Hinterland and foreland structures of the eastern Maghreb Tell and Atlas thrust belts: tectonic controlling factors, pending questions, and oil/gas exploration potential of the Pre-Triassic traps

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Presentation of the special issue Geology of North Africa and Mediterranean regions

This special issue of the AJGS entitled Geology of North Africa and Mediterranean regions is a follow-up of the AGIC (Atlas Georesources International conferences) organized in 2017 by the Georesources Laboratory and CERTE, Tunis, University of Carthage. This event was a major occasion for geoscientists from Arabian, Maghrebian, and European countries to present their recent findings and research results in the characterization of different georesources in North Africa, the Mediterranean, and surrounding areas, thus also including the Arabian plate.

This thematic issue is composed of 33 papers covering a wide spectrum of topics and fields, from architecture and thermicity of sedimentary basins to structural evolution, oil/gas exploration, fractured reservoirs, water resources, aquifer characterization, and applied geophysics.

Architecture and thermicity of sedimentary basins, structural evolution, and oil/gas exploration

This special issue contains 13 papers covering different sedimentary basins in North Africa, Yemen, Egypt, and Greece, with a special attention on the oil and gas potential in the Tell and the Atlas belts and their respective foreland basins, and a particular interest in the salt mobility and petroleum traps characterization, including papers by Bédier et al., Kheilil et al., Khomsi et al., Arfaoui et al., Khouni et al., Tari et al., Naji et al., Boughalmi et al., El Sawy et al., Mezni et al., Tseloras et al., and Bagazi et al.

In this thematic, the authors used different approaches involving structural analysis, seismic data interpretations, balanced cross-sections, modeling of source rocks maturity and petroleum systems, and a description of trap occurrences.

Fractured reservoirs

This thematic comprises 8 papers covering different basins in North Africa, from the Atlas fold-and-thrust belt, the eastern foreland basins and northern Sahara platform, and the western province of Saudi Arabia, including investigations of deep subsurface reservoirs by seismic analysis, applied sequence and seismic stratigraphy techniques, well logging interpretations, and structural analysis at different scales. This thematic is covered by papers presented by Souei et al., Bédier et al., Lachaal et al., Nefzi et al., Hammami et al., Saleem et al., Thebti et al., and Al Ghamdi.

Applied geophysics

A set of 4 papers was presented, dealing with applied geophysics with their use in structural characterization, water

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resources, and subsurface investigations of georesources. Different techniques were presented involving gravity interpretation and modeling, electromagnetic modeling,

wire-logging techniques interpretations and 3 D models. The papers of this thematic were presented by: Mouakhar et al., Al Garni., Azeiz et al., and Lamouchi et al.

◀**Fig. 1** The Maghrebides fold-and-thrust belt within the Circum-Mediterranean Alpine system issued from the collisional tectonics of the Tethyan margins. **a** From Frizon de Lamotte et al. (2011). **b** Kinematic and paleo-tectonic transect in the western Mediterranean during Pleistocene-Quaternary after the slab sinking beneath the Algerian back-arc basin. Notice that the subduction of the northeastern African margin beneath the South Eurasian plate from Cyrenaica to Egypt still continues. **c** Actual movements of the eastern Mediterranean basin structures with rates of convergence in mm/year measured by satellite and GPS equipment (Dotmed Project, 2005; Chamot-Rooke et al. 2005a, b). Notice that in the Sirt offshore and Cyrenaica, high ranges of convergence are now observed (35 mm/year) compared to the Maghreb in Tunisia where the value attains 7 mm/year. The map indicates also continuing Africa/Eurasia convergence after slab sinking in the western Mediterranean Maghrebic basins in the Langhian

Water resources and aquifers characterization

This topic was covered by a set of 8 papers dealing with different aspects of water resources studies in Northern Africa and Arabia, two regions suffering problems of water resources and their impact on regional aridity. The papers present a wide range of approaches involving: geostatistics, environment impacts, re-use of treated waters, pollution, and vulnerability of water resources, rainfall variations, and climate change tendencies. The papers were presented by Chargui et al., Subyani et al., Khaddar et al., Moussa et al., Saleem et al., Lachaal et al., Bedir et al., and ben Hammouda.

Northern Africa Tell and Atlas fold and thrust belts in their geodynamic context

As a whole, the Tell fold-and-thrust belt corresponds to a tectonic wedge (Fig. 1) built from a long and complex evolution at the North African margin of Maghrebic sedimentary basins (Frizon de Lamotte et al., 2000 and 2009; Granath and Casero, 2004; Roure et al., 2012; Khomsi et al., 2016 and 2018; Arab et al., 2020). Several tectonic pulses were recorded over the Cenozoic times, during the NW-dipping subduction of the Ligurian-Tethys ocean segment, linked to the North African margin, underneath the European margin (Roure et al., 1990 and 2019; Jolivet et al., 1999; Vergés and Sàbat, 1999; Hippolyte et al., 1994; Roca et al., 2004; Finetti et al., 2005; Guerrera, 2014; Guerrera et al. 2019). The subsequent SE-directed roll back of this subduction during the Oligocene-Langhian caused the retreat of the Tethys slab, the formation of the Algerian Basin behind, and the collision of the AlKaPeCa domain against the deep margin of the north Atlasic Basin in the Langhian (Roca et al., 2004; Roure et al., 2012;

Van Hinsbergen et al., 2014). Soon after the continental collision, a mantle delamination process followed by slab break-off occurred in post-Langhian times (Roure et al., 2012; Van Hinsbergen et al., 2014) (Fig. 1). The present position of the sinking slabs beneath the Algerian and Tunisian Tell-Atlas systems has been confirmed by seismic tomography by Fichtner and Villaseñor (2015). These major geodynamic events were accompanied by vertical, up and down lithospheric movements controlling the thermal maturity of the organic matter in the different sedimentary basins during their Neogene-Quaternary evolution with flexing during the tectonic loading phase of the Oligocene-Langhian and later unflexing after slab break-off and coeval uplift and erosion (Fig. 1). These lithospheric movements have amplitudes of hundreds of meters and have controlled the thermal as well as subsidence history and source rocks maturity of the basins and preservation/migration of oil and gas in traps and reservoirs. A recent study of the lithospheric structure of the Tunisian margin determined that the combined processes of delamination and slab break-off could affect a region with a wavelength of 100 km reaching dynamic topographies of ≥ 500 m (Kumar et al., 2021).

But the knowledge of their impact on the thermal maturities of the basins is still limited in the Maghreb, and the Tell and future researches should treat specific questions on the thermal maturity of source rocks and their links with the vertical movements of the lithosphere (Roure, 2008 and 2014).

The Tell fold-and-thrust belt of the Eastern Maghrebides constitutes an important mobile segment of the Alpine collisional chains (Fig. 1) issued from the accretion of the ALKAPECA (Alboran-Kabylides-Peloritan-Calabria) domain along the southern margin of the Maghrebic Tethys during post-Langhian times. The collision wedge underwent compressional tectonics with the individualization of internal and external zones (Roca et al., 2004; Roure et al., 2012): the internal zones correspond chiefly to the Kabylides Paleozoic terranes thrust on the Eocene–Oligocene deep-water flexural basins. The external zones correspond to the Eastern Tell of Algeria and Tunisia, characterized by imbricate thrust fan systems thrusting on top of the intracontinental and inverted sedimentary basins of the Northern Atlas to the south.

North of the Kabylides and tectonic suture, the hinterland was impacted by the opening of the Algerian back arc basin (Fig. 1) during the Upper Oligocene–Miocene until now, recording more than 2000 m of sediments over the extended continental to oceanic substratum of the Algerian Basin (Roure et al., 2012): a recent compilation is recently presented in Bellucci et al. (2021).

Fig. 2 Tectonic map of the eastern Maghreb major structures (**a**) and geologic map of the eastern Tell in Tunisia (**b**) together with the positions of Transects 3 a in Kasseb and transect 3 b. For 1 a, captions:

Captions. 1: major arch, 2: major fault, 3: major thrust, 4: major anti-cline, 5: salt bodies, 6: major strike-slip fault, 7: grabens

Tectonic accretion during the Late Eocene inversion events in the Tell and the Atlas: the nature and significance of the major Oligocene unconformity

After the pioneer works and monographies (Vila; 1980; Rouvier, 1985; Raoult, 1974; Raoult et al., 1982), numerous papers published during the last two decades provide a better overview and constraints on the tectonic pulses versus structural styles (Figs. 2 3 4 5 6 to 7) in the thrust wedge of the Eastern Maghreb (Bracène and Frizon de Lamotte, 2002; Benaouali-Mebarek et al. 2006; Masrouhi

et al., 2008; Khomsi et al. 2009a, b and 2019a; Roure et al., 2012; Khelil et al., 2019a, b; 2019b and 2021; Leprêtre et al., 2018; Riahi et al., 2010; Belyaouni et al., 2013). These works agree with thrust tectonics expressed by duplex anticline structures detached above Triassic evaporites and both Cretaceous and Tertiary shale levels as decollement levels separating different structural styles (Fig. 3).

On the other hand, the Atlas belt, at the south-eastern edge of the Tell (Figs. 1 and 5), corresponds chiefly to an inverted intracontinental rift system, issued from positive uplift movements, firstly during the late Eocene and

Fig. 3 Structural transects along the Tunisian Tell (a from Khomsi et al., 2021) and the Sicily arc (b from Roure et al., 2012). The two transects show some similarities concerning the Numidian Flysch transported basin over the Maghrebides wedge in a piggy back configuration. The transects underline also the existence of some normal faults and collapse of the inner parts of the belt. They underline also the duplexing of the Mesozoic series underneath the thrust wedge. Notice that the allochthonous system of the Tunisian Tell overhangs Langhian flexural series, whereas in the Sicilide, the allochthon over-

hangs the Upper Miocene-Quaternary foredeep series. Notice that both in Sicily and Tunisia, the Numidian series lie unconformably on duplicated Cretaceous-Cenozoic thrust structures. **a** 1—Upper Albian, 2—Cenomanian–Turonian, 3—Coniacian–Santonian, 4—Upper Santonian–Lower Campanian, 5—Upper Campanian–Lower Maastrichtian, 6—Upper Maastrichtian, 7—Paleocene, 8—Ypresian basal limestones (Kasseb units), 9—Late Eocene shales, 10—Numidian Flysch, 11—Oligocene to Aquitanian–Langhian, 12—Upper Miocene–Quaternary

subsequently during the Upper Miocene–Quaternary Alpine movements (Frizon de Lamotte et al., 2000 and 2009; Khomsi et al. 2009a, b; Belyaoui et al., 2013; Roure et al., 2012; Bahrouni et al., 2020; Khelil et al., 2020). The late Eocene compressional events are well recorded in the Tell and in the Atlas belt, as well as in its southern and eastern foreland basins (Fig. 5). These events represent the onset of shortening affecting the whole North African Tethyan margin with the climax of the subduction of the North African margin underneath the South European margin. It is well expressed by a regional and wide angular unconformity at the base of the Oligocene–Miocene synflexural series (Figs. 3 4 to 5) of the Numidian flysch deposits in the Tell and the marine to continental Fortuna Formation in the Atlas. The angular unconformity at the base Oligocene

expresses the onset of the tectonic accretion in the moving thrust wedge of the Tell since the late Eocene. This tectonic accretion of the Cretaceous–Eocene basinal series was strong enough to control the erosion and reworking of pre-Oligocene series deposited in deep canyons. In fact, detailed structural analyses of the basal contact of the Oligo-Miocene Numidian Flysch outline a sedimentary contact between the lower Numidian beds, with a downlap to lateral onlapping on underlying Ypresian Kasseb units as well as erosion of the late Eocene series (Figs. 3 and 4) together with some synchronous tectonics affecting the Oligo-Miocene beds (Figs. 3 and 4). In the Kasseb locality (Fig. 3), which is a key area to understand the structural contacts of the Numidian Flysch and the underlying Kasseb units, the Numidian is sealing unconformably Eocene

Fig. 4 Panoramic pictures in Kasseb area looking north (position on Fig. 2b) and corresponding interpretations underlining a regional and enhanced unconformity separating the Numidian Oligo-Miocene flexural series above eroded Ypresian Kasseb limestone allochthonous series. The angular unconformity is materialized by erosion of some Eocene sequences with a lateral onlapping and sealing of extensional structures at the base of the Numidian Flysch (a, b). The panorama

sketches c and d underline downlapping and draping of the Numidian lower beds over late Eocene shales and Ypresian limestones, with important erosion of the Late Eocene beds laterally together with filling of paleo-valleys by the Numidian. Notice that these features underline an important flexural and basinal unconformable megasequence over the Kasseb accreted units

duplex structures. All these features agree with the fact that the late Eocene uplift events related to the Atlas Eocene compressions were strong enough to initiate the tectonic accretion and stacking of the Kasseb units and Cretaceous carbonates series of the foreland (Fig. 3).

Some important pending questions: significance of the Triassic salt as a regional seal for subsurface structures

Despite our increasing knowledge on the structural styles (Figs. 6 and 7) and tectonic events in the Maghrebides and the Atlas, some important structural questions arise concerning specifically on the along-strike variations of this structural

style, the importance of the Triassic salt (Perthuisot and Rouvier, 1992; Vila et al., 1999a, b; Khomsi et al. 2009a, 2018; Masrouhi et al., 2013; Troudi et al., 2017; Soto et al., 2017; Khelil et al., 2019a, b a, b and 2020) in the control of the overall tectonic grain (Fig. 6), the structural configuration of the deep seated structures underneath the Triassic evaporite (Soto et al., 2017; Khomsi et al., 2019a, b), and the nature of the Pre-Triassic series/structures, which remain mostly unknown. All these questions influence not only our knowledge of the deep architecture of the Tell FABT but also the exploration of the oil and gas habitats in these important regional structures in Algeria and Tunisia, both in the Atlas and its foreland basin as well.

In fact, it is questionable whether or not the Paleozoic sequences are involved in the Alpine rejuvenation

Fig. 5 Two structural transects in the Gulf of Hammamet and Sicily Channel underlining inverted Mesozoic structures in the subsurface of the foreland domain. These transects outline two major tectonic pulses materialized by two major angular/erosional unconformities: The late Eocene and the late Miocene-Quaternary Alpine compres-

sions produced the rejuvenation and positive inversions of former extensional basins. Notice that the transects show also Paleozoic structures buried beneath the Mesozoic megasequence. From Casero and Roure (1994) modified by Khomsi et al. (2016). Position map above from the Geologic map of Africa (2016)

Fig. 6 Structural transects in the Tell of Tunisia (from Khelil et al., 2020 and Khomsi et al., 2021). The first transect (labeled CS1 on the position map) shows very important Triassic salt movements materialized by diapiric structures as salt wall and salt plugs thrust over the Upper Miocene-Quaternary Utique Kechabta foredeep basin. The transect also displays major thrusting and ongoing compressions and rejuvenation of the Tell wedge and its foreland basin and Northern

Atlas structures. The second transect (labeled CS2 on the position map) cross-cuts the inner parts of the Tell wedge from Fernana to the Northern Atlas belt at the south-eastern edge crossing the collapsed Mejerda Basin at the front of the Tell. The transect underlines large amounts of vertical Triassic salt motion with diapirs and salt plugs in the inner Tell as well as in the Northern Atlas

of the Tell system. In fact, the Triassic salt regional seal still precludes the unlocking of petroleum exploration in the Paleozoic structures underneath the Meso-Cenozoic subsurface structures of the Tell in Algeria and Tunisia as well. Some recent published transects and cross-sections argue for the existence of possible active petroleum systems and gas traps seated in the Paleozoic (Khomsi et al., 2019a, b and 2021).

Future oil and gas exploration

The Mesozoic-Cenozoic petroleum potential in the Tell of Tunisia was discussed in some papers and regional works during the last years (El Euch et al., 2004; Mejri et al., 2006; Khomsi et al., 2018, 2019a, b and 2021). These studies account for the occurrence of potential oil/gas traps, especially in the northern offshore of Tunisia where the Meso-Cenozoic system is seemingly very interesting and potentially very prolific (Khomsi et al., 2019a, b and 2021).

However, deep seismic records of good resolutions with a dense and sufficient grid are still lacking in the Tell of Tunisia despite the fact that few old 2D seismic campaigns have been somehow re-processed. Meanwhile, the resolution is still insufficient and far beyond what would be expected to unlock the exploration of potential oil/gas plays in the offshore of the Tell.

In addition, the thick Triassic salt and regional seal, which is characterized by its chaotic seismic facies, does not allow to properly image potential traps within the Mesozoic sequences and is also a limiting factor to clearly identifying deeper oil and gas traps in the Paleozoic structures (Roure et al., 2019; Khomsi et al., 2019a, b).

The structural transects presented in the preceding sessions (Figs. 3, 5, 6, and 7) underline the likely occurrence of Paleozoic petroleum structures, but again, the scarcity and limited qualities of seismic profiles still preclude the unlocking of the Paleozoic system too.

Conclusion: on the need of deep seismic sections in the Tell and Atlas

In addition to the Mesozoic-Cenozoic composite petroleum systems of North Africa, assumed to be very prolific and potentially interesting even if not yet discovered, the deep structures in the offshore of the Tell deforming the Paleozoic system beneath the Atlas and Tell belts and their respective forelands basins remain mostly unknown. These Paleozoic systems could be as prolific as those in Algeria and Libya and southern Tunisia, as suggested in the previously discussed cross-sections.

Therefore, we urgently need to identify the potential subsurface Paleozoic structures and traps seated beneath the

Fig. 7 Structural transects in the Tell of Algeria (from Roure et al., 2012). The transect above (labeled a on the position map) shows buried Tethyan rifted system affecting the Jurassic and Cretaceous series, materialized by tilted blocks and half-grabens. This transect crosses the Oued Gueterini oil field sourced from Cenomanian–Turonian Bahloul source rocks. The Miocene foreland sequences lie unconformably on Upper Cretaceous successions in the same way as the Langhian deposits of the Tell of Tunisia. In Oued Guetrini field, the Eocene sedimentary series are duplicated and are thrust on the

Miocene flexural basin as in the Kasab area (Fig. 3). The Chelif transect underlines the transported Chelif basin over the Miocene flexural basin in a piggy-back configuration. Notice the lateral tectonic transport of salt plugs intruding the Cretaceous sequences, which have been transported SE-ward together with the entire Chelif piggy-back basin on top of its Atlasic foreland basin. Notice also the duplication of the Miocene sequences lying SE on the Cretaceous series. This transect crossing Algeria shows many similarities with the transect of Fig. 6 in the Utique-Kechabta basin in Tunisia

Atlas and Tell, likely to be sealed by the regional Triassic salt level. To unravel these structures, we do need a deep seismic imaging project along the North African Maghreb margin with sufficient recording depth (i.e., down to 10 to 15 s TWT) to visualize properly the potential pre-Triassic salt hydrocarbon plays. We hope that in the future, a research consortium involving exploration companies, universities, research centers, and groups from both sides of the Mediterranean Sea will be able to organize and operate such deep seismic imaging project and open new oil and gas perspectives.

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