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ORIGINAL ARTICLE

Basin tectonic history and paleo-physiography of the pelagian platform, northern Tunisia, using vitrinite reflectance data

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Abstract

Constraining the thermal, burial and uplift/exhumation history of sedimentary basins is crucial in understanding the evolution of upper crustal strain and also has implications for understanding the nature and timing of hydrocarbon maturation and migration. In this study, we use Vitrinite Reflectance (VR) data to elucidate the paleo-physiography and thermal history of an inverted basin in the foreland of the Atlasic orogeny in Northern Tunisia. In doing so, it is the primary aim of this study to demonstrate how VR techniques may be applied to unravel basin subsidence/uplift history of structural domains and provide valuable insights into the kinematic evolution of sedimentary basins. VR measurements of both the onshore Pelagian Platform and the Tunisian Furrow in Northern Tunisia are used to impose constraints on the deformation history of a long-lived structural feature in the studied region, namely the Zaghouan Fault. Previous work has shown that this fault was active as an extensional structure in Lower Jurassic to Aptian times, before subsequently being inverted during the Late Cretaceous Eocene Atlas II tectonic event and Upper Miocene Atlas II tectonic event. Quantifying and constraining this latter inversion stage, and shedding light on the roles of structural inheritance and the basin thermal history, are secondary aims of this study. The results of this study show that the Atlas II WNW-ESE compressive event deformed both the Pelagian Platform and the Tunisian Furrow during Tortonian-Messinian times. Maximum burial depth for the Pelagian Platform was reached during the Middle to Upper Miocene, i.e. prior to the Atlas II folding event. VR measurements indicate that the Cretaceous to Ypresian section of the Pelagian Platform was buried to a maximum burial depth of ~3 km, using a geothermal gradient of 30°C/km. Cretaceous rock samples VR values show that the hanging wall of the Zaghouan Fault was buried to a maximum depth of <2 km. This suggests that a vertical km-scale throw along the Zaghouan Fault pre-dated the Atlas II shortening, and also proves that the fault controlled the subsidence of the Pelagian Platform during the Oligo-Miocene. Mean exhumation rates of the Pelagian Platform throughout the Messinian to Quaternary were in the order of 0.3 mm/year. However, when the additional effect of Tortonian-Messinian folding is accounted for, exhumation rates could have reached 0.6–0.7 mm/year.
1 | INTRODUCTION

Understanding the thermal, burial and exhumation histories within sedimentary basins is essential for a range of fundamental and applied purposes (Laughland & Underwood, 1993; Mazurek, Hurford, & Leu, 2006; O’Hara, Hower, & Rimmer, 1990; Sakaguchi, Yanagihara, Ujije, Tanaka, & Kameyama, 2007; Yuan, Hu, Wang, & Sun, 2007). Such understanding is critical to elucidate the geodynamic context and history of sedimentary basins, and is applicable to hydrocarbon source rock analysis in which the prediction of subsurface organic matter maturity distribution remains a key issue for basin modeling (Mahlmann & le Bayon, 2016). In this study, we use structural and vitrinite reflectance (VR) data to investigate the complicated thermal, burial and exhumation history of a tectonically polyphase sedimentary basin, the current-day Atlas Eastern foreland, in order to elucidate its geodynamic evolution in a regional context.

The thermal histories of foreland basins record the regional tectonic evolution of peripheral parts of orogens through space and time; understanding the tectonothermal history of a foreland basin may therefore also shed light on the tectonic evolution of the entire orogen (Allen & Allen, 2005). Influence of pre-existing structural fabrics is well-known in orogens (Audet & Burgmann, 2011; Butler, Tavarnelli, & Grasso, 2006), and inherited extensional structures that have been reactivated during later events of compression may significantly control locations of geologic subsidence (Thomas, 2004; Allen & Allen, 2005; Panien, Schreurs, & Pfiffner, 2005; Bonini, Sani, & Antonielli, 2012 for review; Guiraud & Bosworth, 1997 for Atlas). Since the thermal history is a function of subsidence (and exhumation) and the geothermal gradient, investigating the spatial variations in thermal history may shed light on where/how subsidence was accommodated, and whether pre-existing structural fabrics were exploited.

In this contribution, we investigate the thermal evolution of the folded Pelagian Platform in the Enfidha region (Northern Tunisia), which was deposited during Mesozoic and early Cenozoic times, and deformed through both Eocene Atlas I and Upper Miocene Atlas II tectonic events (Khomsi et al., 2009). We do this in an attempt to unravel the tectonic history of structural domains, and the role of pre-existing extensional structures to accommodate shortening related to Atlas tectonic phases (Guiraud & Bosworth, 1997). In doing so, we provide an example where VR and structural data are used to investigate the thermal history of a sedimentary succession through space, which in turn is used to decipher the burial/uplift spatiotemporal evolutions of two distinct structural domains.

Although previous studies have shed light on the kinematic history, structural style and depositional evolution of the basin (e.g. Bouaziz, Barrier, Soussi, Turki, & Zouari, 2002; Khomsi, Bedir, Soussi, Jemia, & Ismail-Lattrache, 2006; Khomsi et al., 2009; Morgan, Grocott, Richard, & Moody, 1998), the thermal evolution of the Pelagian Platform, currently located to the east of the Tunisian Atlas, and its tectonic relation to the Tunisian Furrow remains poorly understood.

The specific main goal of this study is to elucidate/quantify the tectonothermal, burial and exhumation history of two distinct structural domains separated by a major polyphase structural feature, using structural data and VR data. This is done through focusing on the case of the Zaghouan-Ressas structural belt (Morgan et al., 1998) of the Pelagian Platform in Northern Tunisia, and we address this main goal through the following set of specific objectives: (i) elucidate the role of structural inheritance in the evolution of the Pelagian Platform basin in the Atlas foreland; (ii) assess the maximum temperature reached by the studied succession; (iii) quantify the differential burial history of two main structural domains in the studied area (Hezzi, 2014); and ultimately (iv) quantify their exhumation rates.

2 | GEOLOGIC SETTING

The Tunisian Atlas consists of intra-continental fold and thrust belts that mainly result from the collision between Africa and Eurasia in two distinct episodes of convergence, one in the Middle-Late Eocene and another in the Miocene-Pliocene (Frizon de Lamotte et al., 2009). The study area is located in the Enfidha region of Northern Tunisia where two structural domains coexist, the Tunisian Furrow and the Pelagian Platform (Figure 1). The Pelagian Platform forms part of the Pelagian Province that extends offshore into shelf area of northern Libya and east-central Tunisia, and northwards towards Malta (Kett, 2001). The western boundary of the Pelagian Platform is located onshore Tunisia, along the so-called ‘North-South axis’...
Within the studied area, the North-South axis is expressed by the Zaghouan fault, which in Jurassic times was an extensional structure that controlled the location of the eastern margin of a marine carbonate platform; the Zaghouan Fault delineated the ‘Tunisian Furrow’ structural domain where this carbonate platform was located (Ben Ayed & Viguier, 1981; Chihi, 1995; Saadi, 1990; Melki, Zouaghi, Ben Chelbi, Bédir, & Zargouni, 2010 & Melki et al., 2011; Hezzi, 2014).

Previous work has shown that the following deformation events have subsequently affected the study area: (i) Compressive deformation began by the Santonian and is followed by a Paleocene period of relative quiescence (Laffite, 1939). (ii) Evidence for episodic Atlas I transpressive deformation, thrust faulting and folding is recorded during the middle/late Eocene (Khomsi et al., 2009). This Eocene-aged event related to the Atlas I phase has triggered local uplift, imposed a probable structural control on basin geometry, influenced the local sedimentation patterns and
ultimately caused reverse reactivation of the Zaghouan Fault in the study area (Burollet, 1967; Guiraud, 1998; Khomsi et al., 2009; Morgan et al., 1998). The Atlas I contractional phase is also characterized by angular unconformities of middle Eocene age identified on the flanks of anticlines from 2D reflection seismic sections and sealed by a pre-Oligocene unconformity (Frizon de Lamotte, Michard, & Saddiqi, 2006; Khomsi et al., 2006). (iii) A period of relative tectonic quiescence characterized the Oligocene-early Miocene, with only minor extension taking place (Khomsi et al., 2009) and the development of associated isolated extensional structures. In particular, a Lower to Middle Miocene transtensional phase is expressed by W-NW to E-SE striking faults in the studied area (Philip, Andrieux, Dlala, Ben Chihi, & Ayed, 1986). The Flexure in the South Eastern frontal region of the Intermediate Atlas, and the onset of incipient extension in the Pantelleria-Linosa-Malta Rift System were the dominant factors controlling the Oligo-Miocene development of the study area (Frizon de Lamotte et al., 2009; Khomsi et al., 2009). (iv) The most significant event recorded in the studied region is the second phase of Atlas shortening, called the Atlas II event, which affected both the Pelagian Platform and the Tunisian Furrow in Tortonian to Messinian times (Castany, 1951; Richert, 1971; Rouvier, 1977; Philip et al., 1986; Khomsi et al., 2009; Figure 1 and 3). (v) A Pliocene episode of transtensional deformation partly overprinted the contractional structures (Philip et al., 1986), and led to the formation of W-NW to E-SE striking normal faults. This transtensional event is likely related to the final stage of the Pantelleria-Linosa-Malta Rift System in Plio-Quaternary times (Frizon de Lamotte et al., 2009).

In addition to the afore-mentioned series of tectonic events, halokinesis is thought to have been active from Jurassic to early Eocene times in Eastern Tunisia (Mejri, Burollet, & Ben Ferjani, 2006). Brahim and Mercier (2007) as well as Rigane and Gourmelon (2011) have proposed that middle Eocene unconformities of the Pelagian Platform can locally result from progressive salt diapirism within the studied region. However, Pre-Oligocene unconformity has been recognized in the whole Magreb and thereby cannot be only explained by local diapirism (Frizon de Lamotte et al., 2009).

A mechanically layered stratigraphy, with weak evaporitic horizons separating more competent rocks, may therefore have exerted strong controls on the structural style of the study area throughout its tectonic history outlined above. Related to this, Morgan et al. (1998) proposed two models for the structural evolution of the Zaghouan-Ressas structural belt (ZRSB): (i) the ZRSB developed as a result of thin-skinned Miocene contractional deformation expressed as thrusting localized onto detachments within a Triassic evaporitic interval (Anderson, 1991, 1996; Baird, Grocott, Sandman, Grant, & Moody, 1990; Outtani, Addoun, Mercier, Frizon de Lamotte, & Andrieux, 1995); this model assumes that the deformation of both Pelagian Platform and ZRSB was largely thin-skinned, with no or minor involvement of the Zaghouan Fault; or (ii) the ZRSB developed as a result of thick-skinned deformation and inversion of pre-existing extensional basement faults; this model implies that, in the studied area, the Zaghouan Fault was reactivated and inverted since Paleocene times (Morgan et al., 1998).

3 | METHOD AND SAMPLING STRATEGY

3.1 | VR, temperature and burial

Vitrinite is one of the primary components of coals, representing organic compounds derived from ‘gel’ ligno-cellulosic debris (Baudin, Tribollard, & Trichet, 2008). The reflectance of vitrinite, (vitrinite reflectance -VR), is commonly used to constrain the thermal maturity of both coal and hydrocarbon source rocks in the range of late diagenesis to very low grade metamorphism. i.e. 40°C to 320°C, Kubler & Jaboyedoff, 2000; Arkai, Sassi, & Desmons, 2007; Baudin et al., 2008). An increase in VR with depth is commonly observed in borehole profiles, as predicted by ‘Hilt’s Law’, and is caused by increasing temperature with depth (Stach et al., 1982). Therefore, accurate field observations and related rock sampling allow for a reliable determination of thermal history, and by inference, burial history, based on VR data (e.g. Cavaillhes et al., 2013; Green, Duddy, Japsen, Bonow, & Malan, 2016; O’Hara et al., 1990).

3.2 | Strategy to unravel basin paleo-geometry

VR data can be used to quantitatively describe paleo-basin physiography near major faults, such as the Zaghouan Fault. The paleo-basin geometry can be inferred by combining the information about the thermal history extracted using the VR method and an accurate sampling based on a structural study, particularly in cases where deformation events post-date the time of maximum burial (see results for maximum burial time, in “Structure” section). Figure 2a displays a simplified and conceptual cross-section of the present-day structure in order to highlight our strategy. In Figure 2b through F five alternative hypotheses are presented for the pre-folding geometry of the study area; the sampling strategy was designed to test these competing hypotheses. Figure 2b shows a hypothetical scenario of a pre-existing normal fault dipping to the west and burial of the western block deeper than the eastern block (hanging-wall). The hypothesis illustrated in Figure 2c
is similar to the case in Figure 2b with the exception of an eastward dip of hanging-wall strata. An alternative hypothesis with an overall westwards tilt of the basin, and where stratinal thickening is not influenced by the fault, is shown in Figure 2d. Figure 2e shows an alternative hypothesis, where the western block can be interpreted as a paleo-high, whilst the eastern block (footwall) is west-ward tilted due to major reverse fault kinematics i.e. with the maximum subsidence being located in the footwall, at the vicinity of the thrust. Figure 2f shows a similar case to Figure 2e, yet in this model the basin does not display any regional tilting of the eastern footwall block. All these five new hypothetical paleo-basin geometry scenarios are assumed to be at the time of maximum burial.

3.3 | Sample analytical procedure

Samples of limestone and sandstone containing organic matter were analysed as shown in Table 1. The samples were crushed, set in a cold epoxy resin block, ground and polished. VR determination was performed in a dark-room using a Zeiss Standard Universal research microscope-photometer system (MPM01K) equipped with a tungsten-halogen lamp, a 40× Epiplan oil immersion objective, filtered 546 nm incident light and Zeiss immersion oil (ne 1.517 @ 23°C). The applied method is consistent with the guidelines stated in the International Organization for Standardization publications ISO 7404-2, ISO 7404-3 and ISO 7404-5. Analysis have been performed in Intertek Sunbury Technology Centre of the Petroleum Geochemistry company.

3.4 | Sample locations and derived ages

In order to test the competing hypotheses shown in Figure 2, twenty representative rock samples with significant TOC content along an E-W transect across the studied area were selected for VR analysis (Figure 1). The sampling transect is oriented perpendicular to the main N040 fold axes (Figure 3). Sampling locations include: Jebel Edjehaf, Jebel Garci, Jebel Medhaker, Jebel Fadhloun, Jebel Nassir (east of the Zaghouan Fault) and Chenanfa, (west of the Zaghouan Fault; Figure 1 and Table 1). The 20 high-TOC samples cover the following ages and subages: Valanginian/Barremian- (one sample); Barremian (four samples); Bedoulian (one sample); Albian (two samples); Vraconian (three samples); Cenomanian-Turonian (five samples); Campanian (one sample); Ypresian (two samples) and Oligocene (one sample) (see right part of Figure 1). All samples are marine carbonate samples except the fluvio-deltaic Oligocene sandstones. The samples were mostly selected from structural highs where relatively older rocks were exposed (crest of anticlines or reverse-fault hanging-wall). However, this strategy does introduce a sample bias that is discussed later in this paper.

4 | RESULTS

4.1 | Structure

Figure 3 shows a W-E structural cross-section that has been constructed using (1) outcrop data, (2) satellite
TABLE 1  Age, sample location, structural domain, Zaghouan Fault Block, lithology, Kerogen type, Total Organic Content for each sample of this study. Kerogen type in bracket (III) corresponds to some terrestrial input in addition to the main type II. Vitrinite reflectance data are given with standard deviation and number of measurements. The temperature calibration is based on vitrinite reflectance-temperature correlations of (1) Vassoyevich, Korachagina Yu, Lopatin, and Chernyshev (1970) and Tobin and Claxton (2000), (2) Barker and Pawlewitz (1994).

| Sample | Age and (formation name) | Location | Domain | Zaghouan Fault-block | Lithology | Kerogen | TOC | Ro (%) | SD | Nb. | (1) T°C | Errors | (2) T°C | Errors |
|--------|--------------------------|----------|--------|----------------------|-----------|---------|------|--------|-----|-----|---------|--------|---------|--------|
| 1      | Turonian (Bahloul)       | Edjehaf  | Eastern (EFB) | Limestone | Type II | 2.72% | 0.89 | 0.11 | 11 | 100 | ±10°C | 121  | ±10°C |
| 2      | Albian (Fahdene)        | Edjehaf  | Eastern (EFB) | Limestone | Type II (III) | 1.84% | 0.79 | 0.06 | 2  | 91  | ±06°C | 109  | ±06°C |
| 3      | Ypresian (Boudabbous)   | East Garci | Eastern (EFB) | Micritic limestone | Type II | 2.20% | 0.84 | 0.08 | 5  | 96  | ±08°C | 114  | ±08°C |
| 4      | Barremian (M’Cherga)    | West Garci | Eastern (EFB) | Marly limestone | Type II | 2.08% | 0.89 | 0.11 | 4  | 100 | ±10°C | 121  | ±10°C |
| 5      | Barremian (M’Cherga)    | West Garci | Eastern (EFB) | Marly limestone | Type II | 2.12% | 0.87 | 0.03 | 2  | 98  | ±03°C | 118  | ±03°C |
| 6      | Barremian (M’Cherga)    | West Garci | Eastern (EFB) | Marly limestone | Type II | 1.97% | 0.91 | 0.04 | 2  | 102 | ±04°C | 124  | ±04°C |
| 7      | Valanginian/Barremian   | Medhaker  | Eastern (EFB) | Marly limestone | Type II | 1.98% | 0.87 | 0.06 | 6  | 98  | ±06°C | 118  | ±06°C |
| 8      | Bcdoulian               | Fadhoun   | Eastern (EFB) | Limestone | Type II | 2.10% | 0.81 | 0.04 | 2  | 92  | ±04°C | 120  | ±04°C |
| 9      | Cenomanian Turonian     | Chenanfa  | Tunisian furrow | Marly limestone | Type II | 3.15% | 0.38 | 0.10 | 8  | 48  | ±10°C | 58   | ±10°C |
| 10     | Cenomanian Turonian     | Chenanfa  | Tunisian furrow | Marly limestone | Type II | 3.15% | 0.45 | 0.06 | 3  | 55  | ±06°C | 70   | ±06°C |
| 11     | Oligocene (Fortuna)     | Edjehaf   | Eastern (EFB) | Sandstone | Type II | 1.60% | 0.51 | 0.04 | 8  | 59  | ±04°C | 81   | ±04°C |
| 12     | Ypresian (Boudabbous)   | Edjehaf   | Eastern (EFB) | Micritic limestone | Type II | 2.36% | 0.85 | 0.06 | 6  | 97  | ±06°C | 115  | ±06°C |
| 13     | Cenomanian (Bahloul)    | Edjehaf   | Eastern (EFB) | Limestone | Type II | 2.90% | 0.72 | 0.02 | 4  | 84  | ±02°C | 106  | ±02°C |
| 14     | Campanian (Abiod)       | Edjehaf   | Eastern (EFB) | Limestone | Type II | 1.44% | 0.78 | 0.03 | 2  | 88  | ±03°C | 108  | ±03°C |
| 15     | Vraconian (Fahdene)     | Garci     | Eastern (EFB) | Limestone | Type II | 2.12% | 0.92 | 0.02 | 6  | 104 | ±02°C | 125  | ±02°C |

(Continues)
imagery and (3) proprietary 2D seismic data. The seismic data were calibrated against outcrop and well log data, and a burial curve of Jebel Garci (see Figure 1 for location) has been constructed based on known stratal thicknesses and related ages (Figure 3).

From west to east, four main N-NE trending anticlines affecting the Pelagian Platform succession were mapped by the authors. They are all open folds of km-scale-width and are termed, from west to east: Jebel Edjehaf, Jebel Garci, the Takrouna structure, and the Enfidha structure. Both Jebel Medhaker (to the north) and Jebel Fadhloun (to the south) anticlines are structurally equivalent to Jebel Garci anticline.

The Pelagian Platform succession in the Jebel Edjehaf anticline, which is 2 km to the east of the Zaghouan fault, is 5 km wide, 20 km long and exhibits the tightest fold. The 20 km-wide Souaf separates the Jebel Edjehaf and Jebel Garci anticlines (Figure 3); the upper Miocene section of the Souaf Syncline is folded, and the whole syncline is dissected by a N110 transversal graben (i.e. perpendicular to the fold) with Pliocene and Quaternary age infill (Figure 3). The Jebel Garci anticline, located in the eastern part of the Pelagian Platform, is c. 5 km wide and 8 km long, i.e. significantly less elongated than the Jebel Edjehaf. A tight syncline separates Jebel Garci and the Takrouna structure, the latter of which is a 5 km wide anticline expressed at the surface in Oligocene age stratigraphy. Further east, the Enfidha structure is buried below Quaternary deposits but is recognized in both seismic profiles and borehole data (Figure 3). Syn-kinematic ‘growth’ strata, indicate thinning across fold limbs in the Mio-Pliocene succession.

Based on the interpretation shown in Figure 3, shortening of the Pelagian Platform from the Zaghouan fault to the coastline along an ESE-NNW direction is estimated to be in the range of 9% to 12% i.e. between 5 and 8 km (Figure 3). VR study may also narrow the relative timing of the shortening and the amount of subsequent erosion.

### 4.2 VR data

The VR samples are described as a function of their age and structural location relative to the Zaghouan Fault (Zaghouan western fault block, WFB, or Zaghouan eastern fault block, EFB; see Figure 3 for cross-section, Figure 2 for sample transect and Table 1 for VR values). The three Cretaceous samples from the WFB show values between 0.38 and 0.46% for reflectance (Figure 4a). All samples from the EFB (i.e. the Pelagian Platform) range from 0.5 to 0.95%. The Cretaceous samples from the WFB thus exhibit approximately 50% lower reflectance values compared to those of the EFB.

The Oligocene sample from the EFB represents the lowest reflectance value of the dataset (c. 0.5%), which is consistent with the youngest stratigraphic age of the sampled
succession. The Ypresian carbonate rocks of the Jebel Garci and Jebel Edjehaf anticlines (also EFB) show VR of 0.85%, and are therefore in a similar range to the Cretaceous samples of the EFB.

The Cretaceous pre-Aptian samples from the Jebel Medhaker, Jebel Fadhloun and Jebel Garci within the EFB exhibit reflectance values ranging from 0.85 to 0.95% (Figure 4a); pre-Aptian age rocks are not exposed at Jebel Edjehaf (Figure 3).

The post-Aptian rocks of the EFB, excluding the Oligocene sample, have values ranging from 0.7% to 0.9% in Jebel Edjehaf, c. 0.8% in Jebel Fadhloun and c. 0.9% in Jebel Garci.

The graph of the Figure 4b shows the VR values as a function of formation thicknesses for the entire study area. No distinction has been made between the different anticlines studied. The VR values of WFB are significantly lower (~0.5%) than the ones from the Pelagian Platform (EFB) for a similar upper Cretaceous interval. All pre-Ypresian samples of the Pelagian Platform are in a similar VR values range and, surprisingly, do not show any VR decrease in relation with the youngest age of those Pre-Ypresian formations. In contrast, a decrease in VR values clearly appears from the Ypresian samples to the Oligocene sample, where Lutetian-Priabonian Souar clays are present. Graphically, the average slope value is here around ~0.34% per km, assuming that the Souar formation is 981 m-thick. However, due to the sampling gap, we do not know the exact location of the slope break in this stratigraphic interval (Figure 4b).

### 4.3 Temperature calibration

The measured VR value is a function of many parameters, including temperature, time, original oxygen content, pore fluid pressure, fluid chemistry, oil content, type of organic content, CH₄ presence, partial CO₂ pressure, degree of tectonic deformation of the sample, oxidation and weathering (Barker & Pawlewicz, 1986; Hood, Gutjahr, & Heacock, 1975; Huang, 1996; Price, 1983; Waples, 1980). However, Huang (1996) demonstrates that the main controlling parameter of the VR is the maximum temperature reached by the rock through its geological history. In the last four decades, different methods have been used to calibrate the VR with the maximum temperature that rocks were exposed to (e.g. Vassoyevich et al. 1970; Sweeney & Burnham, 1990; Tobin & Claxton, 2000; Barker & Pawlewicz, 1994; Arkai et al., 2007). In this study, thermal calibration following Vassoyevich et al. (1970) and Tobin and Claxton (2000) have been used. Tobin and Claxton (2000) calibrated their method by
FIGURE 4  (a) VR data plot along a West-East profile and as a function to the Zaghouan major fault distance. (b) VR values as a function of formations thicknesses C) Inferred maximum temperature along a similar W-E profile based on vitrinite reflectance-temperature correlations of Vassoyevich et al. (1970) and Tobin and Claxton (2000)
other thermometers such as fluid inclusions and illite crystallinity index.

The calibrated VR values indicate that (Figure 4b) (i) the post-Aptian rocks from the WFB reached maximum temperatures of around 55°C; (ii) the Oligocene sample from the Pelagian Platform (EFB) reached a temperature of approximately 60°C; (iii) pre-Aptian rocks of the Jebel Medhaker, Jebel Fadhlan and Jebel Garci anticlines (all EFB) reached temperatures of approximately 100°C; (iv) the post-Aptian rocks in the Pelagian Platform (EFB) recorded temperatures in the range of 80°C to 105°C, with a mean of 85–90°C for Jebel Edjehaf and Jebel Fadhlan.

Summarized, the temperatures reached in the WFB are significantly lower than the measurements from similar cretaceous stratigraphic intervals in the EFB.

5 | DISCUSSION

In the following discussion we show how the presented VR (Figures 4 and 5) and structural data can be used to decipher foreland basin history in an area where a long-lived pre-existing structure (the Zaghouan Fault) affected deformation and basin subsidence (Figure 6).

5.1 | Temperature

The combination of structural studies and VR analysis across the Pelagian Platform has revealed that the maximum temperatures that were reached by Cretaceous rocks in the study area were between 80°C and 100°C (Figure 4). The Jebel Garci values show similar order of magnitude of VR as the other Cretaceous samples from the Pelagian Platform. Conversely, the Cretaceous samples from the Zaghouan WFB reached temperatures of approximately 55°C.

Regional trends of VR do not show an increase westward toward the present-day thrust belt, therefore suggesting that the thrust location did not have any influence on footwall rock maturation (Figure 4). This is consistent with published work highlighting that no regional thermal diagenesis/metamorphism can be attributed to fault-generated heat, with the exception of very narrow (cm-scale) films immediately adjacent to the fault slip surface (Bustin, 1983; Sakaguchi et al., 2007; Suchy, Frey, & Wolf, 1997), heating processes mostly resulting from frictional heating (Scholz, 1980) or heating related to hydrothermal fluids within the fault zone (Guilhaumau & Dumas, 2005). The particular case of Figure 6c, where the heat flow is sketched as regionally increasing towards the fault, is thus not supported by the results of this study.

5.2 | Maximum burial depth

In order to infer the maximum burial depth using maximum temperatures, it is necessary to estimate/assume a geothermal gradient. This can be estimated using (i) published data considering a regional geological context (e.g. Ben Dhia, 1987 for Tunisia, Labaume, Jolivet, Souquière, & Chauvet, 2008 for the Alps), and (ii) using present-day geothermal gradients inferred from wellbore temperature data; the latter assumes consistency between current-day thermal heat flow and paleo thermal heat-flow at the time of maximum burial depth. Values in offshore wells range from about 3.5°C to 4.5°C/100 m (Lucazeau & Ben Dhia, 1989), higher than published values from onshore wells (Compagnie des Pétroles de Tunisie, 1955). Based on the Jebel Edjehaf well data (Compagnie Des Petroles de Tunisie, 1955), and values from the published literature for the peripheral part of the orogeny (Cavailhes et al., 2013; Labaume et al., 2008; Metcalf, Fitzgerald, Baldwin, & Munoz, 2009; Yuan et al., 2007), we assume a mean paleo-geothermal gradient of 30°C/km for this study.

Based on this assumption, our results suggest that the Pelagian Platform has been uniformly buried to a minimum
burial depth of 3 km (± 500 m) (Figure 5). This burial for Pre-Ypresian samples agrees with overburden sediment thickness estimates, based on seismic profile analysis from the core of the Souaf Syncline, also located in the Pelagian Platform (Figure 3). The Oligocene sample was buried at a shallower depth (2 km) than the Pre-Ypresian samples (3–3.5 km), despite that they are in an equivalent structural position and elevation along the sampling profile, i.e. comparable elevation along the present-day topography crossing the fold. This clearly confirms that the current-day observed fold shape has been mainly acquired after the Miocene maximum burial of studied rocks i.e. during the Atlas II tectonic event.

The observed differences in burial depth (~ 1 km, Figure 5) between the Ypresian and Oligocene samples of the Pelagian Platform may be explained by (i) the principles of “Hilt’s Law”, i.e. decrease in VR towards surface (Stach et al., 1982); (ii) the Oligocene erosion that occurred subsequently to the Atlas I event and probably having removed material (Frizon de Lamotte et al., 2009); or (iii) the probable thermal effects and related thermal compartmentalization caused by relatively low thermal conductivity of the Eocene 981 m-thick clay succession of the Souar Formation (Figure 4b). Indeed, clays have commonly lower thermal conductivity than carbonates (Eppelbaum, Kutasov, & Pilchin, 2014).

Based on the cross-section of Figure 3, we propose that interpretation (i) and (iii) are the most probable. Indeed, according to the previously cited literature (e.g. Khomsi et al., 2009) and this study, no significant burial history occurred subsequent to the Tortonian-Messinian Atlas II folding phase. Moreover, 2 km of additional burial for Oligocene samples is needed if hypothesis (ii) is to be verified (Figure 5).

Regarding the Zaghouan WFB, VR values show that the Cretaceous rocks have been maximally buried to a depth of 1.5–2 km (Figure 5). This study, and related depth calibration, therefore suggest a strong contrast in burial depth between the fault blocks on either side of the Zaghouan fault; therefore, a km-scale vertical displacement of the Zaghouan fault at the time of maximum burial is deduced (Figure 6a). The inherited Zaghouan fault has been widely described as an inverted normal fault/transpressive strike-slip structure (e.g. Hezzi, 2014 and references therein; Guilhaumau & Dumas, 2005). Consequently, we propose two plausible schematic cross-sections to

**FIGURE 6** (a) Paleo-geometry of the Pelagian platform inferred from VR data at the time of middle-upper Miocene maximum burial (Oligo-Miocene basin). These sketches highlight vertical displacement of the Zaghouan fault; note that both kinematics and fault dip is still debated. (b) Sketches showing examples of sampling bias which are assumed in our interpretations. (c) Sketch showing how a regional geothermal anomaly could lead to misinterpretation of VR values. Based on literature (see text for references), this latter case has been excluded of our interpretation. Dotted line shows the top of Cretaceous. Atlas II tectonic event occurred at Tortonian/Messinian times and therefore postdates the drawn configurations.
illustrate the Paleogene kinematics of the Zaghouan Fault and its current-day observed displacement (Figure 6a). The Oligo-Middle-Miocene basin in its Pre-Atlas II tectonic event configuration was therefore bounded by the Zaghouan fault in its eastern part, which was either an inverted normal fault or a strike slip system; in both cases, the Pelagian Platform was subsiding (Figure 6a).

The increase in VR between the Pelagian Platform and a similar stratigraphic interval of the Zaghouan WFB can be attributed to the increased thickness of deposited sediments. Depth calibrations show that the Pelagian Platform samples were uniformly buried to similar burial depths (Figure 5). This suggests that the Zaghouan Fault did not trigger wide-scale-block-tilting between the Atlas I and Atlas II tectonic episodes, and thus excludes asymmetric paleo-geometries for the Pelagian Platform; the hypotheses which are shown in Figure 2b–e are therefore ruled out. The Pelagian Platform was not buried more deeply near the Zaghouan fault, in contrast with what is found in some other peripheral parts of orogens or foreland basins (Bonini et al., 2012). The configuration of Figure 2f is therefore the most probable one and is detailed in Figure 6.

Probable paleo-topographies and pre-existing structures may have existed and areas of subsidence have not been sampled due to vitrinite sampling bias (data are available for only outcropping rocks; Figure 6b). The methodology assumes that both the maximum burial depths within the E-W graben and the hearts of the synclines are slightly higher than what is recorded for the outcropping anticlines of the area (Figure 6b). It is likely that the data does give an under-estimation of burial depth for these present-day buried structures.

All Cretaceous and Ypresian samples show similar ranges of VR values (~0.9%), meaning that maximum burial depth was reached during post-Ypresian time. Consistent with Khomsi et al. (2009), it is improbable that maximum burial occurred during the middle-late Eocene, i.e. during the positive tectonic inversion related to the Atlas I contraction. Our structural data and burial curve do suggest that maximum burial was established prior to the Tortonian–Messinian Atlas II folding phase (Figure 3). This inference is consistent with previous work arguing for a negative inversion (i.e. transtensional phase) recorded during the Oligocene–Middle Miocene (Philip et al., 1986; Morgan et al., 1998; Khomsi et al., 2009; Figure 6a).

Additionally, constant VR values all over the Pelagian Platform for all pre-Ypresian stratigraphic intervals support the interpretation that a pre-Oligocene folding (Atlas I event) followed by erosion probably put all the samples at a similar level before the Oligo-Miocene subsidence (Figure 6a). This Oligocene unconformity (post Atlas I event) may therefore localize the VR values slope break that has not been clearly characterized on the stratigraphic column shown on the Figure 4b (only average slope value has been proposed).

During the time of maximum burial depth for the Pelagian platform, the Zaghouan fault was important as it appears that the Zaghouan WFB (i.e. Tunisian Furrow) was buried at a maximum depth of <2 km below the surface while the Pelagian platform was buried between 3 and 3.5 km (Figure 6). According to these burial values, the cumulative vertical displacement along the Zaghouan Fault was at least 1 km during the prefolding Atlas II episode in middle to late Miocene times. Having therefore cumulated a significant vertical throw, the Zaghouan fault was already increasing the subsidence of the Pelagian Platform. Consistent with the burial curve shown in Figure 3, this km-vertical throw has most likely been accrued throughout the various tectonic phases, including Paleocene/Eocene Atlas I shortening phases (Frizon de Lamotte et al., 2009; Khomsi et al., 2009); the Oligocene – middle Miocene negative inversion (Khomsi et al., 2009; Morgan et al., 1998; Philip et al., 1986), and the contractional deformation (thrusting) along the Zaghouan Fault, the latter probably predating the peak of the Tortonian-Messianian Atlas II event in the foreland studied area (this study). Most of the subsidence has been acquired during the establishment of the Oligo-Miocene basin predating the Atlas II tectonic event as sketched on the Figure 6a.

Regarding the Pliocene to Villafranchian transtensional deformation giving the second main structural overprint of the studied area (Philip et al., 1986), our VR data does not show any clear N-S control of reflectance values (From the North to the South, respectively: Jebel Medhaker, Jebel Garci, Jebel Fahdloun are on a similar structural trend), suggesting that this phase of deformation did not contribute to any significant extent to the burial of the studied area/interval.

### 5.3 Exhumation rates

Using the above structural and thermal data, this study suggests that the Pelagian Platform was buried to nearly 3.5 km (Figure 5), implying that an equivalent magnitude of overburden has since been removed by erosion. Knowing the maximum burial depth of the Pelagian Platform Pre-Ypresian carbonates allows the computation of the average exhumation rates for the study area, by assuming a structural evolution of the succession and its present day surface exposure in the study area.

The onset of the exhumation is most likely triggered by the Atlas II (Tortonian) contractual event. For an exhumation that has been lasting from the Tortonian to the Quaternary (Philip et al., 1986), the mean exhumation rates for the Edjehaf, Medhaker, Fadloun, and Garci anticline structures would need to be in the order of 0.27 mm and 0.32 mm/year (i.e. 3–3.5 km over 11 Ma) to reach the
sampled current-day outcropping position. Assuming the extreme case that the exhumation of the Pelagian Platform could be exclusively related to the Atlas II Folding Event (Tortonian to Messinian), exhumation rates for the aforementioned anticline structures can reach values of up to 0.6–0.7 mm/year (i.e. 3–3.5 km over 5 Ma). The estimated exhumation rate derived for the heart of the Souaf Syncline is around 0 mm/year (negligible, no exhumation), owing to the fact that the maximum burial depth reached by the studied rocks (VR data, Figure 4a) is consistent with the current-day depth computed from our structural cross-sections (Figure 3). However, as already discussed above, maximum burial depths reached by the rocks in the heart of the syncline may have been underestimated (because of no sampling), implying that exhumation rates are also underestimated.

For the Zaghouan WFB, the minimum exhumation rate is around 0.18 mm/year (2 km for 11 my), and can reach even higher values up to 0.34 mm/year when only the Tortonian-Messinian folding event is considered (i.e. 2 km for 5 Ma). It is likely that exhumation rates in the western vicinity of the Zaghouan Fault are higher than the recorded rates in the WFB.

To our knowledge, no exhumation rates have previously been published for this study area. Comparing the data of this study with existing published reference values for exhumation rates from other regions has to be handled with care: for instance, in the Southern Pyrenees (outer part of the belt), the Tortonian exhumation is estimated to be around 0.3 mm/year (Fillon, Huismans, van der Beek, & Munoz, 2003). This range of values is consistent with the values proposed for the Pelagian Platform.

6 | SUMMARY AND CONCLUSIONS

Vitrinite reflectance (VR) is a valuable tool to quantitatively document differential burial histories commonly seen in fault controlled sedimentary basins and basin segments that have undergone multiple tectonic events. We used VR analysis to unravel the tectonic history of the Pelagian Platform and the Tunisian Furrow in Northern Tunisia. The following main conclusions are drawn:

1. Based on our seismic/field data and consistently with the literature, the contractional event related to the Atlas II WNW-ESE compressive phase deformed both the Pelagian Platform (folds) and the Tunisian Furrow during Tortonian to Messinian time
2. Maximum burial depth of Pre-Miocene rocks of the Pelagian Platform was reached during middle to upper Miocene times i.e. prior to the Atlas II folding event.
3. Cretaceous to Ypresian carbonates of the Pelagian Platform were buried to a maximum burial depth of approximately 3 km, assuming a geothermal gradient of 30°C/km.
4. Cretaceous rock samples from the hanging wall of the Zaghouan Fault (current-day Zaghouan WFB) were buried to a maximum depth of less than 2 km.
5. Significant throw along the Zaghouan fault pre-dates the Atlas II Miocene folding event and has controlled subsidence of the Pelagian Platform during the Tertiary.
6. The Zaghouan fault did not trigger any regional-scale block-tilting during the Tertiary, assuming a sampling bias that is discussed in this study.
7. Based on maximum burial depth and its Miocene timing, mean exhumation rates of the Pelagian Platform during the Messinian to Quaternary averaged around 0.3 mm/year. However, once the Tortonian-Messinian Atlas II folding event is taken into consideration, exhumation rates could have reached orders of magnitude of up to 0.6–0.7 mm/year.

These conclusions provide quantitative constraints on the tectonic evolution of Northern Tunisia and have important implications on the timing of hydrocarbon maturation and expulsion, particularly for the Mesozoic and early Tertiary source rock intervals deposited in the Pelagian Platform region. More generally, providing burial data and exhumation rates with respect to structural data are critical inputs for numerical basin modeling and therefore enable petroleum geoscientists to accurately assess source rock maturation such as time-scale for fluid transfer throughout sedimentary basins.

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CONFLICT OF INTEREST

No conflict of interest declared.
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