considerations

The following need to be borne in mind by potential explorationists:

- Evaluation of the Mineralogy of the Tanezzuft Shale (key Uncertainty)
- Source of supply of water needed for fracking operations
- Potential environmental issues and ways of mitigating them?
- Presence of adequate infrastructure/political backing to drive shale gas exploration?
- Availability of specialist oil field services readily
- The effect of civil unrest in Libya, Algeria and Tunisia in recent times on Shale gas exploration

9.0 Conclusion

The following conclusions can be drawn from this study:

- Areas with sufficient TOC (i.e.>2% initial TOC) for shale gas exploration exist in the Tanezzuft gas shale
- The Tanezzuft gas shale is oil prone Type II Kerogen transgressive marine shale
- The thermal maturity map show that western Ghadames basin has the right thermal maturity (i.e.>1.0% Ro) for shale gas exploration.
- A 'Sweet spot' for shale gas development exist in the western Ghadames basin
- Basin modelling result for BRD-4 and ONE-1 is very promising and indicate favourable adsorption potential of the Tanezzuft gas shale in the identified 'Sweet spot'
- Tanezzuft gas shale compares favourably with established shale gas plays in the US.
- Uncertainty pertaining to the Tanezzuft gas shale mineralogy exists since no data was available for this study.

10.0 References

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