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Mohamed Ben Chelbi, Kamel Samir, Harrab Salah, Rebai Noemen, Melki Fetheddine, et al.. Tectonosedimentary evidence in the Tunisian Atlas, Bou Arada Trough: insights for the geodynamic evolution and Africa-Eurasia plate convergence. Journal of the Geological Society, 2013, 170, pp.435-449. 10.1144/jgs2012-095. hal-00940308

# HAL Id: hal-00940308 https://hal.science/hal-00940308

Submitted on 31 Jan 2014  $\,$ 

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# Tectono-sedimentary evidence in the Tunisian Atlas - Bou Arada Trough: Insights for the geodynamic evolution and Africa-Eurasia plate convergence

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22 The Bou Arada Trough (BAT) is an E-W oriented structure located 80 km SW of Tunis, 23 characterizing the central Tunisian Atlas. This trough is filled by a thick Quaternary sand and clay series and is bordered by complex systems of folds generally trending NE-SW. Contacts 24 25 between the BAT and the neighbouring folds are accommodated by NE-SW and NW-SE 26 oriented faults. Contrary to the other troughs of the Tunisian Atlas, which are related to the 27 Plio-Quaternary orogenic period, the geodynamic evolution of the BAT has been started since 28 began in the Maastrichtian and has continued until the present day. Structural, tectono-29 sedimentary and seismic data analyses are undertaken in the studied area to better understand 30 the evolutionary scenario of this trough. Results obtained show that the BAT is fragmented 31 into three NW-SE oriented sub-basins and records a continuous history of downthrow. Indeed, during extensional to transtensional regimes, this trough has evolved in response to 32 the two networks of perpendicular fractures while during compressive to transpressive 33 34 periods, the collapse of the BAT has been induced by a pull-apart mechanism using the same

<sup>21</sup> Abstract:

network of faults but with a strike slip movement. The Bou Arada Trough thus preserves a
 record of the convergence between the European and African plates since the Maastrichtian.

37

38 Key Words:

Bou Arada Trough, Geodynamic evolution, Tunisian Atlas, Transtension, Rifting,
Transpression, pull-apart basin, Eurasia-Africa convergence.

41

#### 42 **1. Introduction**

43 The present configuration of the Tunisian margin has resulted from the convergence and 44 collisional movement between the African and European plates including the Tethys 45 geological domain. The central Tunisian Atlas and the Algerian Sahara Atlas mountain ranges 46 contain several troughs filled with Quaternary deposits arranged in a structural band between 47 the Zaghouan and Teboursouk master faults (Fig. 1A). The average trend of these grabens is 48 NW-SE to WNW-ESE, orthogonal to a set of NE-SW trending folds (Fig. 1B). Castany 49 (1948) and Glangeaud (1951) deduced that these structures developed during Plio-Quaternary 50 orogenic phases. These hypotheses were reinvestigated by Jauzein (1967), Richet (1971), 51 Dlala et al. (1983), Philip et al. (1986) and Chihi and Philip (1998). These authors linked the 52 development of these troughs to slip on the E-W and NE-SW faults, so that the grabens 53 resulted from a compressive tectonic regime related to the convergence between African and 54 European plates (Bousquet and Philip, 1986; Ricou, 1994). Although Plio-Quaternary tectonic movements are significant, our recent work (Ben Chelbi, 2007; Ben Chelbi et al., 2008), 55 56 based on structural, tectono-stratigraphic and seismic analyses, shows that the Tunisian 57 troughs have developed since the Maastrichtian.

59 The ESE-WNW to E-W Bou Arada Trough (BAT), the target of our present study, is located 60 ~ 80km southwest of Tunis (Fig. 1) and, unlike the other Tunisian Atlas troughs, was not studied by our predecessors. The aims of this work are: (1) to analyze the contacts between 61 62 this trough and the neighbouring structures; (2) to explore the deep geometry of this structure using three seismic lines; (3) to examine the spatial and temporal changes in facies and 63 64 thickness of the stratigraphic sequences since Campanian time; (4) to define and characterize 65 links between the evolutionary model of the BAT and the rest of the Tunisian margin; and (5) to correlate the evolution of this graben with other examples in neighbouring regions. 66

67

#### 68 **2. Methodology**

69 The study of tectonic contacts between the BAT and neighbouring geological structures is 70 primarily inferred from cross sections and analysis of fault movements. Ten geological cross 71 sections show the current dynamics of the different faults bordering the BAT. In addition, we 72 devote a particular care to the various geometries of these bordering faults. Four seismic 73 sections obtained from the Tunisian Petroleum Company (ETAP), are interpreted in this study 74 to illustrate the main structural geometry of the BAT at depth. The W1 petroleum well is used 75 to show the succession of different stratigraphic sequences characterizing the trough using 76 time-depth conversion of lithological data.

The geodynamic evolution of the BAT is interpreted, first, through the analysis of vertical facies variations and thicknesses of the different series on both sides of the NW-SE oriented faults. Since the Campanian, sedimentation has been controlled by this network of faults in which we note a large variation of facies and thicknesses. Second, palaeostress regimes are obtained by measurement of syn-depositional faults. These fault plane orientations and directions and senses of slips are subsequently analyzed using Angelier's (1984, 1989) Direct 83 Inversion Method (software version 5.42). This combination of surface and sub surface data
84 will contribute to the development of an evolutionary scenario for the BAT.

85

#### 86 **3. Geological setting**

#### 87 **3.1. Stratigraphy**

88 The stratigraphic series outcropping in the study area are essentially of Triassic, Cretaceous 89 and Palaeogene age (Figs 2 and 3). Triassic beds crop out in Jebel Ech Chehid and Jebel 90 Bessioud (Fig. 3B), composed of clay, marl, limestone, gypsum, salt, anhydrite and sand. The 91 Germanic facies of Triassic, typical of the Tunisian margin, is evident. The Early Cretaceous 92 is formed by thick series of clay, limestone and rare quartzitic intercalations. This 93 sedimentation characterizes the "Sillon tunisien" (Sekatni et al, 2008). The Late Cretaceous is 94 represented by carbonate and argillaceous sedimentation. It begins with alternations of gray 95 marl and limestone (Fig. 3). These alternations characterize the Fahdène and Bahloul 96 Formations, respectively of Albian and Cenomano-Turonian ages (Burollet, 1956). The 97 middle part of the Late Cretaceous corresponds to the argillaceous Aleg Formation, allotted to 98 the Turonian-Coniacian-Santonian-Middle Campanian (Burollet, 1956). The Abiod 99 Formation, Late Campanian to Maastrichtian in age, is composed of two limestone beds inter-100 bedded by marl (Fig. 3). The Tertiary is represented by Palaeocene clay (El Haria Formation), 101 Early Eocene limestone (Bou Dabbous Formation), Late Eocene clay (Souar Formation) and 102 Oligocene alternations of sand and clay (Fortuna Formation). These Tertiary sequences mark 103 marine sedimentation during the Palaeocene and Eocene, and continental units of the 104 Oligocene period. These various Palaeogene units are unconformably covered by Mio-105 Pliocene continental deposits formed essentially of sands and silt (Fig. 3).

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#### 107 **3.2. Structural evolution**

108 The geodynamic evolution of the Tunisian Atlas Mountains and margin has been part of the 109 Tethys geological domain from the first stages of rifting until the present stage of the collision 110 between Eurasia and Africa (Fig. 4). Evidence of first stages of the Tethyan rifting are dated 111 to the Jurassic (Alouani et al., 1992; Soussi and Ben Ismaïl, 2000; Soussi, 2003; Boughdiri et 112 al., 2006; Sekatni et al., 2008; Fig. 4). This Jurassic rifting phase has been inferred from the alkaline composition of the igneous rocks and in the presence of radiolarians in rocks 113 114 associated with the middle Jurassic series. This rifting resulted from N-S extension and this 115 mechanism of opening continued during the Early Cretaceous (Letouzey and Trémolière, 116 1980; Soyer and Tricart, 1987; Morgan et al., 1998). The minimum stress direction was NE-117 SW until the Aptian (Soyer and Tricart, 1987; Ben Chelbi et al., 2008; Melki et al., 2010; Fig. 118 4). This change in the minimum stress orientation was attested by reactivation of the NW-SE 119 trending faults with normal activity, which created several basins elongated NE-SW (Ben 120 Chelbi et al., 2008), and by intense magmatic activity associated with sedimentation. 121 Contemporaneous to this activity, the Tunisian Atlas records intense halokinetic activity (Fig. 122 4) forming a large system of diapirs and/or salt glaciers (Vila et al. 1994).

123 During Late Cretaceous the Tunisian margin was controlled by transtensional tectonics 124 (Zouari et al., 1999; Ben Chelbi et al. 2008), characterized by reactivation of the N-S, E-W 125 and NE-SW trending normal faults with dextral component. The general inversion of the 126 structures was recorded during the Middle Eocene (Masrouhi et al., 2008; Melki et al., 2010). 127 The first period of folding is assigned to the Tortonian (Tlig et al., 1991), while the ultimate 128 compression leading to the building of the Tunisian Atlas Mountains began during the 129 Villafranchian and continues to the present-day (Bouaziz et al., 2002; Fig. 2). This long 130 period of compression controlled by NNW-SSE to N-S stress has contributed to the final 131 configuration of the Tunisian Atlas in which NE-SW, NW-SE, E-W and N-S oriented faults 132 were respectively reactivated with sinistral reverse, dextral reverse, reverse and sinistral slip. The central Tunisian Atlas is characterized by the coexistence of folding and rifting (Fig. 1B). The anticlines and large syncline basins that developed in this part of the Tunisian Atlas and are generally filled up with by Late Eocene deposits are elongated NE–SW. NW-SE oriented rifts, filled up by Mio-Plio-Quaternary deposits, developed orthogonally to these folds (Philip et al., 1986). The NE-SW oriented sinistral and NW-SE oriented dextral normal faults ensured the formation of these rifts following a pull-apart model (Ben Ayed and Viguier, 1981).

Evaporite layers, mostly Triassic in age, are present as a deep decollement level (Ahmadi et al. 2006). During both extensional and compressional phases this Triassic salt has been remobilized throughout the preexistent system of faults. Some of them are considered as diapirs (Gharbi et al. 2005) in which salt occupies the core of the anticlines, others as salt glaciers (Ben Chelbi et al. 2006; Ben Slama et al. 2009) in which Triassic evaporites were interstratified within the Aptian clay series. These salt structures started to grow during the Aptian (Snoke et al., 1988; Perthuisot et al., 1998) or even earlier (Boukadi and Bedir, 1996).

These different tectonic phases that affected the Tunisian margin since the first stage of rifting have affected the structural zoning of Tunisia. The major domains are, respectively, from north to south: the Tell zone; the Atlasic domain, itself subdivided into the northern, central and southern Atlas; the stable Sahara Platform; the Eastern Platform; and the North-South Axis (Fig. 1B).

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#### 152 **4.** Field studies of the structural position of the BAT

Detailed structural analysis of Quaternary deposits that cover the plain and neighbouring folded structures reveals that the history of the BAT is intimately associated with the activity and the evolution of a complex fault system. We present here the main structural features that border the BAT depression.

4.1. Northern contacts: The BAT is bounded to the north by Jebel Rihane, Henchire Bou
Ftis and Jebel Bessioud (Fig. 2A and B). The contact between these structures and the plain is
represented by a complex system of faults having two major NW-SE and NE-SW orientations
(Fig. 2B). Indeed, Jebel Sidi Brahim and Aïn Agueb, which consist of Aptian-Albian
limestone series, are bordered to the south by NW-SE oriented faults (Fig. 5A).

163 These contacts include the so-called Bou Jlida fault (Fig. 2B) that separates the southern El 164 Aroussa plain and northern Jebel Rihane. Detailed examination of these generally SW dipping 165 faults reveals three generations of striations, oriented S60°E and with weak pitch to the SE 166 and strong pitch to the NW, indicating three phases of tectonic activity. Near Sidi Dakhli, the 167 contact between Late Eocene claystone and Cenomanian limestone is represented by a NE-168 SW trending normal fault (Fig. 5B). The latter has a fault plane dipping SE with two 169 generations of striations. The first generation has a pitch towards the SW indicating a dextral 170 movement, while the second one has a pitch towards the NE indicating a sinistral sliding 171 movement. The southern side of the Henchir Bou Ftis structure is truncated by several NW-172 SE trending en echelon faults (Fig. 2B and 5C). All these faults indicate polyphase activity of 173 normal dextral slip with three generations of striations (pitches of 15° to the NW, 45° to the 174 NW and 75° to the SE). In the south-eastern part of the Jebel Bessioud syncline, the 175 Oligocene is missing. Slip on several NW-SE oriented faults has resulted in the submergence 176 of this area below Quaternary alluvial deposits (Fig. 5C). In the east, a NW-SE system of 177 faults delimits the Sabkhet El Korzia depression.

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4.2. Western Contacts: The BAT is bordered to the west by the large Triassic diapir of Jebel
Ech Chehid (Fig. 2B), which is moulded onto the NE-SW oriented El Alia-Téboursouk fault
(Perthuisot and Jauzein, 1974; Ben Slama et al. 2009). The Campanian limestone layers and
related geometry of Draa Sidi Haj Amor shows the sinistral movement of this NE-SW fault

(Fig. 2B). This structure constitutes a drag fold formed on the fault which gave rise to the Jebel Ech Chehid diapir. Moreover, at Faïd Ez Zitoun, slip on a SE dipping and NE-SW trending normal fault may explain the subsidence of the El Aroussa plain (Fig. 5D). On the fault plain we measured two generation of striations. The first shows a strong pitch to the SW (60° SW) while the second one has a weak pitch to the SW (20° SW), indicating two phases of tectonic activity.

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190 4.3. Southern Contacts: The contact between the folded structures of Jebel er Remil and 191 Taref Ech Chena, in the south, and the Quaternary plains of El Aroussa, Bou Arada and 192 Sabkhet Taref Ech Chena, in the north, is represented by two NW-SE and NE-SW trending 193 fault systems (Fig. 2B). Indeed, the Mio-Pliocene sand and clay formations covering the Jebel 194 er Remil syncline are truncated by a succession of NW-SE trending normal faults (Fig. 6E). 195 The slickensides on these faults indicate normal slip with a component of dextral slip. The 196 curvature of Jebel Strassif is truncated by a NE dipping and NW-SE trending normal fault 197 (Fig. 6F). A cross section at this location shows that the last movement recorded on this fault 198 is reverse, given the overlap of the Palaeocene Sidi Ali Ben Ali Formation over Oligocene 199 deposits (Fig. 6G) but without the normal faulting movement recorded during periods of 200 extension. The Campanian dome of Aïn Bou Slama is bordered by a NE-SW oriented normal 201 fault involving the downthrown of the Late Eocene Formation of Jebel er Remil (Fig. 6H). 202 The northern periclinal termination of the Cretaceous Jebel Taref Ech Chena anticline is 203 truncated by a network of NW-SE and NE-SW oriented faults (Fig. 6Í) with several 204 generations of striations. On both sides of these faults no variation of thicknesses or facies is 205 observed in the Late Cretaceous (pre-Maastrichtian) series. Further east, the downthrown of 206 the northern part of the Taref Ech Chena structure (Fig. 6J) is accommodated by NW-SE 207 oriented faults (Fig. 2B).

#### 209 **5** Seismic data analysis and graben formation

We have used four seismic profiles P1, P2, P3 and P4, respectively oriented NS, NNE-SSW,
E-W and NW-SE across the BAT (Fig. 2B). These seismic profiles are calibrated by the W1
well.

213 Profile P1 (Fig. 7) shows that the BAT is bordered on the northern and southern areas by two 214 major faults, named F1 and F2, respectively. At Jebel Rihane, fault F1 shows the downthrow 215 of the Late Campanian calcareous series. The cumulative vertical displacement of this 216 limestone layer is estimated as 1700m. At the surface, F1 corresponds to the Sidi Dakhli fault 217 which places the Late Eocene Formation in contact with the Cenomanian marly-limestone 218 (Fig. 5B). In the south, the BAT is separated from the folded structures by north dipping fault 219 F2. According to vertical displacement between the limestone bed of the Abiod Formation in 220 the centre of the trough and its equivalent forming the Aïn Bou Slama dome, the downthrow 221 is estimated to 1300m. In the same locality, the thick clay series of the Souar Formation is in 222 direct contact with Campanian limestone deposits (Fig. 6H). The general configuration 223 represented by this seismic section is of a negative flower structure in which the maximum 224 subsidence is recorded at the centre of the basin.

Profile P2, with a NNE-SSW orientation, is located west of profile P1 and crosses the principal depocentre of the El Aroussa Trough (Fig. 2B). This profile shows that this trough is formed by two major faults constituting another negative flower structure (Fig 7). The cumulative vertical displacement affecting the top of the Campanian limestone series cropping out at Jebel Zemala and in the centre of the trough is estimated as 2000m. At the surface, the northern fault corresponds to the Jebel Sidi Brahim fault whereas the southern fault corresponds to the Jebel Zemala fault (Figs 2B and 5A). Profile P3 (Fig. 8) crosses Sabkha Taref Ech Chena and continues through the Triassic diapir of Jebel Ech Chehid (Fig. 2B). It shows that the plain of Bou Arada is compartmentalized, from east to west, into three distinct basins along three NE-SW oriented faults, marked at depth by offset in Triassic units, structure this compartmentalization. These bordering faults of hidden basins have normal slip and show small reverse bends which could be induced by progressive structural inversions.

Profile P4 (Fig. 8) crosses the Bled et Tlili anticline and continues to Jebel Hzem Lessoued (Fig. 2B). It shows that this area of BAT is affected by a NE-SW trending normal fault which is also responsible for the subsidence of the El Aroussa plain. The cumulative vertical displacement recorded on this fault by the reference bed of the Abiod Formation is estimated as 1500m. The depressions revealed by profiles P3 and P4 were filled by Mio-Pliocene sand and clay deposits that cover unconformably the Oligocene series.

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#### **6. Tectono-sedimentary evolution since the Campanian**

To determine the structural evolution of the BAT, we measured the orientations of striations on fault planes that affect different formations. Syndepositional fault populations, providing direct dating of tectonic events, have been specially analyzed. We then calculated the orientations of the principal stress axes  $\sigma$  1,  $\sigma$  2 and  $\sigma$  3 and the ratio  $\Phi$  of principal stress differences [ $\Phi = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$ ] using the Angelier Direct Inversion Method software version 5.42 (Angelier, 1984, 1989). Several deformational phases affecting the studied area were thus established (see Table 1; also Ben Chelbi, 2007; Ben Chelbi et al., 2008).

The first phase of deformation thus recognised involved extension towards N64°W-S64°E on the NW-SE oriented normal faults during the Coniacian-Campanian. These NE-SW faults show a dextral normal movement involving the uplift of Triassic series. The maximum downthrow and sediment thickness during this phase developed at Jebel Rihane and Aïn Bou Slam (Fig. 9A). In addition, the activity recorded by this network of faults delimits a high zone with a thin series of sediments, corresponding to the modern BAT (Fig. 9A). The configuration of the sedimentary floor was thus controlled by a succession of horsts and grabens in which the current site of BAT is the uplifted zone and Jebel Rihan and Aïn Bou Slam correspond to the collapsed areas (Fig. 9A').

262 In the second phase, the Maastrichtian to the Middle Eocene period was characterized by a 263 transpressive to compressive tectonics with the maximum compressive strain oriented in the 264 direction N41°W-S41°E. This was determined by analysis of syndepositional micro-faults 265 affecting the formations that characterize this period (Fig. 10 A). This tectonic regime 266 reactivated the NE-SW striking faults with reverse slip and the NW-SE to E-W striking faults with dextral normal slip (Fig. 10 B). This structural configuration involved the downthrow of 267 268 NW-SE to E-W oriented blocks, for example in the BAT (Fig. 9 B and B'). We note the 269 significant thickness (150m) of the limestone series forming the upper member of the Abiod 270 Formation, the argillaceous series of the El Haria Formation and the various limestone layers 271 of the Bou Dabbous Formation. These three formations are missing at Jebel Rihane and much 272 reduced at Jebel Bou Ftis in the north and at Jebel Bou Arada Aïn Bou Slama in the south.

The phase of extension oriented N16°E-S16°W during the Late Eocene-Aquitanian was also deduced by analyzing syndepositional micro-faults (Fig. 11A). At this time the NW-SE to E-W oriented normal faults (Fig. 11 B) accommodated subsidence of BAT and the uplift of its neighbouring areas (Fig. 9). The NE-SW to N-S trending fault system also accommodated normal slip, amplifying the subsidence of the trough (Fig. 11 C and D).

During the Middle Miocene, the micro-faults analysed indicate N25°W-S25°E compression associated with the crustal shortening of the Atlas Mountains (Fig. 12 A). This phase reactivated the NE-SW oriented faults with reverse slip and the NW-SE to WNW-ESE system with normal slip (Fig. 12 B). The structures bounding the BAT were folded, maintaining the downthrown in the interior of the trough (Fig. 12 C and D). The Late Miocene-Pliocene period was marked by continental sedimentation in an extensional tectonic regime associated with a S61°W-N61°E oriented principal strain (Fig. 13 A and B), once again revealed by analysis of micro-faults. The pre-existing faults were reactivated with normal slip that accommodated subsidence in the BAT (Fig. 13 C and D).

From the Early Quaternary to the present, the Atlas Mountains of Tunisia have been subjected to shortening with N-S compressive strain (Letouzey, 1986; Tlig et al., 1991; Mzali and Zouari, 2006; Ben Chelbi et al., 2008; Melki et al., 2010). In our study area this neotectonic regime has reactivated the NW-SE and E-W oriented faults with reverse slip (Fig. 14A). Moreover, the NE-SW and N-S fault system has also been reactivated and shows sinistral movements (Fig. 14B).

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#### 294 **7. Discussion**

295 On the basis of our morphostructural, tectono-sedimentary and seismic analyses and 296 interpretations we infer a complex history of development of the BAT since the 297 Maastrichtian. Moreover, this graben presents a particular geometry different from the other 298 troughs of the central Tunisian Atlas. Indeed, this depressed structure, with an ESE-WNW to 299 NW-SE orientation, is fragmented into three sub-basins, each one oriented NW-SE to WNW-300 ESE. These sub-basins are, from east to west, the Taref Ech Chena, Bou Arada and El 301 Aroussa basins. They are separated by NE-SW trending sinistral faults and are downthrown 302 essentially by the WNW-ESE to NW-SE oriented normal faults (Figs 8 to 14). The evolution 303 of BAT indicates some differences when compared to the other Plio-Quaternary troughs of 304 the central Tunisian Atlas described by Dlala et al. (1983), Philip et al. (1986) and Chihi and 305 Philip (1998), Haj Sassi et al. (2006) and Belghith et al. (2011). Indeed, an intimate 306 relationship exists since the Campanian between the facies distribution and thicknesses, and movements of the NW-SE oriented faults. The BAT shows Palaeogene units unconformably
covered by Mio-Pliocene continental deposits. The facies and thicknesses of these formations
are largely controlled by a complex system of faults.

In principle, two possible scenarios can account for the development of the BAT. The first is extension or transtension, accommodated, on the NW-SE to WNW-ESE and NE-SW to ENE-WSW oriented normal faults; the occurrence of this process would lead to the classification of the BAT as an extension or rift basin. Second, the BAT might develop as a pull-apart basin in response to strike-slip movement associated with compression or transpression (Fig. 15).

315 Our results suggest the following evolutionary model of the BAT (Fig. 10 to 14):

316 (i) - During the Late Maastrichtian to the Middle Eocene, the compressive to transpressive 317 tectonic mode applied a horizontal N319 principal strain and a N220 intermediate extensive strain (Fig. 11A). These strains activate the NE-SW to ENE-WSW oriented faults in reverse 318 319 to dextral reverse movement (Fig. 10 B). The NW-SE to WNW-ESE oriented faults are 320 reactivated into normal mechanism with considerable dextral component (Fig. 10 B). The 321 interference of sliding movements recorded on these bordering faults coupled with the normal 322 movement of the sub-parallel faults to the maximum stress, involves the subsidence of BAT 323 (Fig. 10 C) due to a pull-apart mechanism of opening (Fig. 10 D and Fig. 15). This syn-324 deposits activity is attested by the total absence of the Maastrichtian, Paleocene and Early to 325 Middle Eocene Formations in Jebel Rihane and Bou Ftis. In parallel, at Jebel Taref Ech 326 Chena, Jebel Bou Arada and Drâa Sidi Haj Amor the equivalent deposits are condensed. At 327 these localities the maximum thicknes of these Formations were lower to 40m (Fig 9).

This opening model of BAT is comparable to that proposed for the opening of the Permian basin of Hercynian Morocco described by Saïdia et al. (2002).

330 This considered period is contemporary to the significant convergence between Africa and 331 Eurasia plates (Biju Duval et al., 1977; Dercourt et al., 1985; Carminati et al., 1998;

Carminati and Doglioni, 2004) inducing the obduction of the Maghrebian furrow on the
Alboran-Kabylia-Calabria block and the beginning of the thrust-and-fold tectonics that form
the Maghreb Atlas Mountains (Piqué et al., 1998; Frizon De Lamotte et al., 2009).

335 (ii) - During the Late Eocene-Oligocene-Aquitanian interval, the study area was subjected 336 to extension-transpression tectonic regime implying minimum N16 horizontal strain and 337 N269 intermediate compression strain (Fig. 11 A). In response to this strain distribution, NE-338 SW to ENE-WSW oriented faults have normal mechanism, while the NW-SE to WNW-ESE 339 oriented faults show normal mechanism with oblique component (Fig. 11 B)). This faulting 340 activity shown by the two conjugate systems also involves the uplift of neighbouring 341 structures in the BAT (Fig. 11 C). This syn-sedimentary normal faulting activity is attested by 342 the strong accumulation of the Late Eocene clays and the Oligocene-Aquitanian sands and 343 clays within the graben, and their reduction or absence at Jebel Rihane, Bou Ftis, Jebel 344 Bessioud and Taref Ech Chena (Fig. 9).

This mode of extension tectonics and crustal opening is comparable with the evolution of the Upper Rhine graben (Bergerat, 1977; Granet et al., 2000) which is contemporary to the building of the Numidian basins in Tunisia (Talbi et al., 2008). These extension movements are as well coeval to the opening of the Algerian-Provençal basin (Tapponnier, 1977; Belon and Brousse, 1977) and can be considered as a response to the ongoing convergence between Africa and Eurasia (Biju-Duval et al., 1977; Dercourt et al., 1985).

(iii)- The Middle Miocene ultimate compressive phase responsible for the installation of the Tunisian Atlas (Ben Chelbi et al. 2008) was characterised by a N334 horizontal maximum compression strain, a vertical intermediate extension strain and a N241 oriented minimal strain (Fig. 12 A). These forces reactivated the NE-SW and NW-SE oriented faults in sinistral reverse and dextral to dextral normal movement, respectively (Fig. 12 B). The interaction of movements recorded on these faults may likely guide the continuous opening and subsidence movement of BAT (Fig. 12 C and D). This tectonic configuration is attested by the thick
accumulation of Late Miocene continental deposits in the trough centre and their absence in
the basin borders.

During the Middle Miocene, the North African plate subduction under the Southern European margin was blocked (Dercourt et al., 1985), whereas, the Ionian and Adriatic plates continued to subduct (Aubouin, 1986; Carminati et al., 1998; Doglioni et al., 1999; Faccenna et al., 2004; Panza et al., 2007).

(iv) - During the Late Miocene-Pliocene period, the tectonic regime was essentially extensive to transtensive implying a N241 minimal strain and N150 compressive intermediate strain (Fig. 13 A). This couple of strain distribution reactivated the two pre-existing systems of fractures into normal movement with sinistral and dextral sliding component respectively (Fig. 13 B), thus involving the downthrown of the BAT (Fig. 13 C and D). This activity is here also attested by the strong accumulation of the Mio-Pliocene continental deposits in the centre of the trough, and their absence in its borders.

This basin formation mode is similar to that described by Hurwitz et al. (2002) to explain the mode of opening of the Sea of Galilee and the scenario of installation of some troughs of the Pelagean Sea (Chihi and Philip, 1998).

374 (v) - Since the Quaternary until Present day, the tectonic regime affecting the Tunisian 375 Atlas and North Africa Mountain ranges is compressive as shown by the N359 horizontal 376 compressive stress (Meghraoui et al., 1986; Rebai et al., 1992; Fig. 14 A). This most recent 377 tectonic regime reactivates the NE-SW to ENE-WSW and NW-SE to WNW-ESE pre-existent 378 faults in reverse movement with sinistral and dextral sliding component respectively (Fig. 14 379 B). This tectonic phase involves normal faulting and final trough installation in its current 380 architecture (Fig. 14 C). The persistence of this compressive activity causes the reverse 381 movements recorded by all the faults without compensation of the normal movements

recorded since the first extensional phases of this basin's evolution. This configuration is attested, especially, on the P1 and P2 seismic sections. This situation will lead to the beginning of closing of this structure. This period is contemporary to the phase of installation of troughs in the central Tunisian Atlas (Philip et al., 1986; Chihi and Philip, 1998).

386

#### **8. Conclusions**

388 The BAT has developed during a succession of phases of crustal deformation since the 389 Maastrichtian, in association with slip on major faults oriented NE-SW and NW-SE. It is 390 inferred that during extensional phases the BAT has developed as a rift basin whereas during 391 compressive and transcurrent phases it has developed as a pull-apart basin. Seismic data 392 confirm field observations and indicate that the BAT is segmented into three sub-basins with 393 an overall negative flower structure. Its complex history of development reflects the complex 394 deformation of the wider region as a result of changes in the relative motions of the African 395 and Eurasian plates.

396 During periods of extensional tectonics the basin subsidence is attributed to a simple rifting 397 model, while during the compressive and transcurrent tectonic periods the opening of this 398 graben occurred according to a pull-apart mechanism. This scenario implies a continuous 399 subsidence in the graben. The examination of seismic profiles combined with field 400 observations reveal 1) the NE-SW oriented faults allowed the fragmentation of this trough in 401 three adjacent grabens, and 2) the bordering faults of this depressed structure show flower 402 structures. Furthermore, the sub-surface observations in seismic profiles confirm those 403 performed at the surface and show that the subsidence process is continuous either in 404 extensional period according to a mechanism of the rifting type or in compression movement 405 period according to a pull-apart mechanism of opening.

Our evolution model of the BAT is different from that proposed to explain the modes of graben formation in the central Tunisian Atlas during the Mio-Plio-Quaternary (Philip et al., 1986). The BAT records the complex tectonic evolution in a convergence, subduction and collision system between the African and Eurasian plates outlined here since the Maastrichtian. Moreover, the BAT structural building could be a potential site for oil and water reservoir because formed by thick Cretaceous and Early Eocene limestone series rich in organic matter and a thick Oligocene and Neogene sandy deposits. Detailed geochemical and hydro-geochemical studies, complementary to this structural analysis, are necessary in order to understand the importance of hydrocarbon and hydrological potentialities within the BAT.

416 Acknowledgements: This work was made possible with the collaboration of ETAP (Tunisian 417 Petroleum Company) and funding from the Ministry of Higher Education. Field observations 418 and modelling benefited from fruitful discussion with Chedly Abbès and Noureddine Boukadi 419 (Professors at the University of Tunis). We are thankful to Rob Westaway and two 420 anonymous reviewers for the critical reading of an earlier version of the manuscript.

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637 Figure captions

638

Fig. 1: A- Simplified structural map of the northern and central Tunisian Atlas and
localization of the studied area (T2: Zaghouan Fault, T3: Tunis-Ellès fault, T4: El AliaTeboursouk Fault; After Melki et al. 2010). B- Structural zoning of Tunisia showing the
structural position of the Bou Arada Trough (After Ben Chelbi et al. 2008).

643

Fig. 2: A- Geomorphologic context of the studied area (SRTM 30m). B- Geologic map of the
studied area (1- Triassic; 2- Early Cretaceous; 3- Late Cretaceous; 4- CampanianMaastrichtian; 5- Palaeocene-Middle Eocene; 6- Late Eocene-Oligocene-Aquitanian; 7- MioPliocene; 8- Quaternary; 9: Fault; 10: Localization of the seismic lines; 11: Localization of the
cross sections).

- 649
- 650 Fig 3: Lithostratigraphic column of the study area
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Fig. 4: Synthetic chart of the geodynamics of the Tunisian Atlas showing the relationship
between convergence tectonics and salt tectonics, after Patriat et al. (2003), Mejri et al.
(2006), and Ben Chelbi et al. (2008). Arrows are oriented with respect to the North as a
vertical direction.

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Fig. 5: Geological cross sections (for localization see Fig. 3C) showing the northernmost
contacts of the graben of Bou Arada with the neighbouring structures (Apt.: Aptian; Alb.:
Albian; Cen.: Cenomanian; Con.: Coniacian; Sant.: Santonian; Maast.: Maastrichtian; La.
Eoc.: Late Eocene; Olig.: Oligocene; Mio-Plio.: Mio-Pliocene; Q.: Quaternary)

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Fig. 6: Geological cross sections showing the southernmost contacts of the Bou Arada Trough
with the neighbouring structures (see Figs 2B and 5 for locations). Abbreviations denote:
Apt., Aptian; Alb., Albian; Cen., Cenomanian; Con., Coniacian; Sant., Santonian; Camp.,
Campanian; Maast., Maastrichtian; Ea. Eoc., Early Eocene; La. Eoc., Late Eocene; Olig.,
Oligocene; Ea. Olig., Early Oligocene; La. Olg., Late Oligocene; Mio-Plio., Mio-Pliocene;
Mio-Plio-Q., Mio-Plio-Quaternary; and Q., Quaternary.

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Fig. 7: Raw (P1, P2) and interpreted (P'1, P'2) N-S oriented seismic lines showing the
configuration and the geometry of the Bou Arada Trough (see Fig. 2B for locations). Fine

- lines denote limits of formations, thicker lines denote faults, and broken lines denote limits of
  Triassic series. Abbreviations denote: M.P.Q., Mio-Plio-Quaternary; Ol.Aq., OligoAquitnian; E.3, Late Eocene; M.E.2, Maastrichtian to middle Eocene; Co.Ca., Coniacian to
  Campanian; Al.Tur., Albian-Turonian.
- 675

Fig. 8: Raw (P3, P4) and interpreted (P'3, P'4) E-W and NW-SE oriented seismic lines
showing the configuration and the geometry of the Bou Arada Trough (see Fig. 2B for
locations). Notation is the same as for Fig. 7.

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Fig. 9: Correlation proposed in this study between the lithostraigraphic series on both sides of
the Bou Arada Trough (A, B, C) showing modes of formation (A', B', C') and the evolution
of this trough since the Campanian.

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684 Fig. 10: Evolution of the Bou Arada Trough in response to the various tectonic constraints 685 during Maastrichtian- middle Eocene. A depicts a stereographic representation (Schmidt's 686 projection, lower hemisphere) of the various populations of faults affecting the different layers 687 in studied area (continuous lines); a strike rose diagram, showing principal stress axes 688 orientation and value ( $\sigma 1$ ,  $\sigma 2$  and  $\sigma 3$ )). B depicts interpretations of the stereograms showing 689 the various activities recorded on major faults. C depicts schematic block diagram showing 690 the paleostructuration of the studied area ( $\iff$   $\implies$  extension regime,  $\implies$  Compression 691 regime). D depicts an evolutionary model of BAT in relation to the bordering system of 692 faults).

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Fig. 11: Evolution of the Bou Arada Trough in response to the various tectonic constraintsduring Late Eocene-Aquitanien (same legend as Fig. 11).

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Fig. 12: Evolution of the Bou Arada Trough in response to the various tectonic constraintsduring Middle to Late Miocene (same legend as Fig. 11).

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Fig. 13: Evolution of the Bou Arada Trough in response to the various tectonic constraintsduring Late Miocene-Pliocene (same legend as Fig. 11).

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Fig. 14: Evolution of the Bou Arada Trough in response to the various tectonic constraintsduring Quaternary-Actual (same legend as Fig. 11).

Fig. 15: A) Block diagram schematically showing the pull-apart model of formation of the
BAT during transpression. B) Simplified sketch showing the faults that controlled the
evolution of the BAT.

**Table 1:** Synthetic table of the palaeostress data used for the reconstruction of the tectonic evolution of the study area Tunisia (**N**: number of fault plans;  $\sigma 1$ ,  $\sigma 2$ ,  $\sigma 3$ : Direction and value of the stress;  $\Phi$ : ratio of stress magnitude differences ( $\Phi = \sigma 2 - \sigma 3/\sigma 1 - \sigma 3$ ); **R**: Palaeostress regimes; **C**, **E**, **TT** and **TP**: Compressional, Extensional, Transtensive and Transpressive regimes, respectively.





- 745 Fig.2:

Chrono stratigraphy		Formation	Lithostratigraphy					
Late Miocene -Pliocene				Sands, Silts, Clays and conglomerates				
Oligocene		Fortuna		Yellow sands and clays alternations				
Eocene	Late	Souar		Yellow clays with rare limestone levels				
Lower		Bou Dabbou		White limestones				
Paleo	ocene	El Haria		Green to grey clays and marls				
Maastrichtian Campanian		Abiod		White massive limestones with somes marly and limestones alternation				
Santonian		Aleg		Thick series of green clays				
Coniacian Turonian				Alternations of grey marls and white limestones				
Albian		Fahdene		Green marls and limestones				
Aptian		Bir M'Chei		Green to grey clays with somes limestones levels and turbiditic sat				
Barremian		rga Group		Green clays and quartzits				
Hauterivian				Green Marls and grey limestones				
Triasssic				Clays, Gypsum, Sands and Dolomies				
Fig.3:								

753 Fig.





758 Fig.4:





768 Fi



771 Fig. 7:







779 Fig. 9













Chronostratigraphy	Formation	Ν	σ1	σ2	σ3	Φ	R
Quaternary		12	359.16/	91.9/	210.71/	0.094	С
			-0.51	-0.37	0.88		
Late Mio-Pliocene		11	334.52/	150.38/	241.20/	0.314	SS
			-0.70	-0.20	0.9		
Middle Miocene	Beglia	18	335.13/	119.73/	242.9/	0.855	C to
			-0.97	0.37	0.60		ТР
Oligocene-	Fortuna						Ε
Aquitanian		15	112.29/	269.50/	16.10/	0.147	То
Late Eocene	Souar		-0.55	-0.34	0.88		TT
Lower Eocene	Bou						С
	Dabbous	12	319.9/	220.44/	58.45/	0.696	То
Paleocene	Al Haria		-0.95	0.23	0.77		ТР
Maastrichtian	Top Abiod						
Campanian	Base to	05	95.63/	202.8/	296.26/	0.834	Ε
	Middle		-0.95	0.35	0.61		to
	Abiod						TT

## 882 Table 1: