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Source Rocks and Related Petroleum System of Chelif Basin, (Western Tellian Domain, Algeria)

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1. Introduction

The study area lies in the external zone of the Rif-Tell or Maghrebides fold-and-thrust belt, the southernmost segment of the Alpine orogeny (Durand-Delga et al., 1980; Bracene and Frizon de Lamotte, 2002; Roure et al., 2012), which trends roughly east-west in northern Algeria (Fig. 1). The Chelif Basin is a dominantly Neogene trans-tensional basin located within the Northern Algerian foothills, southwest of the Kabylid ridge, which constitutes the surface expression of the paleo-suture between (1) exotic terranes of European affinities (Kabylides Crystalline Massifs and associated Mesozoic to Eocene sedimentary cover), and (2) the Tellian allochthon, made up of Mesozoic basinal units derived from the former passive margin of North Africa (Benaouali-Mebarek *et al.*, 2006, and references therein). The Neogene sedimentary infill of the Chelif Basin rests on top of the allochthonous basinal Mesozoic to Paleogene carbonates and sandstones units of the southern Tellian allochthon.

Since the discovery of the small oil fields of Aïn zeft and Tliouanet in the Chelif Basin in 1872, followed by Oued Gueterini in 1948 in the Hodna area, Northern Algeria constitutes an interesting zone for explorationists. Besides, many oil and gas shows exist either in the Saharan Atlas, south of the Alpine thrust front, or within the Tellian domain itself. The potential plays relate to Miocene compressional structures in the partially inverted foreland, in subthrust units and intra-mountain basins, as well as in Triassic to Jurassic extensional structures still preserved in the foreland autochthon.

The aim of this paper is to (1) identify potential source rocks in the Neogene Chelif Basin, in its allochthonous Tellian substratum, as well as in the underlying underthrust foreland, (2) locate the hydrocarbon kitchens and study the HC potential of these formations, (3) establish oil to source rock correlations in order to trace the

origin of the oils in the fields, (4) assess the timing of HC migration and trapping, and (5) define the main petroleum systems.

2. Geological setting

The intra-mountain Chelif Basin (Perrodon, 1957) is located in the western part of the Tellian Atlas. It is elongated in the east-west direction, with steep border faults delineating individual pull-apart basins filled by Miocene to Pliocene series (Fig. 1). Its structure developed following the last phases of the Alpine orogeny (Aïfa et al., 1992). For instance, during the Neogene, the plate boundary between the Western Mediterranean and the Kabyliides in the north and Africa in the south was a dominantly transform boundary, slab detachment and strike-slip faulting accounting for the lateral escape of the Gibraltar arc and Alboran block towards the west and Tyrrhenian-Calabrian arc towards the east (Hsü, 1971; Olivier, 1984; Thomas, 1985; Carminati et al., 1998; Spakman and Wortel, 2004, and references therein). Due to strain partitioning, numerous episodes of transpression and transtension were then recorded in the Chelif area, both in the Tellian allochthon and underlying underthrust foreland. The tectonic studies show that the present deformation is mainly compressive with a NNW-SSE direction of shortening (Philip and Thomas, 1977; Meghraoui, 1982; Philip and Meghraoui, 1983; Meghraoui, 1988; Meghraoui and Doumaz, 1996; Meghraoui et al., 1996; Boudiaf et al., 1998; Domzig et al., 2006; Yelles-Chaouche et al., 2006; Guemache, 2010). According to Rebaï (1993), the present state of regional stresses suggests that the Maghreb is subjected to a N-S compression and acts as an indenter in its central Algerian part, the western and eastern parts (Morocco and Tunisia) being allowed to experience a lateral escape (Piqué et al., 1998a & b). Furthermore, based on paleomagnetic measurements, the

relative convergence motion between the Africa and Eurasia plates could be interpreted as a transpressional tectonic deformation model with block rotations along the Algerian continental margin (Derder et al., 2013).

2.1. Geodynamic evolution and tectonic agenda

After the opening of the Tethys Ocean and coeval development of the northern passive margin of Africa during the Triassic and Liassic, the rotation of the African plate as compared to Eurasia induced since the Upper Jurassic a slow convergence between the two plates. This led to a progressive closure of the former ocean, and to the formation of the circum-Mediterranean Alpine mountains (Thomas, 1985). During the Late Cretaceous until the Eocene, foreland inversions developed in the former rift basins of the Saharan Atlas, due to a good coupling between the plate boundary and the African lithosphere, at a time when the oceanic domain was not yet fully subducted (Frizon de Lamotte *et al.*, 2006; Bracène and Frizon de Lamotte, 2002; Roure et al., 2012).

Surprisingly enough, the Tellian allochthon is made up of Upper Cretaceous to Eocene basinal units derived from the distal portion of the former passive margin of North Africa, with a basal decollement located in Triassic evaporites, with no evidence of Lower Cretaceous nor Jurassic series in between. The best interpretation here is to assume, as what has already been described for the Eastern Algerian and Tunisian Tell, that salt canopies made up of Triassic series were already interstratified within the Cretaceous series of the passive margin (Vila et al., 1993; Masrouhi and Koyi, 2012, and references therein), thus allowing a localisation of the main decollement along these interfaces during the subsequent episodes of thrusting. Deep water turbidites of the Oligocene Numidian series were actually deposited in

the distal portion of the African margin and on top of the southward propagating Tellian tectonic wedge.

The paroxysmal phase of thin-skinned deformation resulted in the overthrusting in the Tellian allochthon during the Lower Miocene. As a result, Langhian series are currently located in three distinct tectonic positions in the vicinity of the Chelif Basin (Fig. 2): (1) in the autochthonous flexural basin, where the Lower Miocene deep water turbidites rest directly on top of Upper Cretaceous blackshales in Tiaret, (2) in the footwall of the Tellian allochthon, where the Lower Miocene series still constitute a potential seal for the Mesozoic reservoirs of the subthrust prospects, and (3) on top of the Tellian allochthon, in a piggyback position.

After the final emplacement of the Tellian allochthon on top of its foreland domain, an episode of trans-tension occurred along the plate boundary during the Tortonian and Messinian, accounting for the formation of thrust-top pull-apart basins in the Chelif area (Ghazli, 2001; Roure, 2008; Roure et al., 2012), in a similar way as what has been described for the Vienna Basin at the junction between the Alps and the Carpathians (Sauer et al., 1992; Seifert, 1996), or in the Gulf of Paria between the Serrania del Interior in Eastern Venezuela in the west, and Trinidad in the east (Lingrey, 2007).

Since the Pliocene, there is again a good coupling between the plate boundary and the African foreland, accounting for the transpressional inversion of former normal faults inherited from the Tethyan rifting in the underthrust African foreland. This new compressional episode has resulted in the formation of subthrust anticlines involving the Mesozoic parautochthonous series and in the refolding of the sole thrust of the overlying Tellian allochthon beneath the Chelif Basin, in a similar way as in the Tempa Rossa and Monte Alpi fields of the Southern Apennines and other nappes

anticlines described in Northern Sicily (Casero et al., 1991; Roure et al., 2012), in the eastern part of the Algerian Tell near Constantine (Vila et al., 1994), as well as in the tectonic windows of the Bibans and Ouarsenis Mountains (Mattaue, 1958), where the lower plate is currently exposed to the surface due to the large amount of tectonic uplift and erosion.

2.2. Neogene sedimentary infill of the Chelif Basin

Due to the complex tectonic evolution of the Chelif Basin, its Neogene sedimentary infill can be subdivided into 3 distinct tectonostratigraphic assemblages (Neurdin-Trescartes, 1992 and 1995; Fig. 3):

At the base, the marine Lower Miocene megasequence (MSI) was still deposited during a compressional episode, in a piggyback position on top of the still moving Tellian. During the Lower Miocene, the sedimentary deposits preserved on top of the Tellian units, and especially in the western sub-basin of the Chelif, record the influence of arc-related alkaline and calc-alkaline volcanism.

The thicker Tortonian-Messinian megasequence (MSII) was deposited during the formation of the trust-top pull-apart basin, during the episode of transtension. It still comprises dominantly marine siliciclastic deposits at the base, grading into marl, continental siliciclastic deposits and intense volcanism, like cinerites, that are considered as a chronologic marker at the base of Messinian (Kieken, 1974 and 1975).

The Plio-Quaternary sequence (MS III) was deposited during the reactivation and inversion of the border faults of the Chelif Basin, coeval with the formation of subthrust structural closures in the underthrust foreland. It is made up of shallow marine (Algae limestone) and continental siliciclastic deposits.

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3. Results

3.1. Source rocks characterization

At the scale of the Circum-Mediterranean basins and thrust-belts, numerous stratigraphic intervals have been recognized since a long time as potential source rocks for hydrocarbons. This is the case for Upper Triassic bituminous limestones in Sicily and the Adriatic domain (Southern Alps, Dinarides and Albanides; Ziegler and Roure, 1996, and references therein), Liassic blackshale in the Saharan Atlas in Algeria (Vially et al., 1994), in the Ionian zone in the Albanides, in Epirus in the Hellenides (Karakitzios, 2013, and references therein), Cenomanian-Turonian euxinic facies in the Apennines, Eocene blackshale in the Eastern Tell in Algeria, Oligocene Numidian flysch in Tunisia and Sicily, as well as Messinian series.

In the Chelif area, only the Cretaceous and Cenozoic rocks of the Tellian allochthon and Neogene pull-apart basin have been investigated here, due to the current lack of deep well that would be required to document potential source rocks in the lower plate (underthrust foreland).

3.1.1. Upper Cretaceous (Cenomanian to Campanian)

As is most of North Algeria, Upper Cretaceous series of the Tellian allochthon cropping out in the vicinity of the Chelif Basin are locally preserved around the main Neogene depocenters, either in the form of well stratified Campanian outcrops, or as hard blocks of Cenomanian limestones reworked in the shaley matrix of tectonic mélanges along the sole thrust of the allochthon (Fig. 2). These Upper Cretaceous series have been sampled in outcrops of the northern and southern borders (Fig. 1). The facies is composed of grey to black shales and marls. Their organic richness is

mean to good. TOC varies from 1.5 to 7 % (Roure et al., 2006). TOC values varies from 0.56 to 3% Relizane and Beni Chograne mountain, near Tliouant field the southeast, in the Dahra Mountains it ranges from 0.9 to 8.2 %. The present day maturity shows a frozen oil window in the basin borders (outcrops) and instead a gas window in wells drilled in the central part of the Neogene basin (Fig. 3). Some outcrop's samples display high residual potential with HI varying from 102 to 480 mg/g TOC (Fig. 4 and Tab. 1), they are in oil window (T_{max} = 438- 443 °C), the lower HI (5- 12 mg Hc/TOC) indicate a gas window, the T_{max} is higher (574- 599 °C) (Tab.1).

3.1.2. Oligocene Numidian series

The Oligocene Numidian flysch crops out also in the Tellian allochthon on both sides of the Neogene depocenters, but it may be entirely lacking beneath the whole basin as due to the geometry of the Miocene normal faults. It consists of grey to black marls (Fig. 3) deposited in a deep water environment. Its thickness reaches up to 500 m. TOC varies from 2 to 4%, which gives an equivalent of 10 to 30 % in carbonate composition. The HI/OI diagram (Fig. 5) shows a type-III kerogen. However, the optical observation reveals amorphous sapropelic organic matter. This low potential at lower maturity indicates a poor preservation of the organic matter due to oxidation (Fig. 5). Whole samples display low to fair TOC, ranging from 0.4 to 0.9 % and low maturity. In the central part of the basin, the organic matter reached the oil window at about 2100 m and a wet gas window at about 3,500 m. The environment of deposition, mainly controlled by the geometry of the Maghrebides-Apenninic flexural basin, was probably not in direct communication with the Atlantic Ocean where upwelling streams could have occurred and could have renewed the anoxic zones with minerals that are necessary for the proliferation of the organic matter.

3.1.3. Lower to Middle Miocene

Their thick series of blue marls are characterized by a weakness of organic matter; the TOC is generally lower than 0.5 % (Figs. 6 and 7), this is due mainly to a dilution which is related to a high sedimentation rates (1000/my) . Nevertheless, they contain thin (decimeter-thick) layers which are limited in space with the TOCs ranging from 0.8 to 1%, like in El-Biod and Ain Zeft area (Fig. 6 and 7). The organic matter is from type II marine with probably inclusion of terrestrial material (Fig. 8), regarding the proximity of the land to the deep basin. Although the lower potential could be the result of the thermal maturation process (Figs. 5 and 8), the high oxygen index (IO= 200- 400mg CO₂/g COT) (Figs. 5 and 7) traduces an oxidation and thus a bad preservation of the organic matter (Fig. 8). In terms of maturity the deepest layers are in gas window (Figs. 5 and 8), in the central part of the basin (El-Biod, Nador, Akboub and Belkheir) and in oil window in shallower areas, such as Noisy and Fornaka.

3.1.4. Upper Miocene series

The Upper Miocene series have been sampled in the northeastern (El-Biod and Aïn Zeft) and southwestern parts (Belkhir and Fornaka) of the basin (Fig. 1) at depths varying from 500 to 750 m. Apart of the Tripoli member of the Messinian where TOC values can reach up to 10% or more, the average TOC values of other Miocene intervals range from less than 0.5% to 1% (Fig. 5).

The majority of the samples in Aïn Zeft (Fig. 7), Akboub and Hellil areas display high oxygen and lower hydrogen proportion in the organic matter (Fig. 5). The hydrogen index is around 100 mg HC/g TOC (Fig.5). In the El Biod area, the basal part of the Upper Miocene presents a fair quality of organic matter (fig. 4 and 7). There, the

Hydrogen index (HI) ranges from 100 to 150 mg HC/g TOC, the sample actually recording a maturity grade at the beginning of oil window (Figs. 6 and 7). Besides, close to the northern border of the basin near Ain Zeft and Dahra Mountain outcrop samples have been analysed, they show a good organic richness, with a TOC of 1.18- 2.31% (Fig. 4 and Tab. 1). However, even though the thermal indicators Tmax (<430 °C) and TAI= 1.5) (Tab. 1) traduces an immaturity of the organic matter, only two samples display fair to excellent potential (HI= 211 and 566 mg hc/g TOC). The rest of the samples are characterized by low hydrogen indices, this is due probably to a bad preservation or oxidation of the organic matter. Nevertheless, the oil shows and the Ain Zeft accumulation is an indication that there is an efficient kitchen zone in the vicinity of the area, the lack of the reliable samples does not allow establishing a thermal maturity map.

3.2. Oil-source rocks correlations

The normalized percentage compositions of the aliphatic, aromatic and NSO fractions of each sample of rock extracts and oils are plotted in a ternary diagram (Fig. 9). According to Tissot and Welte (1984), the grey area in the figure represents typical conventional petroleum composition. The samples present a lower proportion of aromatics hydrocarbons (HCA) and polar products (NSO) and high saturated hydrocarbons (HCS) (Fig. 9).

The graph $PR_{nC17} - PH_{nC18}$ (Lumbach, 1975, in Chaouche, 1992) is used for defining the maturity and the type of organic matter of the source rock which has generated oils and extracts that are analyzed by chromatography in the framework of the present study and internal unpublished works of Sonatrach. The extract samples (at 1911 and 1936 m depth) from Hellil area (well W9) are classified in a type II zone

after the graph and humic type zone for the third sample from 1584 m (Fig. 9). At El-Biod well the diagram shows a type-II kerogen and lower maturity as compared to Akboub oils in the western area (Fig. 9).

An oil sample issued from Ain Zeft field (well W3) and a hydrocarbon extract of Messinian marls (outcrops) have been analysed with gas chromatography and the chromatograms of C₁₄+ saturates are compared for a correlation need. The Messinian extract is characterized by a predominance of even number components and a low Pr/Ph fraction (0.5) (Fig. 10), this is an indication of a source rock that has been deposited in a highly reduced evaporitic environment. Besides, as indicated above, the samples are totally immature, C₂₁-C₃₅ being still present in high proportion. The Ain Zeft oil sample displays the same distribution with also a low Pr/Ph fraction (0.16) (Fig. 10). Moreover, the sulphur content in the present oil is higher than 2%, meaning that this oil was most probably generated from a type-IIS organic matter. The chromatogram of Messinian extract (shows a high concentration of biomarkers (Fig. 11a). Although the oil sample is slightly mature than the extract, the two samples seems to be similar. The absence of gas spectrometry data (GCMS) could not allow a complete correlation.

The oils from Tliouanet field are very mature because they contain a higher proportion of C₁₄-C₂₁ components (Fig. 11c), the regular decreasing of the pick heights, from C₁₉ to +C₃₀ component is an indication of a marine environment of the organic matter, from which these oils have been generated (Fig. 11 c).The Pr/Ph fraction is 1.6; it is an indication of a highly reduced environment (Fig. 11 c).The distribution of the extract component is the same as the one of the Tliouanet oil; the predominance of nC₁₅-nC₂₁ components traduces the relatively higher maturity of the samples (Fig. 11 d). Furthermore, the stratigraphic position of the produced

reservoir in Tliounat field (basal Tortonian sandstones) comparing to the Cretaceous allochthon source rock which belongs to the substratum of the Neogene Chelif basin, the migration pathways of this oil came from this Cretaceous level (Fig. 2). According to its geochemical signature, this oil is quite similar to the oils of the Oued Gueterini field farther east in the Hodna Basin, with strong affinities with extracts from Cretaceous source rocks. Because of the geometry of the Chelif Basin and their close association with the main border fault of the basin, these oils were probably generated from a deeper structural unit, with a dismigration from the subthrust parautochthonous units or underthrust foreland, in a similar way as the Jurassic-sourced oils found in the Neogene reservoirs of the Vienna Basin in Austria, which were actually generated in the lower plate, thus accounting for subsequent vertical migration across the sole thrust of the Tellian allochthon.

3.3. Thermal modelling and hydrocarbon generation history

3.3.1. Geothermal boundary conditions

1D thermal modelling in thrust belts remains a difficult task due to the spatial and temporal changes operating in the lithosphere and crustal architecture from the onset of rifting and passive margin development, which are usually characterized by a relatively high thermal regime, until the orogenic paroxysm which is instead likely to account for the development of a thicker crust, but also a thick lithospheric root, most foreland flexural basins being instead characterized by relatively cold heat flows. Alternatively, post-orogenic slab detachment and rise of an asthenospheric diapir beneath the offshore Algerian basin may have restored temporally an elevated heat flow in the vicinity of the Chelif Basin at its Upper Miocene peak of subsidence.

Another problem with 1D models is that they can hardly account for tectonic duplication, the Tellian allochthon recording a completely different thermal evolution as compared to the underthrust foreland until the Langhian, when the two domains were ultimately superposed with only minor subsequent tectonic contraction.

In this paper, the aims of the 1D petroleum modelling with the Genex software was to reconstruct the thermal, source rock maturation and petroleum generation in the Neogene depocenter, with a focus on the evolution of the Neogene source rocks from the post-nappe pull-apart basin. Further coupled 2D kinematic and petroleum Thrustpack modelling has also been attempted in the past in the Chelif Basin to address the thermal evolution of the lower plate and exploration risk of subthrust prospects (Sassi et al., 2006), but these results will not be detailed here, because of strong uncertainties when reconstructing the pre-Miocene thermal evolution of both the Tellian allochthon and underthrust foreland.

In any case, the North Algerian Tellian Atlas presently displays a normal crust which thickness ranges from 30 to 40 km (Marillier and Mueller, 1982; Thomas, 1985).

3.3.2. Geothermal history

According to Louni-Hacini *et al.* (1995), Neogene volcanic rocks from the northwestern coast of Algeria include calc-alkaline to shoshonitic andesites and dacites (Sahel of Oran and M'Sirda areas) and alkaline basalts (Tafna valley). Seventeen new ^{40}K - ^{40}Ar ages indicate that these volcanics were emplaced during two distinct periods, from 11.7 to 7.2 Ma and 4 Ma, respectively. All the andesites and dacites were emplaced during the first period, and their trace element characteristics are typical of subduction- and/or collision-related magmas. During the

1
2 324 Late Pliocene and Quaternary, the volcanic activity occurred in the Moroccan Middle
3 325 Atlas and in Oran area in Algeria (Fig. 1).

4 326 In the Tellian thrust belt the heat flow increases rapidly towards the Mediterranean
5 327 Sea. Its overall pattern is comparable to that measured in the other Tertiary belts
6 328 (Takherist and Lesquer, 1989). According to these authors the present day heat flow
7 329 varies from 80 mW/m² to more than 100 mW/m² near the offshore. At the present day
8 330 the geothermal gradient varies from 30-35°C/km (Normal Geothermic Gradient) to
9 331 more than 50°C/km (Fig. 12), two hyperthermic zones being localized in the central
10 332 part of the Chelif Basin, where it may be due to the local occurrence of Neogene
11 333 diapirs remobilizing the Triassic salt of the Tellian allocthon, (Fig. 2) and the coastal
12 334 zone near the Gulf of Mostaganem (i.e. in the vicinity of the neoformed Neogene
13 335 oceanic lithosphere of the offshore Algerian Basin.

14 336 In the eastern part of the basin, the deduced heat flow varies from 50 mW/m² to 85
15 337 mW/m² (Fig. 13a). For obvious geodynamic reasons, the heat flow model used in the
16 338 present study has been considered variable through the geological time. From the
17 339 Upper Cretaceous to the Lower Miocene (main episodes of tectonic contraction), the
18 340 mean flow value is estimated to 50-55 mW/m². However, related to geodynamic and
19 341 volcanic activity of the basin, we assume a larger heat flow value since the onset of
20 342 slab detachment and Tortonian-Messinian episode of accelerated subsidence in the
21 343 basin (Fenet, 1975; Bellon and Brousse, 1977; Aït Hamou, 1987; Maury *et al.*, 2000).
22 344 Ultimately, the present day heat flow has been deduced from the geothermal gradient
23 345 and thermal conductivities of the sediments. The BHT corrected temperatures
24 346 calibrated the present day heat flow at 85 mW/m² (Fig. 13a), as estimated by
25 347 Takherist and Lesquer (1989).

26 348

3.3.3. Reconstruction of the burial history

At eastern part of the study area, the Neogene series of the Chelif Basin were deposited on top of the Oligocene and Cretaceous Tellian allochthon (Figs. 1 and 2). The Late Oligocene and Burdigalian being still characterized by deep water turbidites along the Tellian allochthonous units underlying the Neogene depocenters of the Chelif, only minor erosion occurred in this formerly basinal domain until the onset of uplift and tectonic accretion.

During the development of the Lower Miocene syn-compressional piggyback basin (Langhian-Serravallian) and subsequent transtensional opening of the thrust-top pull-apart basin (Tortonian-Messinian), the sedimentation rate was very high 250 m/Ma (Fig. 13b). Because of renewed transpressional foreland inversion in post-Miocene times, the sedimentation rate was lower than 100m/Ma (Fig. 13b) during both the Pliocene and Quaternary in the relict depocenters, most of the basin being instead impacted by inversion-related uplift and erosion.

In the western area (W10 well), the sedimentation rate recorded during the Upper Cretaceous- Eocene period) is 30 m/Ma (Fig. 14 a). However, during Upper Miocene-Pliocene period, this parameter reaches 80 m/Ma; this is related to the transtensional extension of the basin (Fig. 14 a).

3.3.4. Hydrocarbon generation and expulsion histories

1D thermal modelling has been undertaken with the Genex software on the W5 Well in the El-Biod area and W10 to the West (Fig. 1). The thermal calibration of the thermal model is established thanks to the measured temperatures in the well and the maturity measurements (Ro converted values) (Fig. 13b). In the former area, the oil generation from the Middle Miocene formations (supposed source rocks) occurred

from 12 to 10 Ma and gas during 10- present day with a burial of 4000- 5200 m, whereas, the Messenia is still immature (Fig. 13c). Besides, the Langhian supposed source expelled oil between 8 and 5 Ma after that period only gas expulsion occurred in this deeper part of the basin (Fig. 13 d).

In the western area, there are two picks of oil expulsion, the first pick happens between 12 and 8 Ma while the second one between happens at 4- 2 Ma (Pliocene) (Fig. 14b).

Besides, the formation of structural traps relate to the Pliocene and Quaternary inversion, thus post-dating the Messinian episode of maximum burial. Considering type-II kerogen in this model, the Messinian which is the source rock of the Ain Zeff oil field was not buried enough there (at 1,000 m depth) to generate hydrocarbons. Alternatively, in the case of type-IIS kerogen as is shown by the n alkanes and biomarkers distribution in the rock extracts, it could generate commercial amounts of oil at lower temperatures (<50°C). A kinetic model of this organic matter would be required in order to confirm such scenario.

The Upper Cretaceous series are considered as the main source rock for the Upper Miocene reservoir in Tliouanet. They are probably also the source of the gas and oil shows documented elsewhere in the Chelif Basin (Fig. 1). The Middle Miocene series display some HC potential in the El-Biod area where the Miocene reservoirs might have been sourced from. The Ain Zeff heavy oil is originated from the Upper Miocene source rock which has also a good generation potential in this area (Figs. 1, 3 and Tab. 1). There are three types of traps, anticlines, roll-over structures and those associated to diapirs. Their age extend from Middle Miocene to Pliocene and even to present day. The early charge is most likely oil whereas the most recent traps could accumulate mainly gas.

4. Discussion

4.1. Petroleum systems analysis

4.1.1. Upper Cretaceous / basal Tortonian sandstone

In the Tellian allochthon, the Upper Cretaceous (Cenomanian to Campanian) source rocks extend only away from the Neogene depocenters, i.e. mainly south of the Tliouanet- Relizane fields in the south (Fig. 1a), and north of the Ain Zeft field in the north, making it difficult to contribute in any way to the petroleum potential of the basin. Actually, due to the Tortonian-Messinian extension, Neogene series rest almost directly above the sole thrust of the Tellian allochthon in the central part of the basin (Fig. 2), where coeval Upper Cretaceous source rocks are instead likely to be found at appropriate depth for HC generation in the underthrust foreland and parautochthonous subthrust prospects.

Although the presence of a thick Miocene sandstones package (200 m) in Djebel Djira area, to the west, there is no petroleum perspective because of the absence of the source rocks (Fig. 15).

The zone B (Fig. 15) is the most prospective thanks to the presence of reservoirs at the base of the Upper Miocene and the presence of both Upper Cretaceous and Upper Miocene source rocks. However, as far as the exploration results are concerned, and with the exception of the Ain Zeft accumulation, there have been only dry holes and hydrocarbon shows. The deficient parameter of the petroleum system in the whole Neogene sedimentary infill of the Chelif Basin is the timing of the trap formation as compared to hydrocarbon migration. This is the case for instance for Pliocene and Quaternary structures. The presence of the small accumulation in Sadra area (Sedra well, eastern part) resulted either from a migration during the

structuration or from a remigration from a deeper accumulation. Such accumulation is not commercial.

In Ain Zeft, Akboub and Hellil areas, the presence of the light oils, more mature than the rock extracts of the nearby source intervals, clearly require the occurrence of a deeper kitchen and both long range lateral and vertical migration, either from deepest parts of the pull-apart basin, or from the lower plate, using the main border faults of the basin to migrate from the underthrust units towards the Neogene pull-apart.

The zone C (Fig. 15) is the deepest part of the basin, it is characterized by a high sedimentation rate, varying from 100 to 1000 m/ma (Fig. 13b) during the Miocene. This might have caused dilution of the organic matter. Such sedimentological conditions and probably the absence of upwelling streams could not favor a development of anoxic conditions during Miocene time.

4.1.2. Messinian (source rock)/ Upper Miocene/Pliocene reservoirs

The Upper Miocene (Messinian) source rock extends along central part of the basin, Dahra Mountain and Ai Zeft area (Fig. 15). To be effective, this petroleum system would require the presence of Upper Miocene reservoirs, i.e. the basal Tortonian sandstone and Pliocene algal limestones (Lithotamnium limestone) and relatively old (pre-Pliocene) structures. The generation of the hydrocarbon from Messinian source rock is also conditioned by the thickness of the Pliocene sediments (burial).

Besides, the hydrocarbon charge of the Upper Miocene reservoirs could relate from deep Neogene kitchens or again, from a vertical migration across the sole thrust of the Tellian allochthon, from Upper Cretaceous source rocks from the lower plate.

Although a thick Pliocene series (500 à 1000 m) (Fig. 3) occurring at Fekrane and Belkheir areas (which could host both reservoirs and seals), there is a challenge for

developing any commercial hydrocarbon accumulation in relationship with this play, because of the lack of source rocks therein. Elsewhere, the Pliocene series are thinner (because mainly of Quaternary erosion), ranging from 0 to 50 m, which is clearly insufficient to expect any sealed reservoir there.

5. Conclusions

The Oligocene Numidian series display locally high organic contents in Sicily and Tunisia, where they are known to account for effective petroleum systems (El Heuchi et al., 2004; Granath and Casero, 2004). Despite the fact that no hydrocarbon field has yet been discovered in Oligocene Numidian sandstones in Northern Algeria, the Oligocene series of the Tellian allochthon in the vicinity of the Chelif Basin shows the same overall characteristics, and could still constitute a target for the exploration.

In the more than 4 km-thick pre-Messinian Miocene series, there are intervals with a mean organic richness (TOC) comprised between 0.5 and 1%, but their generative potential still remains low because of the bad preservation of the organic matter, which is marine with slight continental contribution. The optical observation and the low residual potential (HI) show that there is an effect of oxidation. In contrast, the Tripoli member of the Messinian series displays a very high organic content, with TOC values up to 10% or more, but low maturities ($T_{max} < 430^{\circ}\text{C}$). However, its kerogene is of the type-IIS, which could generate hydrocarbon even at low temperatures ($<50^{\circ}\text{C}$). Alternatively, the Upper Miocene is more buried in the main depocenters of the Chelif Basin than in the modelled wells, implying that it could be already in the oil window in the deepest, not yet inverted parts of the basin. The 1D basin modeling shows that the timing of oil generation from the Middle Miocene source rock occurred during the Upper Miocene and Pliocene period. Considering the

richest levels of the Middle Miocene source rocks, the oil expulsion began at 8 Ma. From 5 Ma to the Present day, mainly gas expulsion occurred. In any case, the GC/GCMS analysis confirms the correlation between Aïn Zeft oils, which contain oleanane, and Upper Miocene extracts. However, the main exploration risk for Neogene hydrocarbon systems relates to the scarcity of clastic reservoirs in the sedimentary infill of the pull-apart basin, most anticlinal structures being controlled by salt domes, with dominantly fine grain growth strata. Stratigraphic traps and sandy paleo-channels would rather occur along the flanks of the structures or in intervening lows, but they can hardly be identified here due to the lack of 3D seismic. Plio-Quaternary anticlines related to the recent inversion of the basin are likely to post-date the episodes of maximum burial in the Miocene depocenters, even if they could host remigrated oils from older structures, or oil escaping vertically from the subthrust units along vertical conduits such as the main border fault of the basin. Similar modes of petroleum charge is known to occur in the Vienna Basin in Austria for instance, where the oil generated in Jurassic source rocks from the lower plate have migrated upward across the Alpine nappes before to be trapped in Neogene clastics of the trust-top pull-apart basin (Sauer et al., 1992; Seifert, 1996).

The Cenomanian source rocks of the Tellian allochthon constitute frequently discontinuous blocks reworked in tectonic melanges along the sole thrust of the Tellian allochthon, or shallow erosional remnants between the main Neogene depocenters and the frontal Tellian thrust. Due to the Tortonian-Messinian extension, it is unlikely that thick Cenomanian series are still preserved in the allochthon beneath the Chelif Basin itself. Alternatively, the occurrence of oils with a geochemical imprint of Upper Cretaceous source rocks in the Tliouanet field near the main border fault of the Chelif Basin rather suggests a dismigration from the underthrusts foreland or

parautochthonous structures which formed during the Plio-Quaternary episode of transpression, making the subthrust plays a potential target. The main exploration risk here would relate to the possible erosion of Cretaceous platform carbonate reservoirs and Albian sands of subthrust prospects prior to the development of the Neogene foreland flexure and deposition of deep water seals, due to Late Cretaceous to Eocene episodes of foreland inversion (Roure et al., 2012).

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Figures captions

Figure 1. (a) Geological setting of Chelif Basin and well location map and petroleum results (b).

Figure 2. Regional structural cross-section of the Chelif Basin, outlining the Neogene flexural basin, the Langhian and Mesozoic series of the underthrust foreland, the Tellian allochthon, and the Tortonian-Messinian series of the thrust-top pull-apart basin and the main hydrocarbon kitchens and petroleum plays.

Figure 3. Typical Neogene stratigraphic and lithological section of the Chelif Basin and its substratum.

Figure 4. Geochemical log (Rock-Eval data) of Miocene section (El Biod , Well W5).

Figure 5. Geochemical log (Rock-Eval data) of Miocene section (Ain Zeft field , Well W3).

Figure 6. Maturity indication: S2/TOC diagram of different source rocks.

Figure 7. HI Vs. OI diagram of Miocene organic matter, Akboub, Hellil areas and outcrops samples.

Figure 8. HI Vs. Tmax diagram of Miocene organic matter (Well W6 and outcrops samples).

Figure 9. Ternary diagram HCS-HCA-NSO for oils and rock extracts.

Figure 10. Pr/nC17 Vs. Ph/nC18 graph of oil indices and rock extracts of Oligocene and Miocene stratigraphic levels.

Figure 11. Gas chromatogram traces of nC14+ saturates in the source rock extracts and oils .

(a) Oil fraction from Upper Miocene reservoir (Well W3; Ain Zeft field).

(b) Messinian hydrocarbon extract (Mesinian marls from outcrops of Ain Zeft area).

(c) Oil fraction from Upper Miocene reservoir (Tliouanet field).

(d) Upper Cretaceous hydrocarbon extract (Western Tellian domain).

Figure 12. Geothermal gradient map (°C/Km) of Chelif basin.

Figure 13. (a, b, c and d) Results of 1D Genex modelling of the burial history and hydrocarbon generation in El-Biod area (Well W5).

Figure 14. (a and b) Results of 1D Genex modelling of the burial history and hydrocarbon generation in Akboub area (Well W10).

Figure 15. Extension of upper Cretaceous source rock and zonation in terms of prospectivity of Upper Cretaceous (SR)/basal Tortonian (reservoir) petroleum system.

50 **Table 1.** Geochemical parameters based on TOC cut-off > 0.5% from Rock Eval
51 Pyrolysis and optical measurements (TOC: Total Organic Carbon; HI: Hydrogen
52 Index; TAI: Thermal Alteration Index).

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CHELIF BASIN

A - Perrodon, 1957
B - Meghraoui, 1982
C - Thomas, 1985
D - Meghraoui, 1982 and 1986

Rock extracts Hellil area (**W9**)

☆ 1- Oligocene (**W9**)

Oils [Aïn Zeft (AZ-4), Akboub (**W1**) and El Biod (**W4**)]

● 1- Upper Miocene (**W3**)

⬡ 2- Middle Miocene (**W4**)

□ 3- Oligocene (**W1**)

Rock extracts [Hellil area (W9)]

☆ 1- Oligocene (W9)

Oils [Ain Zeft (W3), Akboub (W1 and W2) and El Biod (W4)]

● 1- Upper Miocene (W3)

○ 2- Middle Miocene (W2, W3 and W4)

□ 3- Oligocene (W1)

HYDROCARBONS WINDOWS HISTORY

Study Name: Cheliff Basin

Well Name: **W10**

Time (Ma)

Depth (Km)

Computing Parameters:

No Calibration
Variable Heat Flow
Imposed Pressure
Open System

EXPULSED HC PER TIME INTERVAL

Study Name: Cheliff Basin

Well Name: **W10**

Time (Ma)

Expelled
Hydrocarbons
(mg HC/g
initial dry rock)

Gas

C6+

Computing Parameters:

No Calibration
Variable Heat Flow
Imposed Pressure
Open System