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Z. Amri: Conceptualization, Field work, Writing - original draft, Writing - review & editing, Formal analysis. **A. Masrouhi:** Conceptualization, Field work, Writing - original draft, Writing - review & editing, Formal analysis. **C. Naji:** Field work, Writing - review & editing, Formal analysis. **O. Bellier,** Field work, Writing - review & editing, Formal analysis, **H. Koyi.** Field work, Writing - review & editing, Formal analysis

Mechanical relationship between strike-slip faulting and salt tectonics in the Northern Tunisian Atlas: the Bir-El-Afou salt structure

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Abstract

Wide variety of salt structures –from typical diapirs to large allochthonous salt sheets– are recognized in the Northern Tunisian Atlas. In this study, we present for the first time the presence of a diapiric structure, Bir-El-Afou Salt Structure (BEASS), which has formed in response to strike-slip tectonics. Structural mapping, mesoscale field observations, fault kinematic analysis, and interpretation of gravity data are used to interpret BEASS, which is currently associated with a restraining bend. The present-day NNE– trending restraining stepover is formed as a result of E-W dextral fault system. We assume that the restraining stepover is a product of the inversion of a pre-existing pull-apart basin that formed during the Cretaceous South Tethyan extension. Tectono-sedimentary relationship is used to argue for an early Cretaceous NW-SE regional extension and local transtension. During the opening of the pull-apart basin, salt movement took place in the southwestern corner of the basin which must have thinned due to its extension facilitating diapiric emplacement. Diapir growth during Aptian was followed by brief salt flow from the diapir crest towards the basin forming a salt sheet. A period of Tertiary contraction resulted in the inversion of the pull-apart basin and consequently, squeezing of BEASS.

Keywords: Salt diapir; Pull-apart; restraining bend; Inversion; Tunisia

1 | Introduction

The Atlas fold-and-thrust belt hosts abundant salt structures widely scattered between Morocco and Tunisia. The salt bodies are more abundant in Northeast Algeria and North Tunisia Alpine belt. This area (called “Northeastern Maghreb salt province”, Fig. 1) shows unequivocally Triassic evaporites widely implicated in the evolution of the structures and strongly influence their tectonic style. For decades, the focus has been only on two main models for these structures: diapir model with vertical growth without considering extrusion of allochthonous salt (e.g. Perthuisot et al., 1998; Rouvier et al., 1998); and salt glacier model suggesting salt flow on a submarine slope (e.g. Vila et al., 1996; Ghanmi et al., 2001; Slama et al., 2009; Masrouhi and Koyi, 2012). This study is part of a structural revision where we compare data from salt structures in Tunisia with well-documented salt-tectonic systems in the Northeastern Maghreb salt province and other halokinetic systems (e.g., Masrouhi et al., 2013; Masrouhi et al., 2014a; Amri et al., 2020).

For the Alpine chain in the northeast of the Maghreb, we expect to have a different type of salt structures similar to those in the Gulf of Mexico, the West African margin, the Santos basin, and the Betics, among others. A submarine salt glacier was firstly identified in the Medjez-Bab area (Masrouhi and Koyi, 2012), in addition a large salt canopy was identified for the first time in this province (Masrouhi et al., 2013). The presence of individual diapirs was also recently identified (Masrouhi et al., 2014b). A large allochthonous masse of Triassic evaporites suggesting Mesozoic salt flow on a continental-slope was identified in Bled Doghra area (Masrouhi et al., 2014a). An Atlantic-type passive margin salt tectonics was also identified from Jerissa to Nebeur area (Jaillard et al., 2017). Recently, an interconnected salt diapir–allochthonous salt sheet was moreover recognized in the Lansarine-Baouala structure (Amri et al., 2020). In this paper, we present, for the first time, a salt structure associated with strike-slip fault systems in Northeastern Maghreb Salt Province (Fig. 2), namely the Bir-El-Afou salt structure (BEASS).

During the last three decades, a large number of studies have been focused on salt tectonics identifying salt structures at different tectonic settings (Jackson and Talbot, 1986; Vendeville and Jackson, 1992; Rowan et al., 2003; Hudec and Jackson, 2007; Koyi et al., 1993; Koyi et al., 1993 and 2008; Callot et al., 2012; Tari and Jabour, 2013; Jackson and Hudec, 2017; Alsop et al., 2018 and references therein). Based on these studies, three well documented main settings can be identified: extensional salt-tectonic systems, contractional salt-tectonic systems and inverted salt-tectonic systems (e.g., Jackson and Hudec, 2017; Hudec et al., 2020). The first tectonic system, which is more abundant, encompasses salt structures of rift basins and passive margins (e.g. Vendeville and Jackson, 1992; Koyi et al., 1993; Jackson et al., 2000; Hudec and Jackson, 2004; Brun and Fort, 2011; Quirk et al., 2012; Rowan, 2014). The second system includes the role of salt in the orogens (e.g. Davis and Engelder, 1985; Koyi, 1988; Jourdon et al., 2020), and also the contractional structures formed by major folding and faulting detachment in the far deep zones of passive margins (e.g. Rowan, 1995; Davison, 2007). The third tectonic system consists of the subsequent inversion of basins including evaporites (e.g. Burliga et al., 2006; Trocme et al., 2011; Kergaravat et al., 2016; Hudec et al., 2020, and references therein). However, salt tectonics related to strike-slip fault systems is less documented (Jackson and Hudec, 2017). Two areas are presented to display the relationship between strike-slip systems and salt tectonics: Dead Sea (e.g. Al Zoubi et al., 2002; Smit et al., 2008; Alsop et al., 2015, 2018) and the Zagros fold and thrust

belt (Talbot and Alavi, 1996; Sherkati and Letouzey, 2004; Koyi et al., 2008; Callot et al., 2012). In addition to these type-areas, recent publications demonstrate the existence of strike-slip related salt tectonics in other contexts such as the Spanish Betic Cordillera (Martin-Martin, 2018), Carpathian Mountains (Schleder et al., 2019), the Brazilian Santos basin (Wischer and Mohriak, 2020), North German Basin (Ahlrichs et al., 2020), and the Adriatic Sea (Teofilo et al., 2016).

Strike-slip systems are present at different scales. In intra-plate settings, strike-slip systems may form as transfer zones connecting large normal faults in rifts and passive margins or linking major thrust faults in fold-and-thrust belts (e.g. Woodcock, 1986; Wu et al., 2009). It is well established, in natural and experimental setting, that strike-slip faults are made of en échelon stepovers (e.g. Riedel, 1929; Wilcox et al., 1973; Woodcock and Schubert, 1994; Bellier and Sebrier, 1994; McClay and Dooley, 1995; Dooley and Schreurs, 2012; Rache et al., 1998; El Sawy and Masrouhi, 2019). The linked areas between two consecutive strike-slip fault segments define a rhomboidal-shaped stepovers. These bends or stepovers are referred as restraining when they accommodate local contraction and as releasing when they accommodate local extension (Bellier and Sebrier, 1994; McClay and Bonora, 2001; Dooley et al., 1999; Smit et al., 2008; Corti and Dooley, 2015). The local tectonic regime associated with these areas is referred to as transpressional in case of restraining bends and transtensional in releasing bends.

In this study, we use field observations, structural mapping and analysis, and geophysical data to study the relationship between a strike-fault system and the BEASS. We argue that BEASS is one of few examples of a salt diapir, which is developed within a pull-apart basin that was active during Early Cretaceous in South Tethyan margin. To analyze the relationship between strike-slip faults and the diapir emplacement and growth, detailed geologic mapping was carried out both in the field and through the use of satellite images. The outcropping contacts of the salt structure with overburden layers are used to define its spatial and temporal evolution. Fault kinematic analysis is conducted to determine the tectonic regime during Tertiary and Cretaceous times. The Bouguer map is examined to outline the subsurface signature of the salt structure.

2 | Geological Setting

2.1 | Geodynamic outline

The Maghreb fold-and-thrust belt is interpreted as a Tertiary orogeny related to the convergence between Africa and Europe (e.g., Frizon De Lamotte et al., 2002; Stampfli et al., 2002; Bahrouni et al., 2020). This belt is widely accepted as resulting from the Alpine inversion of the pre-existing Permian to Mesozoic South Tethyan basin (e.g., Guiraud, 1998; Rosenbaum et al., 2002; Roure et al., 2012; Moragas et al., 2018; Leprêtre et al., 2018). The breakup of Pangea, formation of the Tethys, and the opening of the Atlantic, resulted in formation of a series of rift basins from Morocco to Tunisia (present-day coordinates). In Tunisia, the present-day Northern Atlas system is usually divided into two structural units: first, the Teboursouk thrust unit which is a major southeastward-vergent thrust unit incorporating thick Aptian-Albian sediments with abundant outcropping salt structures. The second unit is the Zaghouan-Ressass unit which marks the southern limit of the Alpine range in Tunisia. The Zaghouan thrust fault has been described as a major paleogeographic boundary separating a northern deep basin from the southern shallower basin during the Mesozoic time (e.g., Ben Ferjani et al., 1990; Naji et al., 2018b).

The Mesozoic-Cenozoic tectono-sedimentary evolution in Tunisia resulted from main periods of deformation. The first one is during the Tethyan evolution followed by the opening of the Atlantic Ocean. The first episode, from rifting to passive continental margin, was initiated approximately during late Permian and persisted until the early Cretaceous (Guiraud, 1998; Stampfli and Borel, 2002; Stampfli et al., 2002). It was responsible for the configuration of Triassic basin largely filled with evaporitic deposits across major parts of Tunisia (Kamoun et al., 2001; Soussi et al., 2017). During Jurassic to early Cretaceous, a major extensional event correlated to the opening of Central Atlantic Ocean prevailed (Soussi et al., 2000; Boughdiri et al., 2007; Bahrouni et al., 2016) and was accompanied in some locations in northern Tunisia with volcanic and halokinetic activities (Mattoussi Kort et al., 2009; Jaillard et al., 2017; Amri et al., 2020). Moreover, early to middle Albian seems to coincide with the final stage of the Atlantic Ocean opening (Jaillard et al., 2013). During Aptian–Albian times, the northern Tunisian basin underwent rapid extension (El Amari et al., 2016; Naji et al., 2018a; Masrouhi et al., 2019), which is manifested in an increasing Cretaceous salt movement (Fig. 3) associated with mixed thick- and thin-skinned tectonics (Amri et al., 2020). This period is characterized by syn-sedimentary faulting resulted in tilted blocks which controlled the configuration of the irregular seafloor (e.g. Souquet et al., 1997; Jaillard et al., 2017; Naji et al., 2018b). Block rotations are characterized by high sedimentation rate, wide slump folding and abundant syntectonic sequences (Jaillard et al., 2013, 2017; Naji et al., 2018a). In contrast, the late Cretaceous period defines a post-rift stage since it is mainly dominated by carbonate and open marine shale facies (Robaszynski, 2000; Li et al., 2000). Following the Mesozoic rifting, convergence between African-Eurasia plates, which began during the Senonian time (Maastrichtian?), resulted in the closure of the Tethys seaway and the inversion of the Tethyan basins (e.g. Doglioni et al., 1997; Guiraud and Bosworth, 1997). This convergence phase was followed by yet another compressional phase in middle Miocene during Alpine compression. In essence, two major tectonic events seem to be recorded from late Cretaceous to present. First is what corresponds to the Atlasic compressional event which led to the closure of several Mesozoic basins during middle to late Eocene (e.g. Khomsi et al., 2006, 2009; Masrouhi et al., 2008), and the second is correlated to the middle Miocene Alpine compression and represents the major orogenic contractional event in Tunisia. The later compressional phase is considered to be a key factor for the establishment of the present-day NE-trending Northern Tunisia orogen (e.g. Chihi, 1995; Gharbi et al., 2015; Masrouhi et al., 2019; Khomsi et al., 2019). It is also important to note that the alpine compression is considered to be still active (Gharbi et al., 2014, Bahrouni et al., 2020). In Northern Tunisian Atlas, there is another phase of extension and rejuvenation of diapirism in Oligocene-lower Miocene (Perthuisot, 1978; Perthuisot et al., 1998). However, we do not see any field evidences to suggest that the Bir-El-Afou salt structure is rejuvenated during this known extensional period (Fig. 3).

2.2 | Lithostratigraphic outline

The BEASS shows very well-exposed outcrops of Mesozoic and Cenozoic sequences (Fig. 3). All the lithostratigraphic units are accessible on outcrops, and easily recognized and mapped (Fig. 4). The Triassic sequences are mainly evaporitic. In the BEASS, this Formation (called the “Trias evaporites”) shows a sequence of gypsum, halite and rare dolostone. Along the northern part of the El Aouinet-Ez Zebaz (AOZE) restraining bend, which shows two subparallel Triassic salt sheets interbedded in the two limbs of the present-day anticline, the outcropping unit consists mainly of

gypsum (Fig. 4). The absence of halite is probably due to the dissolution that occurred during extrusion and/or later during the successive Tertiary compressional events. The thickness of the Triassic Formation cannot be estimated from the diapir. However, some studies (e.g., Ben Ferjani et al., 1990) have estimated the thickness of the evaporitic sequence to be about 1000 m in north Tunisia.

In the Northern Tunisian Atlas, BEASS is exposed in an area covering about 50 km². The outcropping stratigraphic successions of central part of this structure are from Barremian to Oligocene, excluding the Quaternary alluviums that are not described in this study. Barremian sequences are made of black marls with limestone intercalations. These sequences are part of the M'cherga Formation (Burolet, 1956). They are defined as "Barremian sequences" and correspond the middle member of the M'cherga Formation which are deposited in deep basins, classically described as South Tethyan basin in Tunisia (Ben Ferjani et al., 1990; Souquet et al., 1997). The Aptian–lower Albian sequences constitute the upper member of the M'cherga Formation (Fig. 3). These series are considered in Northern Tunisia to reflect a deep-water environment. The Aptian–Albian period is highlighted in Tunisia as the most active salt tectonics period (Perhuisot et al., 1978; Ghanmi et al., 2001; Vila et al., 2002; Masrouhi et al, 2014a; Amri et al, 2020) and the most active extensional event during the South Tethyan evolution in North Tunisia (Jaillard et al., 2017; Naji et al, 2018b). Overall, the lower Cretaceous deposits in Northern Tunisian domain basin are characterized by deep-water sequences interbedded locally by siliciclastic turbidites and tempestite units, together with frequent calcareous nodules and habitually abundant slump folding. This period is also characterized by significant variations in facies and thickness. Unlike the lower Cretaceous, the late Cretaceous sediments are characterized by homogenous facies over the entire north Tunisian basin. This period, which is interpreted to be a post-rift period (Souquet et al., 1997; Jaillard et al., 2017; Naji et al, 2018b), is characterized by significant variation in thickness but without noticeable facies variation. The late Cretaceous sediments include the Fahdene Formation (Albian–Cenomanian sequences) which is made of deep-water facies. They consist essentially of grey to black marls alternating with abundant decametric to metric limestones. These sediments are overlain by Bahloul Formation (late Cenomanian–early Turonian), which corresponds mainly to laminated organic rich Black Shales. Bahloul Formation in turn is overlain by a thick package of gray shales and marls alternating with metric limestone beds which are affiliated to Aleg/Kef Formation of Coniacian–Santonian age. The late Cretaceous series are topped by the Campanian–Maastrichtian Abiod Formation, which is mainly composed by two fine grained limestone bars intercalated by marl-limestone alternations (Fig. 3).

The Cenozoic sequences begin with the El Haria Formation (uppermost Maastrichtian–Paleocene) and is mainly characterized by green to dark shales. The lower Eocene sequences are characterized by slightly laminated and Globigerina rich limestone sequences, which is called Bou Dabbous Formation and is defined in Tunisia as Globigerinidae Facies. The late Eocene is defined as the Souar Formation, which corresponds, mainly in this structure, to clay sequences with very rare limestone intercalations. This Formation shows the first (oldest outcropping) angular unconformity in the study area (Figs. 3 and 4). The top of the sedimentary sequences in the central part of the BEASS is the Oligocene strata outcropping in the adjacent synclines of J. Seba and J. Moraba. The early Oligocene is marked by the first appearance of thick detrital facies with clastic sediments (Fig. 3).

3 | The Bir-El-Afou Salt Structure

3.1 | General style and outcrop-scale units

BEASS is less explored compared to other salt structures in the Northeastern Maghreb Salt Province (Solignac, 1927; Jauzein, 1967; Ben Chelbi et al., 2003; Ben Chelbi et al., 2006). In this study, we have mapped a 50 km² area of the AOZE to understand its structural and facies evolution. The dominant Atlassic structures of the north Tunisia are NE-trending faults and folds (Fig. 1). In this context, the AOZE is a distinctive feature that corresponds to a sigmoidal-shaped structure and seems to have been controlled by two en-echelon E-trending fault segments (Fig. 2). The evolution of this structure. The first one, which we define as the Si Hamida fault segment, is ~ 5-km long that bounds the northern part of the AOZE. The second, which we define as the Si Ali El Moudjeh fault segment, is also ~ 5-km-long that bounds the southern side of the AOZE. Besides, these two en-echelon fault segments delineate a stepover of about 3 X 3.5 km manifested by the sigmoidal-shaped anticline of Jebel el Aouinet and Jebel Ez Zebaz, which we define in this study as the AOZE anticline (Fig. 4). The middle part corresponds to the NNE-trending faulted AOZE anticline, whose northeastern plunge is bent eastwards whereas the southwestern plunge is bent westwards. A prominent NE-trending dextral fault cuts along the entire trend of the AOZE anticline (Fig. 4). The core of anticline is made of the Barremian–Aptian dark green marls and limestones (Fig. 5). On either limb of the anticline, Aptian to lower Eocene sequence (i.e., M'cherga, Fahdene, Aleg, Abiod, El Haria and Bou Dabbous formations) are outcropping. Dip of bedding decreases significantly in the Upper Eocene sequences at both the eastern and western plunges (Fig. 2). Two E-trending synclines (J. Seba in the East and J. Moraba in the West) where Oligocene sequences outcrop are bounding the eastern and western sides of AOZE. In general, the AOZE appears to be a structure with a complicated deformation history indicating a multiphase tectonic evolution. Within this structure, the two limbs of the AOZE anticline show two 5-km-long (± 0.5 km) Triassic salt sheets which are interbedded within Aptian sequences (Figs. 6 and 7). These allochthonous salt sheets, which likely to have extruded prior to Tertiary folding were described for the first time by Ben Chelbi et al. (2003). The two present-day parallel bands of allochthonous salt sheets, over 5 km of exposures, are “interlayered” in the Aptian sequences and follow the core of AOZE anticline indicating that they were folded during inversion of BEASS (Figs. 8 and 9). The biostratigraphic data reveal that the allochthonous-salt body extruded over Upper Aptian and is covered by uppermost Aptian (for more detail about stratigraphy see Ben Chelbi et al., 2003, 2006; Ben Chelbi, 2007). The well-exposed biostratigraphic markers allow suggesting a rapid submarine salt flow (less than one biozone, ± 0.5 Ma). Moreover, this basinward (north-northeast ward) salt flow is linked well with the main diapiric salt body of Bir-El-Afou located in the southern part of BEASS. The connection between the salt diapir and its salt sheet, which is clearly exposed in the south, is not obliterated by the Tertiary compression episodes (Figs. 10 and 11). This is in favor of a consistent hypothesis that the sheet was initially a flat salt body connected to the Bir-El-Afou diapir before it was shortened.

The northern salt sheet is folded and can be traced for ca. 5 km from south to north. A series of recumbent folds are clearly seen within the salt sheet (Fig. 12). The vergence of these indicate a of north transport direction (Fig. 12) during a rapid salt flow on a preexisting synsedimentary slope (northward). The trend of these folds is consistently ranged from 090°E to 100°E, which indicate a broadly North-verging submarine paleoslope (perpendicular to the main axial planes strike) on

which salt extruded from the BEASS diapir in the south. In addition, this ductile deformation is only localized within the salt sheet and are not observed in the Cretaceous beds underlying and overlying the salt, indicating salt flow on a synsedimentary slope toward the basin during a brief period. All these observations are in agreement with an interpretation that recumbent folding was a direct consequence of gravity driven salt flow on a preexisting submarine synsedimentary slope.

3.2 | Fault and fracture patterns

Deformation within the Cretaceous and Tertiary sequences in the BEASS is well marked especially by steeply dipping strike-slip fault systems with dominant E-W striking ones (Fig. 4). Larger fault systems are well developed in the northern and southern boundaries of the BEASS and correspond to the main strike-slip fault systems of Si Hamida in the North and Si Ali El Moudjeh in the South. These fault systems display tens of meters to hundreds of meters of displacement and are typically strike-slip faults in the northern and southern borders of BEASS and strike-slip to oblique-slip in the central area. The smaller fault zones are located in the central part and correspond to E to NE-trending meter-scale fractures (Fig. 9). However, some of NE-trending transverse faults are kilometer-scale and cut across the entire basin. Three faults are well identified inside the BEASS and are scattered (in term of separation distance) in northern, central and southern parts (Fig. 4). The northwest and southeast corners of BEASS show an imbricated thrust system well observable in the field (Figs. 4 and 11 d). The main salt body of Bir-El-Afou is bounded by and seems to be controlled by the E-trending fault systems in the southern part of BEASS. The abundant fault systems show usually more than one generation of striation which indicates a polyphase evolution (Fig. 10). In addition, the right-lateral strike-slip fault system is likely the inversion of pre-existing Mesozoic oblique faults (normal and left-lateral strike-slip) (Fig. 9). Even though numerous strike-slip faults show polyphase evolution, some of them still show sinistral inside the BEASS. Moreover, drag-folding observed beneath some faults clearly exhibit this multiphase evolution (Fig. 9). Further constraints and fault kinematic analysis are provided in a later section (stress field consideration).

3.3 | Main shortening events

The Mesozoic series, described above, are unconformably covered by Tertiary series with two main angular unconformities highlighting two successive Tertiary compressional events. This succession corresponds to the two major non-coaxial phases of folding, well-known throughout the entire Maghreb geological belt (Buroillet, 1956; Vila et al., 1975; Frizon de Lamotte et al., 2002; Khomsi et al., 2009). Inside the AOZE, the interference of these two folding phases is contributing to the apparent discrepancy of the small folded structures between a middle NNE-trending S-shaped anticline and the adjacent E-trending synclines (Figs. 2-4). It is well known now that the first WNW-ESE compression, dated as middle to late Eocene, is labelled the Atlasic compression and produces a N30° to 40°E trending folding referred to as Atlasic direction (Khomsi et al., 2006; Masrouhi et al., 2008; Dhahri and Boukadi, 2010). This compression phase began by the inversion of Tethyan structures at the end of the Cretaceous, probably Campanian–Maastrichtian (Masrouhi et al., 2008). This event is well known and recorded in nearby structures (Medjez-El-Bab, Lansarine) by the absence of Maastrichtian–Paleocene strata with reworked elements in the open folds (Perthuisot, 1978; Masrouhi et al., 2008). While the second compression phase (Alpine

event), dated as Tortonian-Messinian, is due to a $\sim$ N-S shortening. The Atlassic compression resulted in the inversion of the pull-apart basin (Figs. 4-8) and formation of the middle fold (AOZE) (Fig. 7). The post-Tortonian N-S Alpine compression resulted in formation of mainly E-trending folds (e.g., synclines of J. Es Seba and J. Moraba displayed by folded Oligocene strata).

4 | Stress Field Estimation

The fault systems affecting the study area have overprinted almost the entire strata outcropping along the BEASS (Figs. 10 and 11). The number of fault sites selected for paleostress analysis are generally well distributed and representative (Fig. 10 and 11). Twenty-one sites from the study area were selected to show the distribution and the high interference related to the tectonic phases (Fig. 13). These sites show brittle tectonic overprint on Barremian to Oligocene sequences. In these two sites, a regional stress regime is performed by inversion of fault slip data (striation) of the main fault plains (MFP) in addition to data on cross-cutting relationship of striations. Fault kinematic analysis, by the Inversion results, include orientation of the principal stress axes of the computed stress tensor (σ_1 , σ_2 and σ_3) and the stress ratio R , defined as

$$R = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \quad (1)$$

where $0 \leq R \leq 1$ (for more details see Mercier et al., 1991; 2013; Bellier and Zoback, 1995; Delvaux and Sperner, 2003; Shabanian et al., 2010; Hippolyte et al., 2012; Tranos, 2017, and references therein).

4.1 | Fault kinematics analysis

The first fault population collected in the core of the structure (S_0171) indicates extensional regime with SE-trending σ_3 . This site shows faults affecting the Barremian sequences and some of them are clearly syndimentary attesting a growth faulting. The second site (S_0173) shows fault affecting the lower Aptian sequences (Figs. 4, 13). This site exhibits mainly NE-trending faults with privileged dip toward the SE. This fault population reveals a SE-trending horizontal minimum stress axis σ_3 (Fig. 13). Another site measured in the Aptian sequences (S_0174) also displays a NW-SE extension. However, one single site (S_0172) for the Aptian tectonic shows a NE-SW extension. This fault population corresponds to NW-trending faults. This stress tensor is likely influenced by the two major strike-slip faults that limit this site. Site S_0176 where faults affect the Turonian sequences shows a similar stress tensor as that of site S_0172. The trends seen in sites 172 and 176 are exclusively located between two main NW-trending main fault. These tensors cannot be taken as representative of the tectonic regime inside the BEASS as they seem to be influenced by local fault trends. The separation of data will resolve this ambiguity (described in the section on the regional tectonic). During Albian and Cenomanian times, the NW-SE tectonic extension persists (sites S_0184 and S_0185). However, in addition to normal faulting, strike-slip component seems to be more represented than early stages (Fig. 13). These fault sites characterize NW- to NNW-trending tectonic extension.

The six faults sets measured in the central part of the BEASS provide evidence for a strike-slip regime (Fig. 13). Two main cases can be distinguished with (i) strike slip tectonic regime characterized by NNW-trending σ_1 and ENE-trending σ_3 (0186). (ii) strike-slip tectonic regime with NW-trending σ_1 and NE-trending σ_3 corresponding to the sites S_2020, S_2029, S_2025,

S_3021, S_2021 and S_2023, measured in Cretaceous Formations (Fig. 13). In site 1915, fault population is measured in the lower Eocene limestones and corresponds to a local compressional stress field with ENE-trending σ_1 (Fig. 13).

Five fault populations (sites 2028, 2031, S_BE_A_3033, 3035 and S_BE_A_3038) measured in late Cretaceous and Eocene formations indicate a compressional tectonic regime with NW-trending σ_1 (Fig. 13). This stress tensor is remarkably consistent with the well-known Alpine tectonic phase from Miocene to present day (El Ghali and Ben Ayed, 1995; Bahrouni et al., 2014; Gharbi et al., 2014).

4.2 | Regional versus local tectonic regimes by the Mean Representative Fault Planes

In order to constrain the kinematics and the stress state as well as the temporal and the spatial variation along the BEASS, we performed a data separation of fault population. We use the Main Representative Fault Planes selected on the basis of field observations (Sealed faults, cross-cutting striations, etc. ...). Fault kinematic analysis is performed by inversion of the fault slip data into stress tensor (Fig. 14). This kinematic analysis has achieved by the use of the Win-tensor computer program (Delvaux and Sperner, 2003, Delvaux and Barth 2010). Ten sites were selected from the BEASS.

Inversion of five Barremian-aged major striated faults indicates an extensional tectonic regime that prevailed inside the BEASS (M_0171, Fig. 14). This tectonic regime is characterized by horizontal SSE-trending minimum stress tensor σ_3 (00/149), a sub-horizontal WSW-trending intermediate stress tensor σ_2 (11/240), and a steep NNE-trending maximum stress tensor σ_1 (77/024) and $R=0.7$. The R Ratio shows a trend toward a transtensional regime. Restoration of the major faults clearly illustrates a NW-SE striking extensional tectonic that persisted during Early Aptian time (M_0173, Fig. 14). This tectonic regime is characterized by the following parameters obtained from five MRFP data inputs. The stress tensor shows horizontal SE-trending σ_3 (02/128), near horizontal (16/218) SW-trending σ_2 and steeply plunging (74/003) N-trending σ_1 (Fig. 14). Six measurements are processed from upper Aptian-lower Albian (synchronous with the main salt flow event) main representative fault plane (M_0174, Fig. 14). The fault data collected from Albian corresponds to a pure extensional regime (M_0184, Fig. 14). The stress tensor is characterized by NW-trending σ_3 (05/293), gently plunging (20/202) SSW-trending σ_2 and NE-trending steeply plunging σ_1 (69/036).

Two MRFP sites (M_2020 and M_3021), located in opposite NW and SE corners of the BEASS, respectively, suggest a pure strike-slip stress regime (Fig. 14). The M_2020 site display evidence for tensor with steeply plunging σ_2 (68/239) and stress ratio $R=0.5$. The main representative faults are ENE dextral and NNE sinistral ones. This site shows a regional stress regime with SE-trending σ_1 and a NE-trending minimum stress axis (σ_3 is 21/048). The M_3021 permits to determine a strike-slip deviator characterized by horizontal SSW-trending minimum stress axis σ_3 (02/204), subhorizontal (06/114) SE-trending σ_1 and subvertical (84/309) WNW-trending σ_2 (Fig. 14). Inside the BEASS, strike slip faults are synchronous with tectonic compression (transpression). This is well illustrated by the M_0186 site which shows a S-trending σ_1 and W-trending σ_3 . This stress tensor shows a local σ_{hmax} of 05/179 and a local σ_{hmin} 12/270. The intermediate stress tensor is steep (77/067). The Tertiary evolution of the BEASS is governed by a regional compressional regime (M_2021 and M_3038, Fig. 14). This regime is NW-trending compressional

one during Eocene to Miocene and NNW-trending from Miocene to present. The first compressional regime is demonstrated by the M_2021 with horizontal SE-trending (00/122) maximum stress tensor σ_1 , horizontal WSW-trending (04/212) intermediate stress tensor σ_2 and vertical (86/028) minimum stress tensor σ_3 . These parameters with $R=0.47$ represent a regional pure compressional tectonic regime. The second compressional regime is characterized by horizontal NNW-trending (08/335) maximum stress tensor σ_1 , horizontal NE-trending (04/065) intermediate stress tensor σ_2 and a vertical (81/183) minimum stress tensor σ_3 . These parameters with $R=0.33$ represent a regional compressional tectonic regime with tendency to transpressional regime. Due to these two episodes of compression during Tertiary, the BEASS shows a pop-up nature where the local tectonic regime is characterized by horizontal WNW-trending maximum stress axis σ_1 (01/277), gently plunging (26/187) SSW-trending σ_2 and steeply plunging (64/008) NNE-trending σ_3 (Fig. 14, site M_2023).

5 | Comparison with Gravity Data

5.1 | Data reliability

A Bouguer gravity anomaly map which is derived from the computer processing of at least one measurement per km², sometimes from a denser network (Gabtni et al., 2009; Frifita et al., 2019) is used (Fig. 15). This Bouguer gravity anomaly map is provided by the National Office of Mine of Tunisia (Bouguer map of Bir M'cherga sheet, 1999). The data are of Gravimétrie en Tunisie-CG5 by Sagax Maghreb S.A. These data are therefore perfectly adapted to the multi-kilometric surfaces of the studied structure, in particular to that of the salt outcrops. Therefore, these data can be used without stripping or modeling operations (Nely, 1980) to correlate field observations and structure with the gravity signature delivered by the Bouguer gravity anomaly map.

5.2 | The Bouguer gravity-anomaly map

The gravity anomaly map of the BEASS appears to reflect the overall structure outlined by structural mapping (Fig. 15). Gravity anomalies depicted in the map are broadly E-trending in the North and the South, and NNE-trending in the central part (Fig. 15a). In the central part of the BEASS, gravity values are ranging from 12 to 14 mGal. The average Bouguer gravity anomaly values decrease toward the East and the West. These peripheral structures coincide with values ranging from 8 to 10 mGal in the East and 3 to 4 mGal in the West. The correlation between main structures and the gravity signature shows that the NNE-trending gravity maxima coincide with the sigmoidal shaped J. el Aouinet–J. Ez Zebaz anticline with higher Mesozoic density material (Fig. 15b). Toward the East and the West, the lower density region coincides with the E-trending synclines of J. Seba in the East and J. Moraba in the West formed by Oligocene and recent lower density Cenozoic sediments (Fig. 15b). The complete Bouguer anomaly map shows noticeable E-trending gravity anomalies in both North and South BEASS borders. The superposition of the gravity value trends on the main fault systems shows that the sharp gravity contrast between the high and low amplitude anomalies coincides with the major E-trending main faults (Fig. 15 c and d). The superposition of the geologic map with the Bouguer gravity anomalies map indicates a fairly accurate correspondence between the features of the BEASS observed on the geologic map and their gravity signature (Fig. 15d). Triassic evaporites do not show any clear signature on the Bouguer gravity anomalies. Due to its scale (0.9 square km), the lack of clear signature of this diapir is expected; the Diapir simply does not show a contrasting gravity signature. Furthermore,

in the northern part, the thin sheets of salt (2 to 4 m) embedded in the Aptian marls and limestones, do not show any gravity signature either.

6 | Discussion

6.1 | BEASS Structure: Geometry and Timing

Field observation of mesoscale features, geologic mapping, fault kinematic analysis and gravity signature indicate that the BEASS is located at a left-step restraining bend between the East-West trending dextral strike-slip fault segments of the Si Hamida in the North and the Si Ali Moudjeh in the South (Figs. 16).

AOZE appears as typical and well-documented model of restraining stepover as defined by the models of McClay and Bonora (2001). Fault kinematics analysis reveals an Early Tertiary WNW-ESE to NW-SE regional compression (Fig. 16) and a later regional NNW-SSE compression in Late Tertiary (Fig. 16). This stress state is accompanied by right-lateral movement of the main E-trending Si Hamida and Si Ali Moudjeh strike-slip faults. This configuration shows a rhomboidal central structure of a left stepover bonded by dextral E-trending fault systems. The E-trending faults have been identified as active along the northern Tunisian domain, producing low-to moderate seismicity with focal mechanisms consistent with a NNW-SSE compression (Gueddiche et al., 1992). The E-trending dextral fault systems are also highlighted as major structures in many regions throughout Tunisia (e.g., Hamdi et al., 2019; Soumaya et al., 2020). This central part makes an angle of 30° to the principal E-trending principal displacement zone. Within the pop-up structure, three sets of faults are developed and linked to the principal strike-slip faults in the north and south (Fig. 16). The stress field changes locally. For example, in site M_2023, fault kinematic analysis indicates a local E-W compression confirming the local central restraining stepover of the AOZE (Fig. 14, M_2023). The central zone displays a pop-up structure having two major sets of reverse faults associated with a positive flower structure. Equally important, the two NW and SE corners of the central pop-up structure (AOZE) show an imbricate system of thrust faults (Aridhi et al., 2014) in agreement with Tertiary regional NW-SE compressional tectonic. AOZE shows a strongly deformed central pop-up structure (Figs. 4 and 6). This uplift zone is almost symmetrical in the rhomboid central zone but changes in symmetry toward the northern and the southern borders (Fig. 6). All these features, that characterize an elongate deformed rhomboidal restraining area, represent the surface expression of a fault system forming a dominant positive flower structure. Consequently, the present-day AOZE is a slightly asymmetric NNE-trending restraining stepover formed along the main E-trending faults of Si Hamida in the North and the Si Ali Moudjeh in the south (Fig. 16). The present-day restraining structure shows a NNW-SSE compressional stress state which is well correlated with geodynamic framework of Tunisia. Recent GPS measurements and associated velocity together with the stress and the strain distribution analysis published by Bahrouni et al. (2020) provide evidences for a WNW to NNW-trending GPS velocities and earthquake slip vectors. Their findings are consistent with the stress directions deduced from fault analysis reported in this study.

The rhomboidal shape of AOZE, its fracture distribution and fault data separation are indicative of a pre-existing pull-apart structure which was active during Mesozoic times. The reconstruction of the Cretaceous structural style indicates the predominance of NE-trending faults inside the basin that is located between two left step E-trending fault zones in the north and south (Fig. 16).

These fractures are indicative of regional tectonic regime that persist during the lower Cretaceous and corresponds to the regional NW-SE extension (Fig. 14). The common system of fractures shows a NW-highly dipping (70°-85°) normal faulting well integrated inside a pull-apart basin (Figs. 8-16). The separation of fault slip data into four stages confirms the same regional tectonic regime: (1) NW-trending regional minimum stress axis and contemporaneous (2) E-trending local minimum stress axis inside the pull-apart (Fig. 16). The active Cretaceous normal faulting, the abundant slumping and calcareous nodules usually on the hanging-wall of normal faults inside the basin characterized a graben evolution (Fig. 11). This NE-SW graben is bounded by the major E-trending J. Moraba and J. Seba faults. This graben is asymmetric and shows northward preferential deepening. This evolution is marked at the Aptian – Albian transition by the rise of the Bir-El-Afou diapir located at the southern edge of the pull-apart (Figs. 2-6). This position seems to be well integrated in this setting and can be explained by the north deepening vergence (compared to the South edge) giving route to the salt to rise in the southern pull-apart corner (Fig. 4). In addition, a 5-km-long salt sheet flowed from the diapir stem toward the North. This later is well documented by our field investigation. Along the structure, the salt sheet exhibits usually internal folding (Fig. 12). This salt sheet exhibits regularly asymmetric micro-folding with dominant North-facing transport verging (broadly from 000° to 010°E).

6.2 | Evolution of BEASS

Over the last three decades, several studies have focused on different salt structures, including salt glaciers, large evaporitic allochthonous sheets and salt canopies in Northwestern Africa (e.g., Perthuisot et al., 1998; Troudi et al., 2017; Benassi et al., 2006; Masrouhi et al., 2014b; Masrouhi and Koyi, 2012; Dhahri and Boukadi, 2017; Ghanmi et al., 2001; Ben Chelbi et al., 2006; Vila et al., 2002; Ghanmi et al., 2006; Masrouhi et al., 2013; Vergés et al., 2017; Amine et al., 2020;). Recently, a link between a salt diapir and an allochthonous salt sheet was identified in the northern Atlas of Tunisia (Amri et al., 2020). In the central and the southern Tunisian Atlas, few studies have attributed the evolution of salt structures to strike-slip tectonics (Hlaïem, 1999; Zouaghi et al., 2005, 2013), which is absent in the Northeastern Maghreb Salt Province.

This study reports for the first time a diapir genetically formed in response to strike-slip tectonics in the northern Tunisian Atlas. The BEASS appears as a singular salt structure in the Northeastern Maghreb Salt Province induced by strike-slip tectonics. The data collected in this study indicate lower Cretaceous transtensional tectonics that formed a pull-apart basin where salt movement was triggered. The present-day BEASS is a slightly asymmetric NNE-trending restraining stepover formed in Tertiary along the main E-trending faults of Si Hamida in the North and Si Ali Moudjeh in the south (Fig. 16). This restraining stepover is a result of the inversion of a pre-existing pull-apart basin that formed during the evolution of South Tethyan in Cretaceous. AOZE is a mature, but relatively small scale (3.6 X 2.7 km) pull-apart basin (Fig. 16 b). fault kinematics analyses, including slip-vectors (striae) chronology display evidence for regional and local significant temporal and spatial variations in the stress states between the central rhomboidal area and outer portions of AOZE (Figs. 13-16). Moreover, the distinction between Cretaceous and Tertiary faults allows us to outline the pre-existing releasing bend (i.e., the AOZE pull-apart), within a left stepover. Within the basin, Aptian–Albian sequences are characterized by abundant slump features and frequent calcareous nodules associated with numerous metric to decametric growth normal faults (Fig. 11). In addition, many normal faults are observed with predominantly N-dips

and NE- to ENE trends (Figs. 4-11). Fault slip data presented in this study are compatible with an E-W local extension inside the basin and NW-SE regional Cretaceous tectonics (Figs 13 and 14). The Aptian–Albian period is characterized in north Tunisia by the maximum extensional South Tethyan stage (Naji et al., 2018b). During the opening of the pull-apart basin, a salt diapir was initiated in the southwestern corner of the releasing structure (Fig. 16). This salt structure has subsequently extruded a 5-km-long salt sheet towards the basin in the northeast (Fig. 16). The rapid extension and high opening rate of the pull-apart basin are probably the factors that caused the rapid growth of the diapir (≤ 0.5 Ma) and extrusion of its overhang northward (Fig. 16).

In the BEASS, two stages of halokinesis are recognized: a lower Cretaceous diapir intrusion in the southwestern corner of the pull-apart structure, followed by a brief period of salt extrusion from the diapir towards the pull-part basin in the northeast. The BEASS seems to have been passively deformed (within the overall structure) without noticeable influence of the Tertiary folding on the former Cretaceous salt structure. During the pull-apart basin inversion, the main diapiric body in the south is squeezed, whereas the northern salt sheet is folded with its Cretaceous overburden. This relatively small diapir (about 1 km²) has survived presumably because it is not located within the central zone of the inverted pull-apart basin, but at its southwestern corner where the stress regime is transpressional. Regionally, BEASS is located between two main deformation fronts corresponding to the Zaghouan thrust belt in the South and the Teboursouk thrust belt in the North. These two major belts accommodate the major shortening in the northern Atlas domain with BEASS accommodating part of the shortening by inversion of the pre-existing pull-apart basin. The most plausible hypothesis for the origin of the E-W faults bounding BEASS is that they were developed during the Jurassic period. Fault with such trends are generally well known in Tunisia as well as Maghreb and usually assigned to the Alpine Tethys tectonics. Geodynamically, this period is well documented as an active and rapid extension period within the South Tethyan context (Patriat et al., 2003; Martin-Martin et al., 2017; Moragas et al., 2018; Masrouhi et al., 2019).

As a summary, the BEASS appears as a singular structure (in the Northeastern Maghreb Salt Province) genetically related to strike-slip tectonics. The E-trending sinistral strike-slip faults form, during Aptian times, a pulled apart rhomboidal shaped area. The pull apart corner, recognized as preferential weakness zone, gives route for salt to be emplaced as diapir located between main fault systems. In addition, the relatively fast extension and high opening rate of the pull-apart basin have probably contributed to the rapid growth of the diapir (≤ 0.5 Ma). An extrusive salt sheet has rapidly advanced from the diapir toward the north. This fast advance typically typifies an extrusive salt advance (Hudec and Jackson, 2007), as evidenced by widespread recumbent folds in the internal structure of the salt sheet.

7 | Conclusions

Based on the results of detailed geologic mapping, field observation of mesoscale features, fault kinematic analysis, detailed Triassic evaporites contacts with the surrounding sequences, together with interpretation of gravity data, in this study, we outline for the first time, a salt diapir associated with a releasing bend (AOZE) in response to strike-slip tectonics in the Northern Tunisia Atlas. We draw the following conclusions on AOZE:

- The present-day AOZE is a slightly asymmetric NNE–trending restraining stepover formed between two E–trending dextral major faults.
- This restraining stepover is a product of the inversion of a pre-existing rhomboidal pull-apart basin that formed during Cretaceous time along a releasing stepover.
- During early Cretaceous, a diapir formed in the southwestern corner of the pull-apart basin.
- Salt extrusion resulted in formation a 5-km–long salt sheet that extends to the north from the main diapir.
- This study confirms that the diapir was a triggered as a consequence of strike slip tectonics.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Z. Amri: Conceptualization, Field work, Writing - original draft, Writing - review & editing, Formal analysis. **A. Masrouhi:** Conceptualization, Field work, Writing - original draft, Writing - review & editing, Formal analysis. **C. Naji:** Field work, Writing - review & editing, Formal analysis. **O. Bellier,** Field work, Writing - review & editing, Formal analysis, **H. Koyi.** Field work, Writing - review & editing, Formal analysis

REFERENCES

- Ahlrichs, N., Hübscher, C., Noack, V., Schnabel, M., Damm, V., Krawczyk, C.M. 2020. Structural Evolution at the Northeast North German Basin Margin: From Initial Triassic Salt Movement to Late Cretaceous-Cenozoic Remobilization. *Tectonics*, 39 (7), art. no. e2019TC005927.
- Alsop, G. I., R. Weinberger, T. Levi, and S. Marco, 2015, Deformation within an exposed salt wall: Recumbent folding and extrusion of evaporites in the Dead Sea Basin: *Journal of Structural Geology*, 70, 95–118, doi:10.1016/j.jsg.2014.11.006.
- Alsop, G.I., Weinberger, R., Marco, S., Levi, T., 2018. Fault and fracture patterns around a strike-slip influenced salt wall *Journal of Structural Geology*. 106, 103–124.
- Al-Zoubi, A., Shulman, H., Ben-Avraham, Z., 2002, Seismic reflection profiles across the southern Dead Sea basin: *Tectonophysics*, 346, 61–69.
- Amine, A., El Ouardi, H., Zebari, M., El Makrini, H., 2020. Active tectonics in the Moulay Idriss Massif (South Rifian Ridges, NW Morocco): New insights from geomorphic indices and drainage pattern analysis. *Journal of African Earth Sciences*, 167, art. no. 103833.
- Amri, Z., Naji, C., Masrouhi, A., Bellier, O., 2020. Interconnection salt diapir–allochthonous salt sheet in northern Tunisia: The Lansarine–Baoula case study. *Journal of African Earth Sciences*, 170, 2020, 103876.
- Aridhi, S., Aridhi, K., Ghanmi, M., Zargouni, F., Mercier, E., 2014. Structural context of meso-scale and cartographical duplex structure genesis in thrusting tectonics: Role of tear faults. Zaghouan thrust belt. Case of Bir M'Cherga-Ain Asker area. *Arabian Journal of Geosciences*, 7, 6, 2499–2514.
- Aydin, A., Nur, A., 1982. Evolution of pull- apart basins and their scale independence. *Tectonics* 1, 91–105.
- Bahrouni, N., Bouaziz, S., Soumaya, A., Ben Ayed, N., Attafi, K., Houla, Y., El Ghali, A., Rebai, N., 2014. Neotectonic and seismotectonic investigation of seismically active regions in Tunisia: a multidisciplinary approach. *J. Seismol.* 18 (2), 235–256.
- Bahrouni, N., Houla, Y., Soussi, M., Boughdiri, M., Ali, W.B., Nasri, A., Bouaziz, S., 2016. Discovery of Jurassic ammonite-bearing series in Jebel BouHedma (South-Central Tunisian Atlas): Implications for stratigraphic correlations and paleogeographic reconstruction. *Journal of African Earth Sciences*, 113, 01, 101–113.
- Bahrouni, N., Masson, F., Meghraoui, M., Saleh, M., Maamri, R., Dhaha, F., Arfaoui, M., 2020. Active tectonics and GPS data analysis of the Maghrebian thrust belt and Africa-Eurasia plate convergence in Tunisia. *Tectonophysics*, 785, art. no. 228440.
- Bellier, O., Sébrier, M., 1994. Relationship between tectonism and volcanism along the Great Sumatran Fault Zone deduced by spot image analyses. *Tectonophysics* 233 (3–4), 215–231.
- Bellier, O., Zoback, M., 1995. Recent state of stress change in the Walker Lane zone, western basin and Range province, USA, *Tectonics*, 14, 564–593.

Ben Chelbi, M. 2007. Analyse tectonique des structures liées à la faille de Tunis-Ellès. Ph.D. thesis, Tunis El Manar University. 244p.

Ben Chelbi, M., Masrouhi, A., Ben Youssef, M., Ghanmi, M., Zargouni, F., Vila, J.M., 2003. The Triassic mass of Bir El Afou (30 km SW of Tunis) and its long salt sheets towards the NW, does it correspond to the most Eastern submarine “salt glacier” of northern Tunisia? [A 30 Km au SW de Tunis, la masse triasique de Bir El Afou et ses longs appendices vers le NW, correspond-elle au “glacier de sel” sous-marin le plus oriental de la Tunisie du nord ?]. 2eme Séminaire National de Stratigraphie, Algeria, 2003, 86–87.

Ben Chelbi, M., Melki, F. Zargouni, F. 2006. Mode of salt bodies emplacement in Septentrional Atlas of Tunisia. Example of a Bir Afou salt body [Mode de mise en place des corps salifères de l’Atlas septentrional. Exemple de l’appareil de Bir Afou]. *Comptes Rendus Geosciences*, 338, 349–358.

Ben Ferjani, A., Burolet, P. F., Mejri, F., 1990. Petroleum Geology of Tunisia. ETAP publication, 194p.

Benassi, R., Jallouli, C., Hammami, M., Turki, M. M., 2006. The structure of Jebel El Mourra, Tunisia: a diapiric structure causing a positive gravity anomaly. *Terra Nova*, 18, 432–39.

Boughdiri, M., Cordey, F., Sallouhi, H., Maalaoui, K., Masrouhi, A., Soussi, M., 2007. Jurassic radiolarian-bearing series of Tunisia: biostratigraphy and significance to western Tethys correlations. *Swiss Journal of Geosciences*, 100, 431–441.

Brun, J.-P., Fort, X., 2011, Salt tectonics at passive margins: Geology versus models: Marine and Petroleum Geology, 28, 1123–1145, doi:10.1016/j.marpetgeo.2011.03.004.

Burliga, S., Koyi, H.A., Chemia, Z., 2012. Analogue and numerical modelling of salt supply to a diapiric structure rising above an active basement fault. *Geological Society Special Publication*, 363 (1), 395–408.

Burolet, P.F., 1956. Contribution à l’étude stratigraphique de la Tunisie centrale. In: *Annales des Mines et de la Géologie (Tunisie)*. vol. 18 (350 p).

Callot, J., Trocmé, V., Letouzey, J., Albouy, E., Jahani, S., Sherkati, S., 2012. Pre-existing salt structures and the folding of the Zagros Mountains, in G. I. Alsop, S. G. Archer, A. J. Hartley, N. T. Grant, and R. Hodgkinson, eds., *Salt tectonics, sediments and prospectivity*: London, Geological Society, Special Publication 363, 545–561, doi:10.1144/SP363.27.

Calvez, J. H., Vendeville, B. C. Experimental designs to model along strike fault interaction. 2002. *Journal of virtual explorer*, 7, 1–17.

Chihi, L., 1995. Les fossés néogènes à quaternaires de la Tunisie et de la mer pélagienne: étude structurale et leur signification dans le cadre géodynamique de la Méditerranée centrale. Thèse Doct. Es Science. Géol., Tunis (325 pp.).

Corti, G. Dooley, T.P., 2015. Lithospheric-scale centrifuge models of pull-apart basins. *Tectonophysics*, 664, 154–163.

- Davis, D. M., Engelder, T., 1985. The role of salt in fold-and-thrust belts: *Tectonophysics*, 119, 67–88.
- Davison, I., 2007, Geology and tectonics of the South Atlantic Brazilian salt basins, in A. C. Ries, R. W. H. Butler, and R. H. Graham, eds., *Deformation of the continental crust: The legacy of Mike Coward*: London, Geological Society, Special Publication 272, 345–359.
- De Graciansky, P.-C., Rudkiewicz, J.-L. Samec, P., 1986. Tectonique salifère d'âge Jurassique dans la zone sub Briançonnaise (Alpes de Savoie, France) : Rôle dans le découpage en nappes de charriage et leur progression : *Comptes Rendus de l'Académie des Sciences, Paris, Série II*, 302, 891–896.
- Delvaux, D., 2020. Win-tensor Program (Version 5.8. of Jul-25-2020), Tensor Program Fault-kinematic Analysis and Tectonic Stress Tensor Inversion. <http://www.damiendelvaux.be/Tensor>
- Delvaux D., Barth A., 2010 African stress pattern from formal inversion of focal mechanism data; *Tectonophysics*. 482 105–128.
- Delvaux, D., Sperner, B., 2003. Stress tensor inversion from fault kinematic indicators and focal mechanism data: the TENSOR program. *Geological Society, London, Special Publication*, 212, 75–100.
- Dhahri, F., Boukadi, N., 2010. The evolution of pre-existing structures during the tectonic inversion process of the Atlas chain of Tunisia. *Journal of African Earth Sciences* 56, 139–149.
- Dhahri, F., Boukadi, N., 2017. Triassic salt sheets of Mezzouna, Central Tunisia: new comments on late cretaceous halokinesis and geodynamic evolution of the northern African margin. *Journal of African Earth Sciences* 129, 318–329.
- Doglioni, C., Gueguen, E., Sabat, F., Fernandez, M., 1997. The western Mediterranean extensional basins and the Alpine orogen. *Terra Nova*, 9, 109–112.
- Dooley, T.P., McClay, K., 1997. Analog modeling of pull-apart basins. *AAPG Bull.* 81 (11), 1804–1826.
- Dooley, T.P., McClay, K., Bonora, M., 1999. 4D evolution of segmented strike-slip fault systems: applications to NW Europe. In: Fleet, A.J., Boldy, S.A.R. (Eds.), *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, pp. 215–225.
- Dooley, T.P., Schreurs, G., 2012. Analogue modelling of intraplate strike-slip tectonics: a review and new experimental results. *Tectonophysics* 574–575, 1–71.
- El Amari, E.A., Gharbi, M., Youssef, M.B., Masrouhi, A., 2016. The structural style of the southern Atlasic foreland in northern Chotts range in Tunisia: field data from Bir Oum Ali structure. *Arab. J. Geosci.* 9, 389.
- El Ghali, A., Ben Ayed, N., 1995. The mechanism of the opening of lacustrine basins in the strike-slip faults of Sbiba-Cherichira, central Tunisia | [Mecanisme d'ouverture des bassins recents lies au systeme décrochant de Sbiba-Cherichira (Tunisie centrale)]. *Geologie Mediterraneenne*, 22(3-4), 141–151.

El Ghali, A., Ben Ayed, N., Bobier, C., Zargouni, F., Krifa, A., 2003. Les manifestations tectoniques synsédimentaires associées à la compression éocène en Tunisie, implications paléogéographiques et structurales sur la marge Nord-Africaine. *C. R. Geoscience* 335, 763–771.

El-Sawy, E.-S.K., Masrouhi, A., 2019. Structural style and kinematic evolution of Al Ji'lani area, Ad Dawadimi terrane, Saudi Arabia. *Journal of African Earth Sciences*, 150, 451–465.

Ferrer, O., Jackson, M. P. A. Roca, E. Rubinat, M., 2012. Evolution of salt structures during extension and inversion of the offshore Parentis Basin (Eastern Bay of Biscay), in G. I. Alsop, S. G. Archer, A. J. Hartley, N. T. Grant, and R. Hodgkinson, eds., *Salt tectonics, sediments and prospectivity*: London, Geological Society, Special Publication 363, 359–377.

Festa, V., Teofilo, G., Tropeano, M., Sabato, L., Spalluto, L., 2014. New insights on diapirism in the Adriatic Sea: The Tremiti salt structure (Apulia offshore, Southeastern Italy). *Terra Nova*, 26, 3, 169–178.

Frifita, N., Mickus, K., Zargouni, F., 2019. Gravity contribution to the geological study of grabens in the northwest region of Tunisia including the Kef Basin region. *Journal of African Earth Sciences*, 150, 811–822.

Frizon de Lamotte, D., Bezar, B.S., Bracène, R., Mercier, E., 2002. The two main steps of the atlas building and geodynamics of the Western Mediterranean. *Tectonics*, 19 (4), 740–761.

Gabtni, H., Jallouli, C., Mickus, K.L., Zouari, H., Turki, M.M., 2009. Deep structure and crustal configuration of the Jeffara basin (Southern Tunisia) based on regional gravity, seismic reflection and borehole data: How to explain a gravity maximum within a large sedimentary basin? *Journal of Geodynamics*, 47, 2-3, 142–152.

Ghanmi, M., Ben Youssef, M., Jouirou, M., Zargouni, F., Vila, J.M., 2001. Halocinèse crétacée au Jebel Kebbouch (Nord-Ouest tunisien) : mise en place à fleur d'eau et évolution d'un "glacier de sel" albien, comparaisons. *Eclogae Geol. Helv.* 94, 153–160.

Ghanmi, M., Vila, J.M., Ben Youssef, M., Jouirou, M., Zargouni, F., 2006. Variety of north-eastern Maghreb salt bodies: the Triassic sheets and lenses from Touireuf to Nebeur (middle Mellegue River, northwestern Tunisia): an early Cretaceous composite and segmented submarine "salt glacier"; petroleum interests. In: E.T.A.P. (Ed.), *Tunisian Petroleum Exploration and Production Conference Exploring Deep Targets and New Areas for more Reserves*, Tunis, October 30th–November 3rd, 144–172.

Gharbi, M., Bellier, O., Masrouhi, A., Espurt, N., 2014. Recent spatial and temporal changes in the stress regime along the southern Tunisian Atlas front and the Gulf of Gabes: new insights from fault kinematics analysis and seismic profiles. *Tectonophysics*, 626, 120–136.

Gharbi, M., Espurt, N., Masrouhi, A., Bellier, O., Amari, E.A., 2015. Style of Atlasic tectonic deformation and geodynamic evolution of the southern Tethyan margin, Tunisia. *Mar Pet Geol*, 66, 801–816.

Gharbi, M., Masrouhi, A., Espurt, N., Bellier, O., Amari, E., Ben Youssef, M., Ghanmi, M., 2013. New tectono-sedimentary evidences for Aptian to Santonian extension of the Cretaceous rifting in the Northern Chotts range (Southern Tunisia). *Journal of African Earth Sciences*, 79, 58–73.

Giles, KA, Lawton, T.F., 2002. Halokinetic sequence stratigraphy adjacent to the El Papalote diapir, northeastern Mexico. *Am Assoc Pet Geol Bull* 86(5):823–840.

Gueddiche, M., Harjono, M., Ben Ayed, N., Hfaeid, M., Diamant, M. Dubois, J., 1992. Analyse de la sismicité et mise en évidence d'accidents actifs dans le nord de la Tunisie. *Bull. Soc. Géol. France*, 163, 415–425.

Guiraud, R., 1998. Mesozoic rifting and basin inversion along the northern African Tethyan margin: an overview. In: MacGregor, D.S., Moody, R.T.J., Clark-Lowes, D.D. (Eds.), *Petroleum Geology of North Africa*. Geological Society, London, Special Publication, 133, 217–229.

Guiraud, R., Bosworth, W., 1997. Senonian basin inversion and rejuvenation of rifting in Africa and Arabia: synthesis and implications to plate-scale tectonics. *Tectonophysics*, 282, 39–82.

Hamdi, M.S., Soumaya, A., Kadri, A., Ben Ayed, N., Braham, A., Shimi, N., 2019. Evolution of E-W strike-slip fault network, the northwestern foreland of Tunisia. *Journal of African Earth Sciences*, 153, 278–290.

Hippolyte, J.-C., Bergerat, F., Gordon, M.B., Bellier, O., Espurt, N., 2012. Keys and pitfalls in mesoscale fault analysis and paleostress reconstructions, the use of Angelier's methods. *Tectonophysics*, 581, 144–162.

Hlaiem, A., 1999. Halokinesis and structural evolution of the major features in eastern and southern Tunisian Atlas. *Tectonophysics* 306, 79–95.

Hudec, M. R., Jackson, M. P. A., 2004, Regional restoration across the Kwanza basin, Angola: Salt tectonics triggered by repeated uplift of a metastable passive margin: *American Association of Petroleum Geologists Bulletin*, 88, 971–990.

Hudec, M. R., Jackson, M. P. A., 2007. *Terra infirma: Understanding salt tectonics*: *Earth-Science Reviews*, 82, 1–28, doi:10.1016/j.earscirev.2007.01.001.

Hudec, M. R., Jackson, M. P. A., 2011. *The salt mine: a digital atlas of salt tectonics*: Austin, TX, The University of Texas at Austin, Bureau of Economic Geology, Udden Book Series 5; Tulsa, OK, American Association of Petroleum Geologists, Memoir 99, 305 p.

Hudec, M.R., Dooley, T.P., Peel, F.J., Soto, J.I., 2020. Controls on the evolution of passive-margin salt basins: Structure and evolution of the Salina del Bravo region, northeastern Mexico. *Bulletin of the Geological Society of America*, 132, 5-6, 997–1012.

Jackson, M. P. A., and C. J. Talbot, 1986, External shapes, strain rates, and dynamics of salt structures: *Geological Society of America Bulletin*, 97, 305–323.

Jackson, M. P. A., Cramez, C., Fonck, J.-M., 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: Implications for salt tectonics and source rocks: *Marine and Petroleum Geology*, 17, 477–498.

Jackson, M.P.A., 1995. Retrospective salt tectonics. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), *Salt Tectonics: A Global Perspective*, vol. 65. American Association of Petroleum Geologists Memoir, 1–28.

Jackson, M.P.A., Hudec, M.R. 2017. *Salt Tectonics Principles and Practice*. Book, Cambridge University Press. 463p. DOI: 10.1017/9781139003988.

Jackson, M.P.A., Talbot, C.J., 1986. External shapes, strain rates, and dynamics of salt structures. *Geol. Soc. Am. Bull.* 97, 305–323.

Jackson, M.P.A., Vendeville, B.C., Schultz-Ela, D.D., 1994. Structural dynamics of salt systems. *Annu. Rev. Earth Planet. Sci.* 22, 93–117.

Jaillard, E., Bouillin, J.P., Ouali, J., Dumont, T., Latil, J.L., Chihaoui, A., 2017. Albian salt tectonics in Central Tunisia: evidences for an Atlantic-type passive margin. *Journal of African Earth Sciences*, 135, 220–234.

Jaillard, E., Dumont, T., Ouali, J., Bouillin, J.P., Chihaoui, A., Latil, J.L., Arnaud, H., Arnaud-Vanneau, A., Zghal, I., 2013. The Albian tectonic “crisis” in Central Tunisia: nature and chronology of the deformations. *Journal of African Earth Sciences*, 85, 75–86.

Jauzein, A., 1967. Contribution à l’étude des confins de la dorsale tunisienne. *Annales des Mines et de la Géologie* n° 22. Tunis, 475p.

Jourdon, A., Mouthereau, F., Le Pourhiet, L., Callot, J.-P., 2020. Topographic and Tectonic Evolution of Mountain Belts Controlled by Salt Thickness and Rift Architecture. *Tectonics*, 39(1), e2019TC005903.

Kamoun, F., Peybernes, B., Ciszak, R., Calzada, S., 2001. Triassic paleogeography of Tunisia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 172 (3–4) 223–242.

Kergaravat, C., Ribes, C., Legeay, E., Callot, J.-P., Kavak, K.S., Ringenbach, J.-C., 2016. Minibasins and salt canopy in foreland fold-and-thrust belts: The central Sivas Basin, Turkey. *Tectonics*, 35, 6, 1342–1366.

Khamsi, S., Bédir, M., Soussi, M., Ben Jemia, M.G., Ben Ismail-Lattrache, K., 2006. Mise en évidence en subsurface d’événements compressifs Eocène moyen-supérieur en Tunisie orientale (Sahel): Généralité de la phase atlasique en Afrique du Nord. *C R Géosci* 338(1–2), 41–49.

Khamsi, S., Ben Jemia, M.G., Frizon de Lamotte, D., Maherssi, C., Echihi, O., Mezni, R., 2009. An overview of the Late Cretaceous-Eocene positive inversions and Oligo-Miocene subsidence events in the foreland of the Tunisian Atlas: structural style and implications for the tectonic agenda of the Maghrebian Atlas system. *Tectonophysics*, 475, 38–58.

Khamsi, S., Roure, F., Khelil, M., Mezni, R., Echihi, O., 2019. A review of the crustal architecture and related pre-salt oil/gas objectives of the eastern Maghreb Atlas and Tell: need for deep seismic reflection profiling. *Tectonophysics* 766, 232–248.

Koyi, H., Jenyon, M.K., Petersen, K., 1993. The effect of basement faulting on diapirism. *Journal of Petroleum Geology*, 1993, 16, 3, 285–312.

- Koyi, H.A., Ghasemi, A., Hessami, K., Dietl, C., 2008. The mechanical relationship between strike-slip faults and salt diapirs in the Zagros fold-thrust belt. *Journal of the Geological Society*, 2008, 165, 6, 1031–1044.
- Leprêtre, R., De Lamotte, D.F., Combier, V., Gimeno-Vives, O., Mohn, G., Eschard, R., 2018. The Tell-Rif orogenic system (Morocco, Algeria, Tunisia) and the structural heritage of the southern Tethys margin. *BSGF-Earth Sciences Bulletin*, 189, 2, Art. Nb. 2018009.
- Li, L., Keller, G., Adatte, T., Stinnesbeck, W., 2000. Late Cretaceous sea-level changes in Tunisia: A multi-disciplinary approach. *Journal of the Geological Society* 157, 2, 447–458.
- Martín-Martín, J.D., Vergés, J., Saura, E., Moragas, M., Messenger, G., Baqués, V., Razin, P., Grélaud, C., Malaval, M., Joussiaume, R., Casciello, E., Cruz-Orosa, I., Hunt, D.W., 2017. Diapiric growth within an Early Jurassic rift basin: the Tazoult salt wall (central High Atlas, Morocco). *Tectonics* 36 (1), 2–32.
- Martín-Martín, M., Estévez, A., Martín-Rojas, I., Guerrero, F., Alcalá, F.J., Serrano, F., Tramontana, M., 2018. The Agost Basin (Betic Cordillera, Alicante province, Spain): a pull-apart basin involving salt tectonics. *International Journal of Earth Sciences*, 107, 2, 655–671.
- Masrouhi, A., Bellier, O., Ben Youssef, M., Koyi, H., 2014a. Submarine allochthonous salt sheets: gravity-driven deformation of North African Cretaceous passive margin in Tunisia – Bled Dogra case study and nearby salt structures. *Journal of African Earth Sciences*, 97, 125–142.
- Masrouhi, A., Bellier, O., Koyi, H., 2014b. Geometry and structural evolution of Lorbeus diapir, northwestern Tunisia: polyphase diapirism of the North African inverted passive margin. *International Journal of Earth Sciences (Geol Rundsch)*, 103, 881–900.
- Masrouhi, A., Bellier, O., Koyi, H., Vila, J. M., Ghanmi, M., 2013. The evolution of the Lansarine–Baouala salt canopy in the North African Cretaceous passive margin in Tunisia. *Geological Magazine*, 150 (5), 835–861.
- Masrouhi, A., Ghanmi, M., Ben Slama, M.M., Ben Youssef, M., Vila, J.M., Zargouni, F., 2008. New tectono-sedimentary evidence constraining the timing of the positive tectonic inversion and the Eocene Atlasic phase in northern Tunisia: implication for the North African paleo-margin evolution. *Comptes Rendus Geoscience*, 340, 771–778.
- Masrouhi, A., Gharbi, M., Bellier, O., Ben Youssef, M., 2019. The Southern Atlas Front in Tunisia and its foreland basin: Structural style and regional-scale deformation. *Tectonophysics*, 764, 1–24.
- Masrouhi, A., Koyi, H. A., 2012. Submarine ‘salt glacier’ of Northern Tunisia, a case of Triassic salt mobility in North African Cretaceous passive margin. *Geological Society, London, Special Publications*, 363, 579–593.
- MattoussiKort, H., Gasquet, D., Ikenne, M., LaridhiOuazaa, N., 2009. Cretaceous crustal thinning in North Africa: implications for magmatic and thermal events in the Eastern Tunisian margin and the Pelagic Sea. *Journal of African Earth Sciences*, 55 (5), 257–264.
- McClay, K., Dooley, T., 1995. Analogue models of pull-apart basins. *Geology* 23, 711–714.

- McClay, K.R., Bonora, M., 2001. Analog models of restraining stepovers in strike-slip fault systems American Association of Petroleum Geologists Bulletin., 85, 233–260.
- Mercier, J. -L., Carey-Gailhardis, E., Sébrier, M., 1991. Paleostress determinations from fault kinematics: Application to the Neotectonics of the Himalayas-Tibet and the central Andes, Philos. Trans. R. Soc. London, 337, 41–52.
- Mercier, J.L., Vergely, P., Zhang, Y.Q., Hou, M.J., Bellier, O., Wang, Y.M., 2013. Structural records of the Late Cretaceous-Cenozoic extension in Eastern China and the kinematics of the Southern Tan-Lu and Qinling Fault Zone (Anhui and Shaanxi provinces, PR China). Tectonophysics, 582, 50–75.
- Moragas, M., Vergés, J., Saura, E., Martín-Martín, J.D., Messenger, G., Merino-Tomé, Ó., Suárez-Ruiz, I., Razin, P., Grélaud, C., Malaval, M., Joussiaume, R., Hunt, D.W., 2018. Jurassic rifting to post-rift subsidence analysis in the central High Atlas and its relation to salt diapirism. Basin Res. 30, 336–362.
- Naji, C., Gharbi, M., Amri, Z., Masrouhi, A., Bellier, O., 2018a. Temporal and spatial changes of the submarine Cretaceous paleoslope in Northern Tunisia, inferred from Slump folds analysis. Proceedings of the Geologists' Association, 129, 40–56.
- Naji, C., Masrouhi, A., Amri, Z., Gharbi, M., Bellier, O., 2018b. Cretaceous paleomargin tilted blocks geometry in northern Tunisia: stratigraphic consideration and fault kinematic analysis. Arabian Journal of Geosciences, 11, 583 (2018).
- National Office of Mine–Tunisia, 1999. Bouguer map of Bir M'cherga sheet n°28. data of Gravimétrie en Tunisie–CG5 by Sagax Maghreb S.A.
- Nely, G. 1980. Seismic facies and morphology of evaporates. Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine. 4, 395–410.
- Patriat, M., Ellouz, N., Dey, Z., Gaulier, J.M., Ben, Kilani H., 2003. The Hammamet, Gabes and Chotts basins (Tunisia) a review of the subsidence history. Sediment. Geol. 156, 241–262.
- Perthuisot, V., 1978. Dynamique et pétrogenèse des extrusions triasiques de Tunisie septentrionale, vol. 12. Travaux du Laboratoire de Géologie, presses de l'Ecole Normale Supérieure, Paris, 312 p.
- Perthuisot, V., Rouvier, H., Smati, A., 1998. Style et importance des déformations anté-vraconniennes dans le Maghreb oriental: exemple du diapir du Jebel Slat. Bull. Soc. Géol. France 8, 389–398.
- Quirk, D. G., Schodt, N., Lassen, B., Ings, S. J., Hsu, D., Hirsch, K. K., Von Nicolai, C., 2012. Salt tectonics on passive margins: Examples from the Santos, Campos and Kwanza Basins, in G. I. Alsop, S. G. Archer, A. J. Hartley, N. T. Grant, and R. Hodgkinson, eds., Salt tectonics, sediments and prospectivity: London, Geological Society, Special Publication 363, 207–244.
- Rache, B., Ferill, D.A., Morri, A.P., 1998. Physical analogue modeling of pull-apart basin evolution. Tectonophysics 285, 21–40.

- Ramos, A., Fernández, O., Muñoz, J. A., Terrinha, P., 2017. Impact of basin structure and evaporite distribution on salt tectonics in the Algarve Basin, Southwest Iberian margin. *Marine and Petroleum Geology*, 88:961–984. Doi: 10.1016/j.marpetgeo.2017.09.028
- Riedel, W., 1929. Zur mechanik geologischer brucherscheinungen. *Centralblatt für Mineralogie, Geologie, und Paleontologie* 1929B, 354.
- Robaszynski, F., 2000. The upper cretaceous of the kalaat Senan region, central Tunisia. Integrated litho-biostratigraphy based on ammonites, planktonic foraminifera and nannofossils zones from upper Turonian to Maastrichtian. *Bulletin des Centres de Recherches Elf Exploration Production* 22, 2, 359–490.
- Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics* 359, 117–129.
- Roure, F., Casero, P., Addoum, B., 2012. Alpine inversion of the North African margin and delamination of its continental lithosphere. *Tectonics*, 31, TC 3006.
- Rouvier, H., Henry, B., Le Goff, M., Hatira, N., Laatar, E., Mansouri, A., Perthuisot, V., Smati, A., 1998. Preuves paléomagnétiques de la non-interstratification des évaporites du Trias dans l'Albien du Maghreb oriental. *Comptes Rendus de l'Académie des Sciences, Paris* 326 (IIa), 363–368.
- Rowan, M. G., 1995, Structural styles and evolution of allochthonous salt, central Louisiana outer shelf and upper slope, in M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., *Salt tectonics: A global perspective*: Tulsa, OK, American Association of Petroleum Geologists, Memoir 65, 199–228.
- Rowan, M. G., 2014. Passive-margin salt basins: Hyperextension, evaporite deposition, and salt tectonics: *Basin Research*, 26, 154–182, doi:10.1111/bre.12043.
- Rowan, M. G., Lawton, T. F., Giles, K. A., Ratliff, R. A., 2003, Near salt deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: A general model for passive diapirism: *American Association of Petroleum Geologists Bulletin*, 87, 733–756.
- Schleder, Z., Tamas, D.M., Krezsek, C., Arnberger, K., Tulucan, A., 2019. Salt tectonics in the Bend Zone segment of the Carpathian fold and thrust belt, Romania. *International Journal of Earth Sciences*, 108, 5, 1595–1614.
- Sherkati, S., Letouzey, J., 2004. Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. *Marine and Petroleum Geology*, 21, 5, 535–554.
- Slama, M.-M.B., Masrouhi, A., Ghanmi, M., Youssef, M.B., Zargouni, F., 2009. Albian extrusion evidences of the Triassic salt and clues of the beginning of the Eocene atlasic phase from the example of the Chitana-Ed Djebbs structure (N.Tunisia): implication in the North African Tethyan margin recorded events, comparisons. *Compt. Rendus Geosci.* 341 (7), 547–556.
- Smit, J., Brun, J.-P., Cloetingh, S., Ben-Avraham, Z., 2008. Pull-apart basin formation and development in narrow transform zones with application to the Dead Sea Basin. *Tectonics* 27, (TC6018).

- Shabanian, E., Bellier, O., Abbassi, M.R., Siame, L., Farbod, Y., 2010. Plio-Quaternary stress states in NE Iran: Kopeh Dagh and Allah Dagh-Binalud mountain ranges. *Tectonophysics*, 480, 1-4, 280–304.
- Solignac, M., 1927. Geological Survey of Northern Tunisia [Etude géologique de la Tunisie septentrionale], Dir., Gen., Trav., Pub., carte Geol. De la Tunisie. Thesis Es-Sciences, University of Lyon. 756 p.
- Soumaya, A., Kadri, A., Ben Ayed, N., Kim, Y.-S., Dooley, T.P., Rajabi, M., Braham, A., 2020. Deformation styles related to intraplate strike-slip fault systems of the Saharan-Tunisian Southern Atlas (North Africa): New kinematic models. *Journal of Structural Geology*, 140, 104175.
- Souquet, P., Peybernes, B., Saadi, J., Ben Youssef, M., Ghanmi, M., Zarbout, M., Chikhaoui, M., Kamoun, F., 1997. Séquences et cycles d'ordre 2 en régime extensif et transtensif: exemple du Crétacé inférieur de l'Atlas tunisien. *Bulletin de la Société géologique de France*, 168, 373–386.
- Soussi, M., Mangold, C., Enay, R., Boughdiri, M., Ben Ismail, M.H., 2000. The Lower and Middle Jurassic of Northern Tunisia; correlations with the North-South axis and palaeogeography. *Geobios*, 33, 4, 437–446.
- Soussi, M., Niedźwiedzki, G., Tałanda, M., Drózd, D., Sulej, T., Boukhalfa, K., Mermer, J., Błażejowski, B., 2017. Middle Triassic (Anisian-Ladinian) Tejra red beds and Late Triassic (Carnian) carbonate sedimentary records of southern Tunisia Saharan Platform: biostratigraphy, sedimentology and implication on regional stratigraphic correlations. *Marine and Petroleum Geology*, 79, 222–256.
- Stampfli, G. M., Borel G. D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. *Earth and Planetary Science Letters*, 196, 17-33.
- Stampfli, G. M., Borel, G. D., Marchant, R., Mosar, J., 2002. Western Alps geological constraints on western Tethyan reconstructions. In: Rosenbaum, G. and Lister, G. S. 2002. Reconstruction of the evolution of the Alpine-Himalayan Orogen. *Journal of the Virtual Explorer*, 7, 75–104.
- Stovba, S.M., Stephenson, R.A., 1999. The Donbas Fold belt: its relationships with the uninverted Donets segment of the Dniepr–Donets Basin, Ukraine, *Tectonophysics*, 313, 59–83.
- Talbot, C. J., Alavi, M., 1996, The past of a future syntaxis across the Zagros, in G. I. Alsop, D. J. Blundell, and I. Davison, eds., *Salt tectonics*: London, Geological Society, Special Publication 100, 89–110.
- Tari, G., Jabour, H., 2013. Salt tectonics along the Atlantic margin of Morocco, in W. U. Mohriak, A. Danforth, P. J. Post, D. E. Brown, G. C. Tari, M. Nemčok, and S. T. Sinha, eds., *Conjugate divergent margins*: London, Geological Society, Special Publication 369, 337–353, doi:10.1144/SP369.23.
- Teofilo, G., Festa, V., Sabato, L., Spalluto, L., Tropeano, M., 2016. 3D modelling of the Tremiti salt diapir in the Gargano offshore (Adriatic Sea, southern Italy): Constraints on the Tremiti Structure development *Italian Journal of Geosciences*, 135 (3), 474–485.

- Tranos, M.D., 2017. The use of Stress Tensor Discriminator Faults in separating heterogeneous fault-slip data with best-fit stress inversion methods. *J. Struct. Geol.* 102, 168–178.
- Trocmé, V., Albouy, E., Callot, J.-P., Letouzey, J., Rolland, N., Goodarzi, H., Jahani, S., 2011. 3D structural modelling of the southern Zagros fold-and-thrust belt diapiric province. *Geological Magazine*, 148, 5-6, 879–900.
- Troudi, H., Tari, G., Alouani, W., Cantarella, G., 2017. Styles of Salt Tectonics in Central Tunisia: An Overview. In *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, ed. Juan I. Soto Joan Flinch Gabor Tari, 543–561.
- Vendeville, B. C., Jackson, M. P. A., 1992. The rise of diapirs during thin-skinned extension: *Marine and Petroleum Geology*, 9, 331–353.
- Vergés, J., Moragas, M., Martín-Martín, J.D., Saura, E., Casciello, E., Razin, Ph., Grelaud, C., Malaval, M., Joussame, R. Messenger, G. Sharp, I. Hunt, D.W., 2017. Salt Tectonics in the Atlas Mountains of Morocco. *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, ed. Juan I. Soto Joan Flinch Gabor Tari, 563–579.
- Vila, J.M., Ben Youssef, M., Chikhaoui, M., Ghanmi, M., 1996. Un grand “glacier de sel” sous-marin albien du Nord-Ouest tunisien (250 km² ?): le matériel salifère triasique du “diapir” de Ben Gasseur et de l’anticlinal d’El Kef. *C. R. Acad. Sci.Paris* 322, 221–227.
- Vila, J.M., Ghanmi, M., Ben Youssef, M., Jouirou, M., 2002. Les “glaciers de sel” sous-marins des marges continentales passives du nord-est du Maghreb (Algérie–Tunisie) et de la Gulf Coast (USA): comparaisons, nouveau regard sur les “glaciers de sel” composites, illustre par celui de Fedj el Adoum (Nord-Ouest tunisien) et revue globale. *Eclogae Geol. Helv.* 95, 347–380.
- Vila, J.M., Sigal, J., Coiffait, P.E., Lahondère, J.C., Quinif, Y., 1975. Sur l’allochtonie du Tell sétifien: La fenêtre de la Koudiat Touachra et la nappe de Djemila. *Bull. Soc. Geol. Fr.* 17, 1173–1175.
- Wilcox, R. E., Harding, T. P., Seely, D. R., 1973. Basic wrench tectonics, *American Association of Petroleum Geologists*, 57, 74–96.
- Wischer, S., Mohriak, W., 2020. Halokinetic analysis of the Frade field area, Campos basin, Brazil. *Interpretation*, 8, 4, 1–62.
- Woodcock, N., 1986. The role of strike-slip fault systems at plate boundaries, *philosophical transactions of Royal Society of London*, A317, 13–29.
- Woodcock, N., Schubert, C., 1994. Continental strike-slip tectonics. In: Hancock, P. (Ed.), *Continental deformation*. Pergamon Press, New York, pp. 251–263.
- Wu, J. E., McClay, K. Whitehouse, P. and Dooley, T., 2009. 4D analogue modelling of transtensional pull-apart basins: *Marine and Petroleum Geology*, 26, 1608–1623.
- Zouaghi, T., Bédir, M., Ayed-Khaled, A., Lazzez, M., Soua, M., Amri, A., Inoubli, M.H., 2013. Autochthonous versus allochthonous upper triassic evaporites in the sbiba graben, central Tunisia. *Journal of Structural Geology*, 52, 1, 163–182.

Zouaghi, T., Bédir, M., Inoubli, M.H., 2005. 2D seismic interpretation of strike-slip faulting, salt tectonics, and Cretaceous unconformities, Atlas Mountains, central Tunisia. *Journal of African Earth Sciences*, 43, 4, 464–486.

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Figure captions

Figure 1: [a] Simplified structural map of Northwestern African domain, [b] distribution of salt outcrops along the Northeastern Maghreb Salt Province, [c] Simplified structural map of the northern Tunisian Atlasic domain showing the main fault systems and location of the study area (rectangle): 1- The Numidian Allochthonous units which are formed by southeastward-vergent Numidian flysch during the Alpine orogeny, 2- the Teboursouk thrust unit which is a major southeastward-vergent thrust, 3- The Zaghouan-Ressass unit which marks the southern limit of the Alpine range in Tunisia, 4- the Atlasic Eastern foreland.

Figure 2: Satellite image of El Aouinet-Ez Zebaz restraining stepover showing a NE-trending sigmoidal-shaped structure at the overlap zone between E-W trending main faults (thick dashed white lines) in the north and south. Thin white lines are the cores of the main fold structures. The white box corresponds to the boundaries of the detailed geological map of Fig. 4.

Figure 3: Simplified lithostratigraphic column of the northern Tunisian Atlasic domain. Salt tectonics events and evolution of salt structures, and the major Mesozoic-Cenozoic tectonic.

Figure 4: Detailed geologic map of the AOZE and surrounding areas showing the main structural features and location of four sections shown in Figure 6. 1- Triassic, 2- Barremian, 3- Aptian, 4- Upper Aptian–Albian, 5- Cenomanian–Turonian, 6- Coniacian–Santonian, 7- Campanian–Maastrichtian, 8- Upper Maastrichtian–Paleocene, 9- Lower Eocene, 10- middle to upper Eocene, 11- Oligocene, 12- layering trace, 13- bedding, 14- Faults (a-observed, b- inferred), 15- cross-section.

Figure 5: Field panoramic view (a- original photo, b- interpreted) showing the AOZE structure and the general distribution of the outcropping lithologies. The viewer is standing on the BEASS diapir looking NNE-ward where lower cretaceous units are outcropping in the core of the anticline. The two limbs of the anticline are manifested by Upper Cretaceous and Tertiary series.

Figure 6: a- key Lithostratigraphic support for cross-sections. b- Cross-sections across the AOZE constructed from surface data and stratigraphic relationships. From north to south, these sections show the style of the BEASS structure (see Fig. 4 for location). In the cross-sections, data is presented with thickness exaggeration of salt of the northern allochthonous salt sheet (which have a thickness of few meters in the field) to highlight its position and the link between the main diapir and the allochthonous salt. Red boxes: location of field photos.

Figure 7: Field photos and their location on the geological map. a- Original and b-interpreted photograph of the core of AOZE with upper Barremian sequences showing a spectacular anticline closure. [c] The eastern limb of the AOZE showing continuous cretaceous series with an interbedded Triassic salt sheet. d- original and e- interpreted photograph of the eastern BEASS salt sheet which is 5 km long and 2-to 2.5 m wide salt mass extruded likely from the diapir stem during upper Aptian.

Figure 8: Field photos of Triassic evaporites distribution inside the AOZE restraining bend. [a] An approximately northeast view showing the connection of northern salt sheet to the main diapiric body (BEASS). Field photos of the interbedded position of the salt sheet in (b) the western limb and (c) the Eastern limb of the anticline.

Figure 9: Field photos of tectono-sedimentary features associated to the evolution of BEASS. a and b, Irregular sedimentation highlighted by abundant slump folds; testifying an irregular sea floor on which salt sheet flowed northward. [c, d] Photograph looking north showing two pre-inversion Mesozoic sinistral strike-slip faults preserved in AOZE.

Figure 10. Fields photographs of the structures within AOZE. [a, b] An example of frequent dextral strike-slip faults. [c] Steep fault surface showing subhorizontal striation (white lines) and steps indicating sinistral movement. [d] Steep fault surface showing more than one generation of striae (numbered white lines) indicating polyphase kinematics. Cross-cutting relationship between striation is used to fault data separation performed during this study (see Fig. 14 for more details).

Figure 11. apparent strike-slip fault (a- original photo, b- interpreted), which were initially normal faults, displacing gently dipping layers. [c] Calcareous nodules (red arrows) in the lower Cretaceous sequences genetically related to an irregular sea floor. [d] Panoramic view looking East of the southeastern corner of AOZE present-day pop-up showing an imbricate system of thrusts.

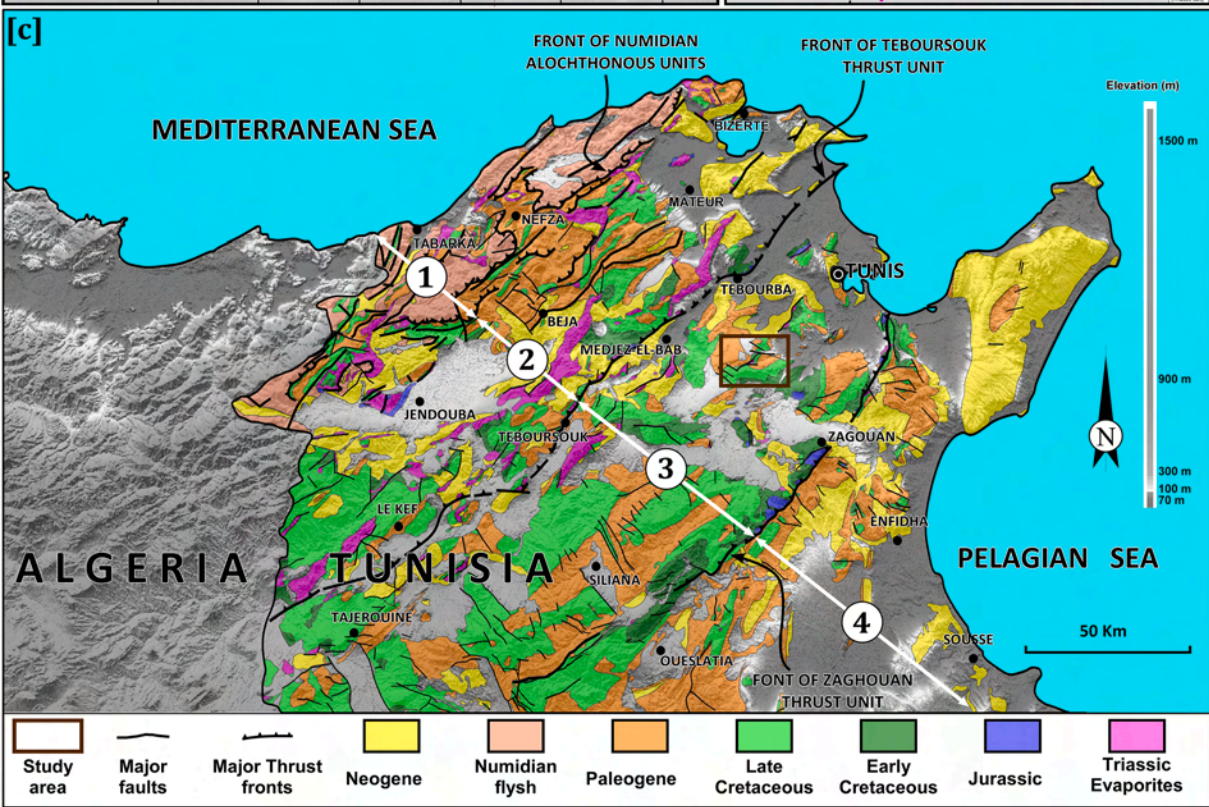
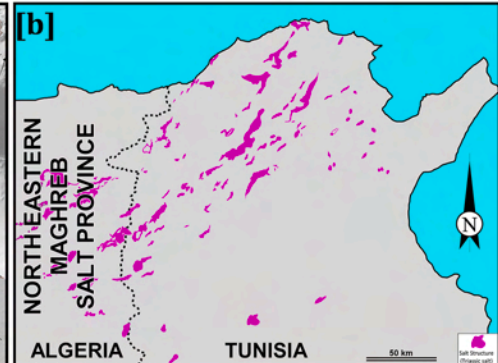
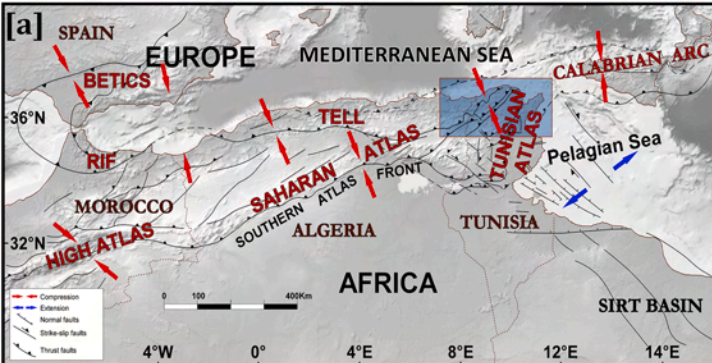
Figure 12: Salt sheet with asymmetric micro-folding showing dominant North-facing transport verging. Arrows indicate the micro-folds vergences. values on the arrows indicate the trends in three digits of the micro-folds vergence (perpendicular to the axial planes).

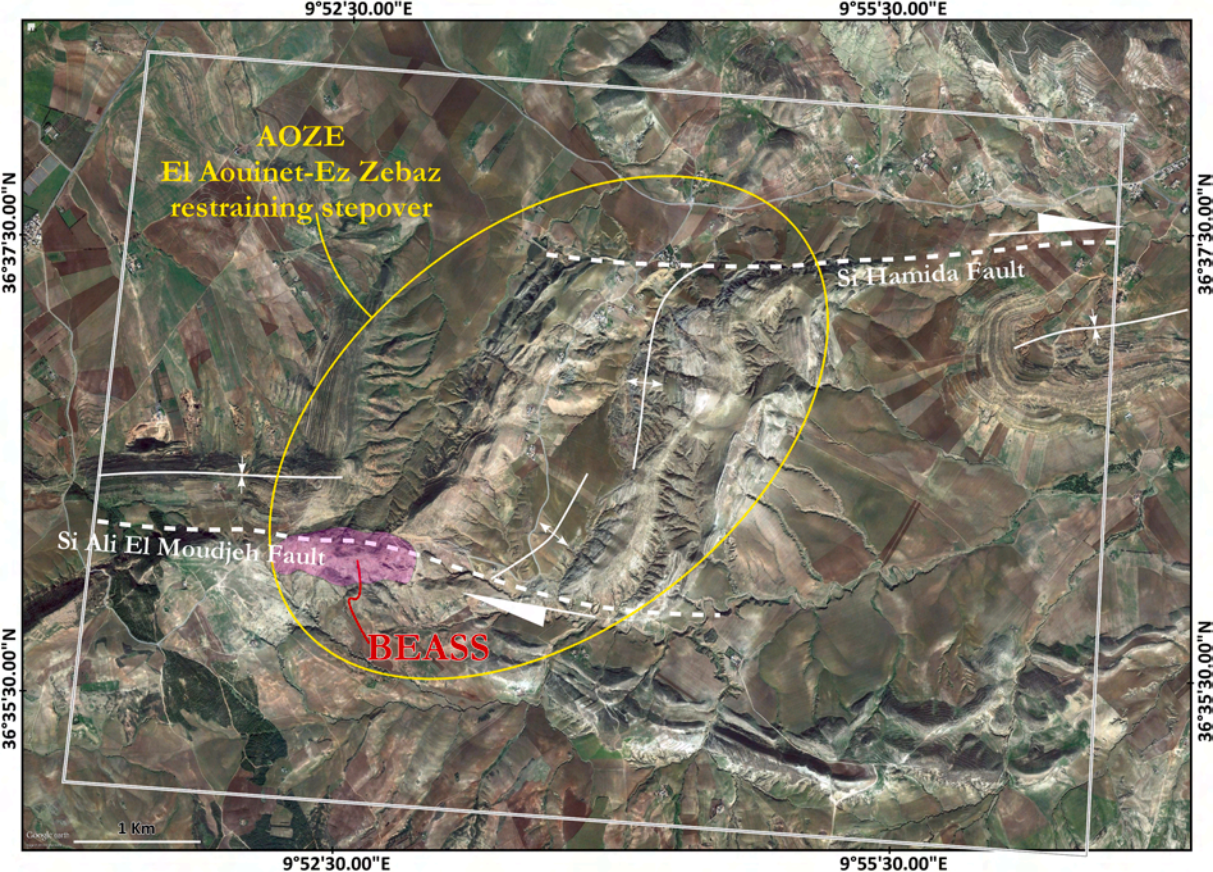
Figure 13: Lower hemisphere projection of fault data sets (without separation) showing the paleostress regime in AOZE. Data are computed using the win-tensor program (Delvaux, 2020).

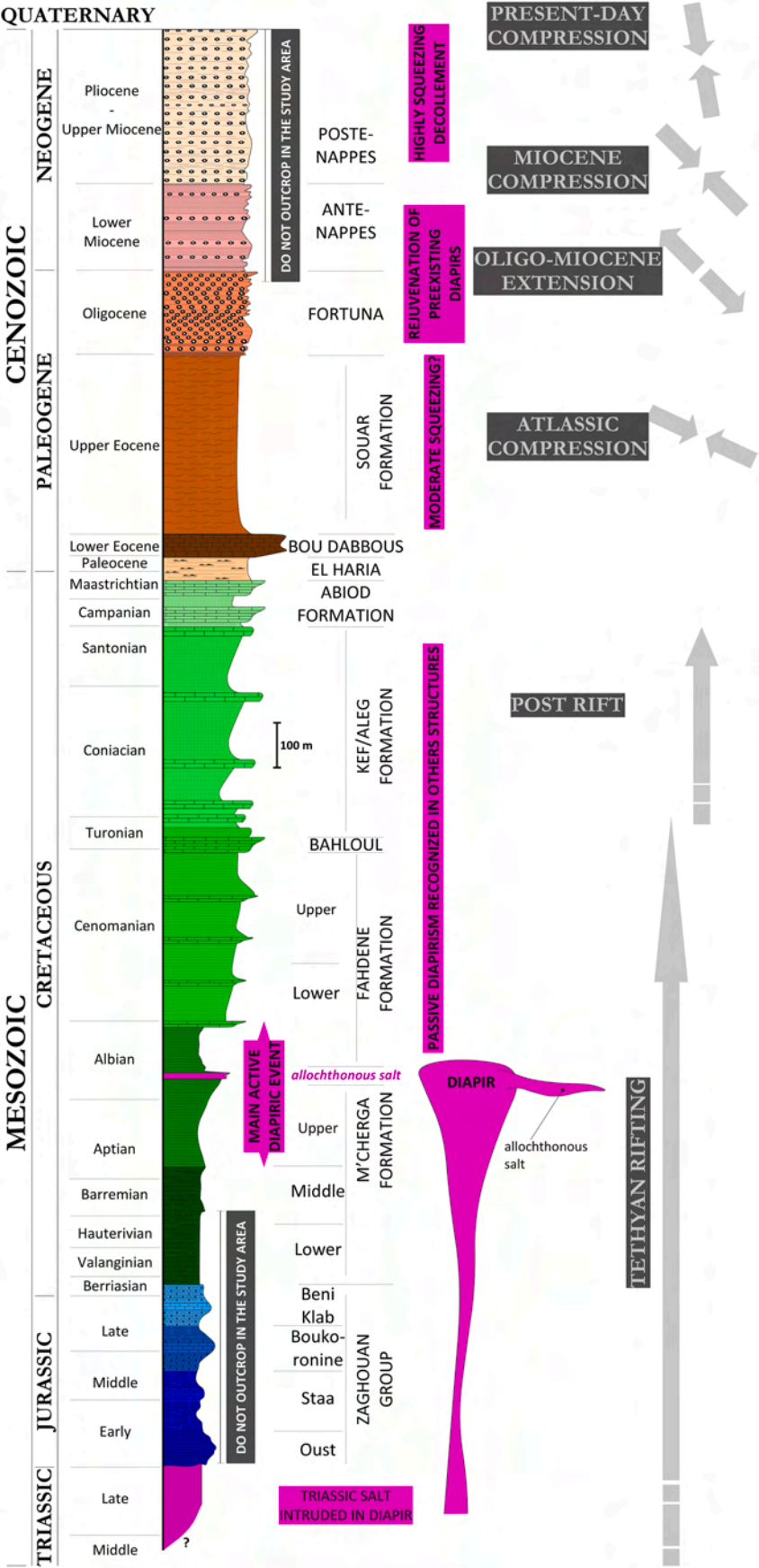
Figure 14: Results of fault slip data inversion of separated and back-tilted major fault sets showing the local and regional paleostress regime in AOZE.

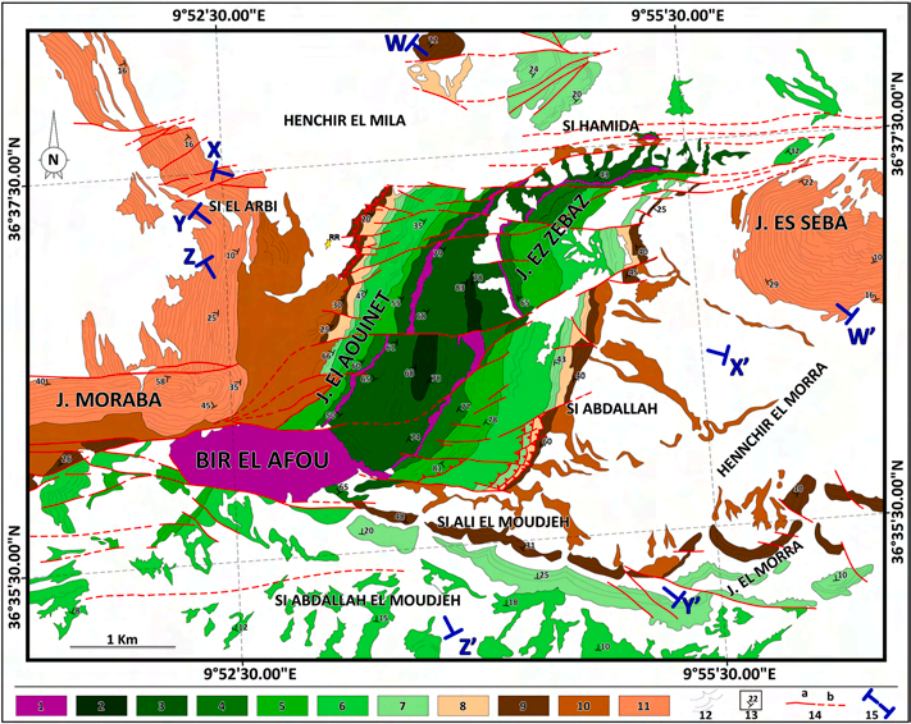
Figure 15: Gravity anomaly map of the Bir-El-Afou Area. Data is from the National Office of Mine of Tunisia (Bouguer map of Bir M'cherga sheet 1: 50000 n°18). The data are of *Gravimétrie en Tunisie-CG5 by Sagax Maghreb S.A*, carte Bir M'Cherga au 1/50000 – plan 50-41. [a] Complete Bouguer Gravity anomaly map, [b] Complete Bouguer Gravity anomaly map superimposed on the satellite image of the area. Major fold trends are indicated with white lines, [c] Major faults outlined on the complete Bouguer Gravity anomaly map, [d] Complete Bouguer Gravity anomaly map superimposed on the geologic map.

Figure 16: a-lower Cretaceous AOZE releasing area, b- Tertiary AOZE restraining area. a-1 – Lower Cretaceous with NW-trending regional extensional tectonic regime, a-2 – summary without salt of sinistral transtensional tectonic regime creating the pull-apart with diapiric salt extrusion in the corner and extruded salt sheet. a-3 – schematic block diagram of the initial pull-apart basin showing salt extrusion in Early Cretaceous. b-1 – Late Tertiary NNW-trending regional shortening with E-trending right lateral strike-slip main faults. b-2 – summary without salt of dextral transpressional tectonic regime creating the pop-up. b-3 – schematic block diagram of the present-day AOZE restraining area with squeezed diapir and folded allochthonous salt sheets.





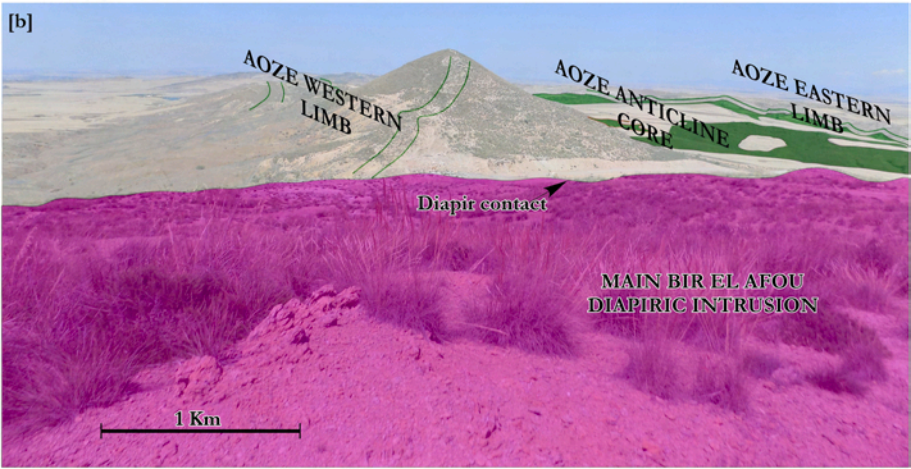


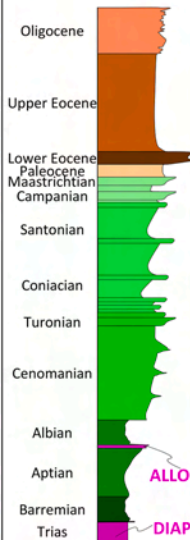
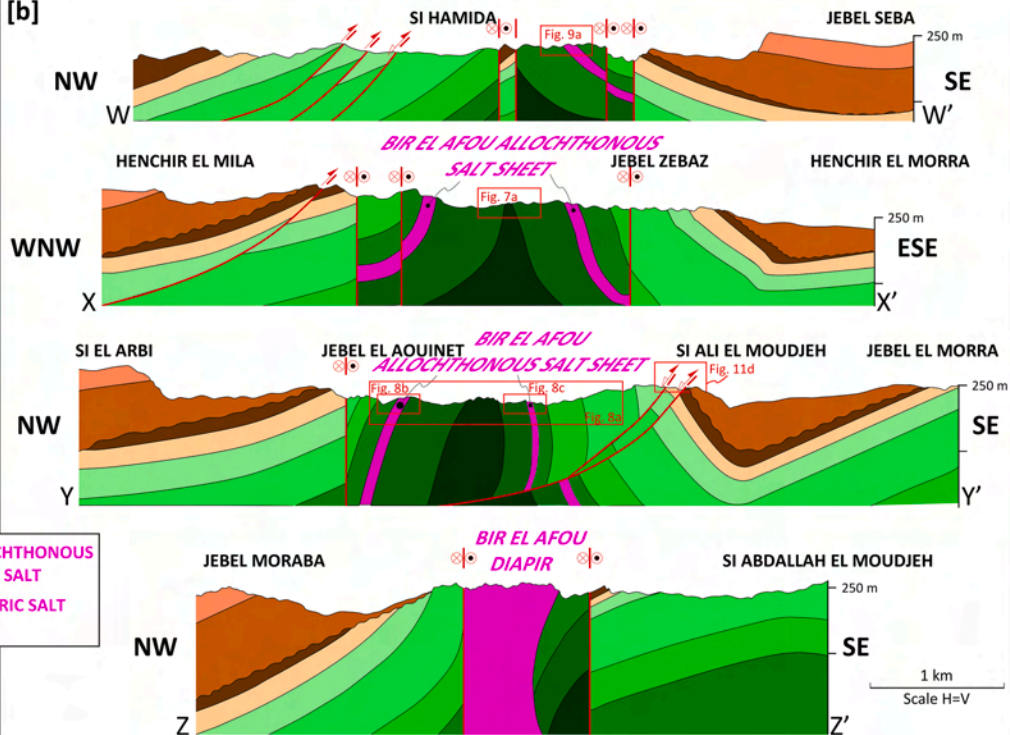


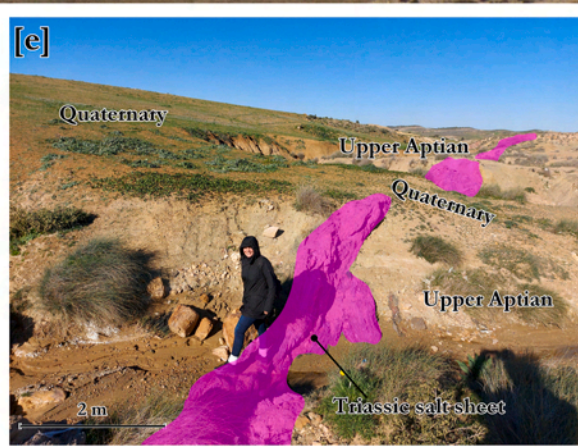
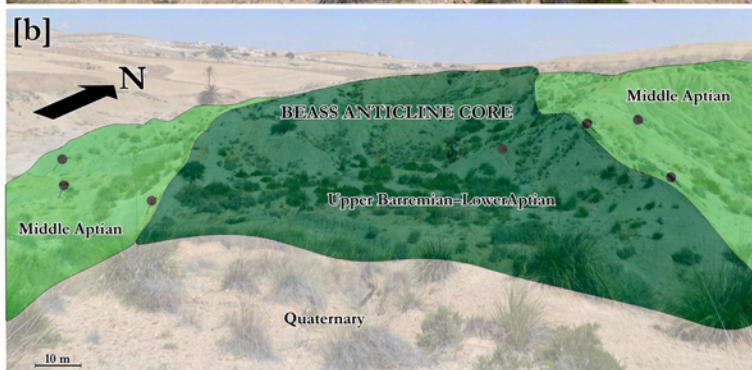
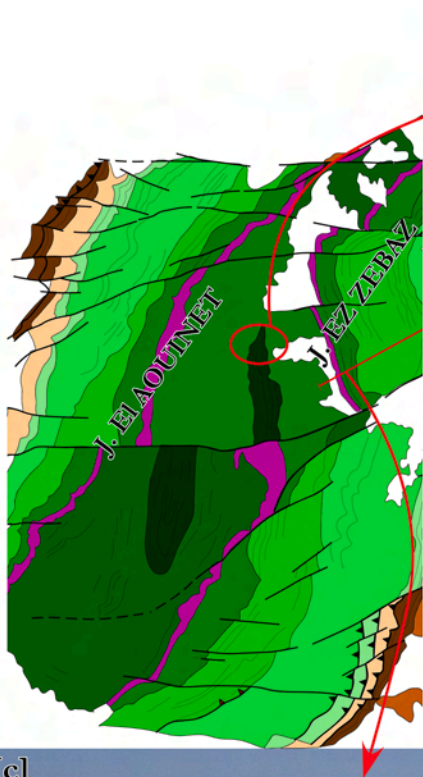
[a]



[b]



[a]**[b]**



[a]

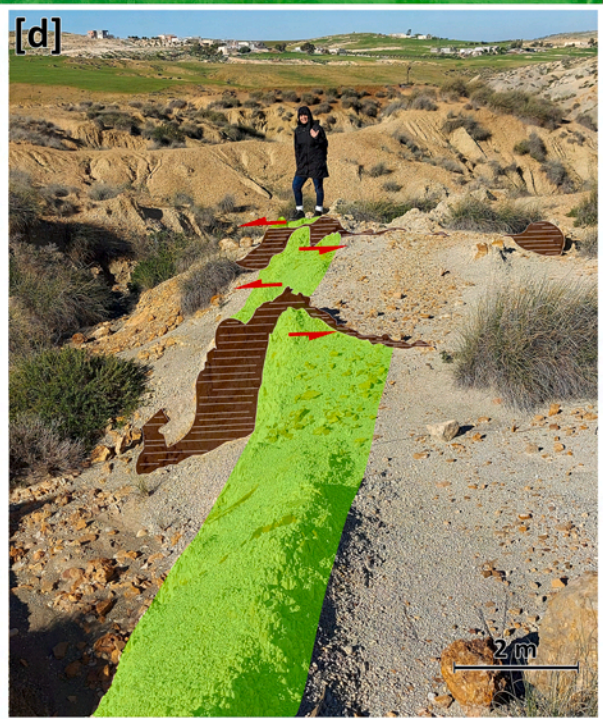


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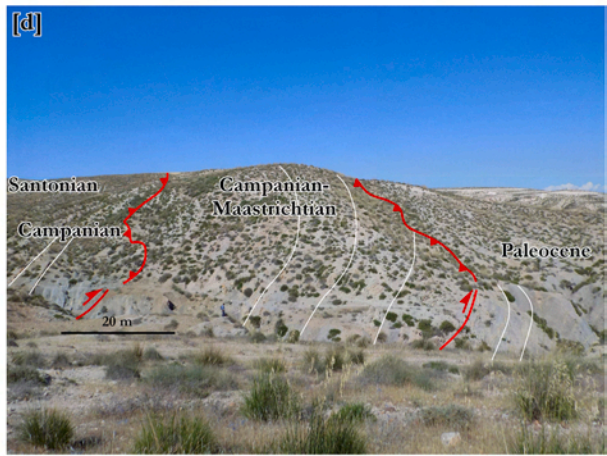
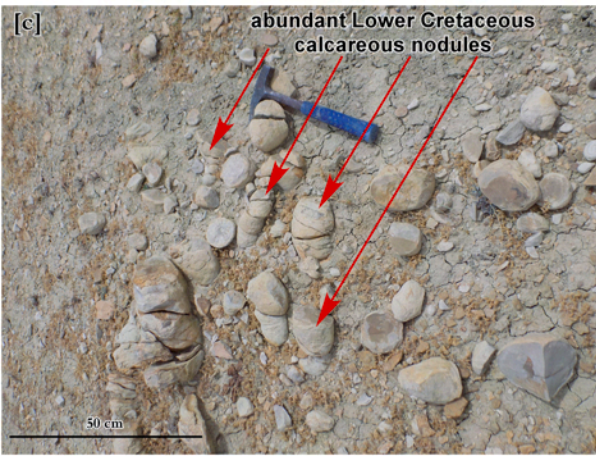
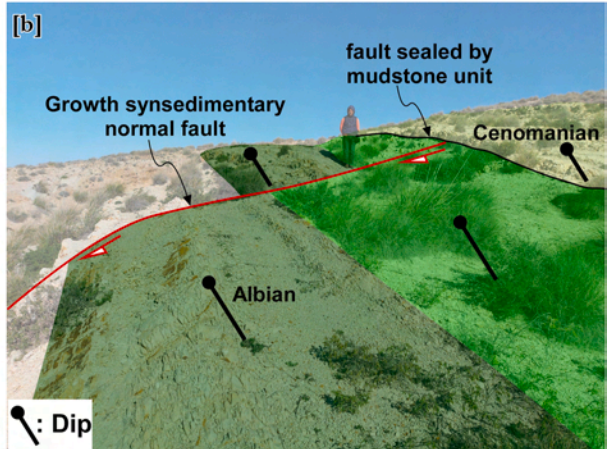


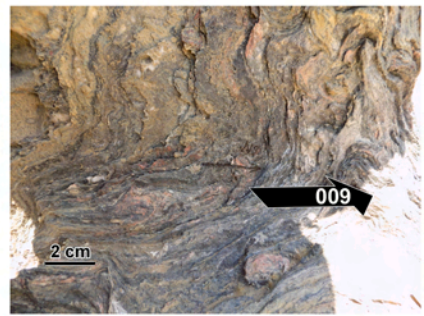
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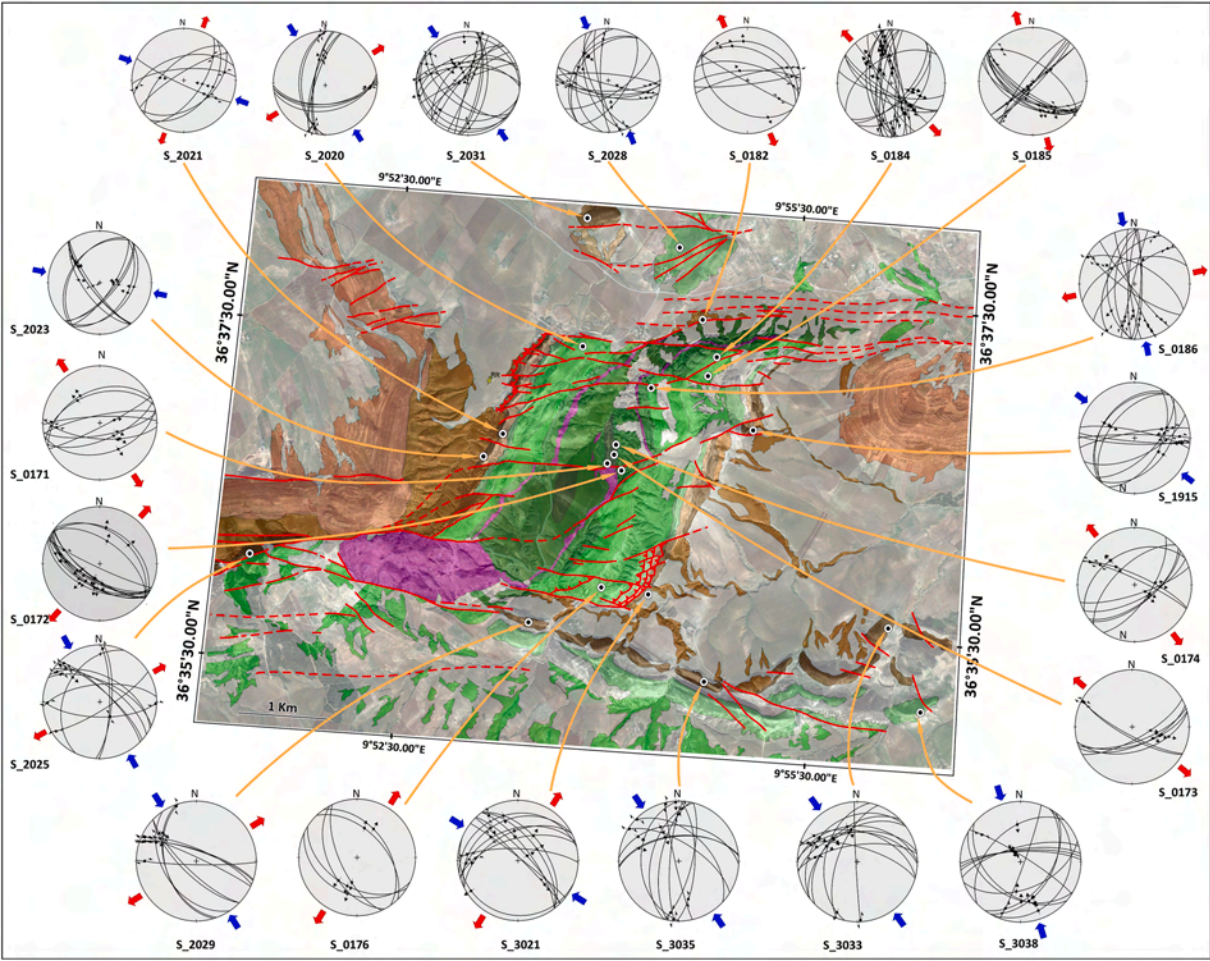


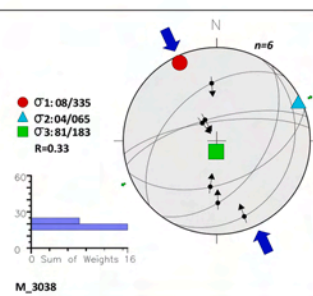
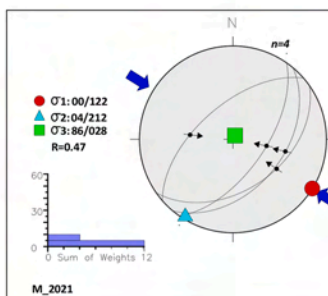
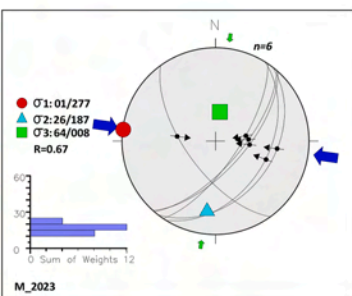
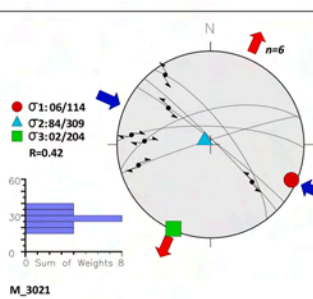
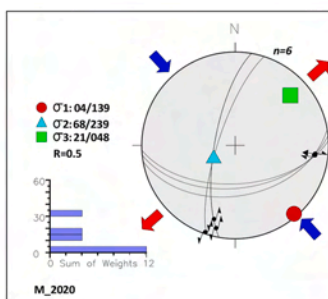
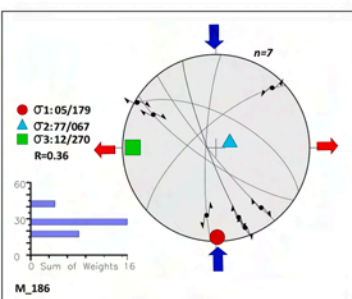
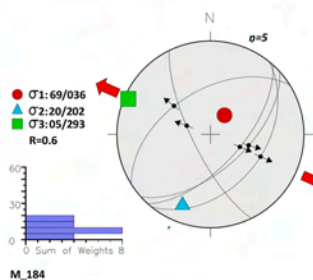
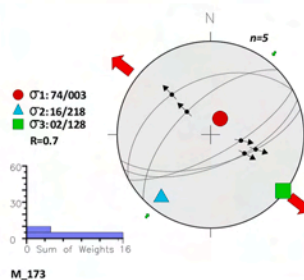
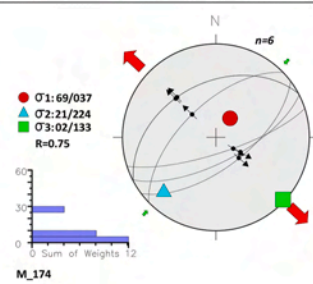
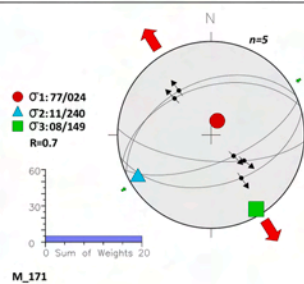
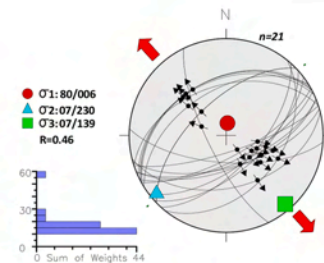


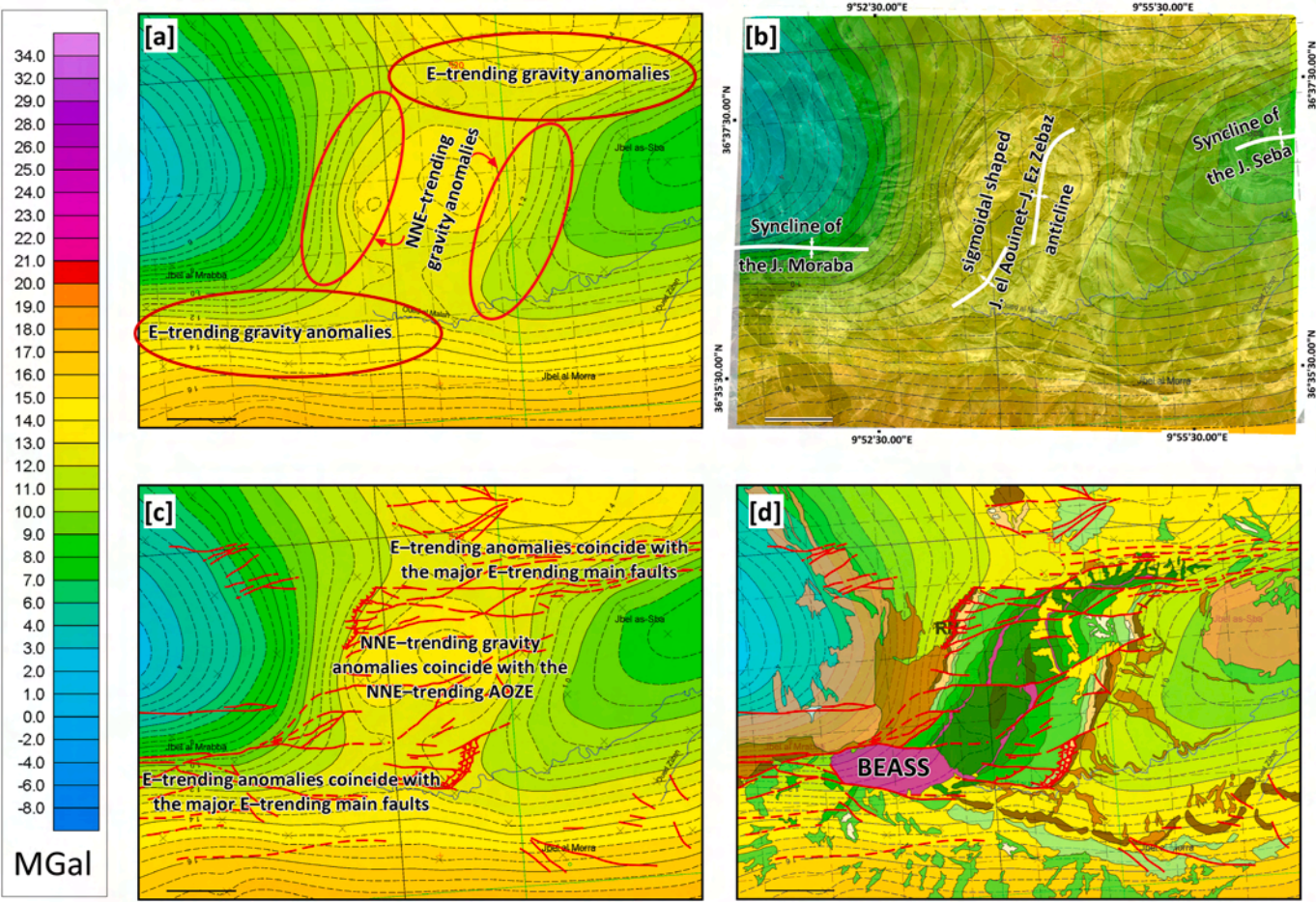


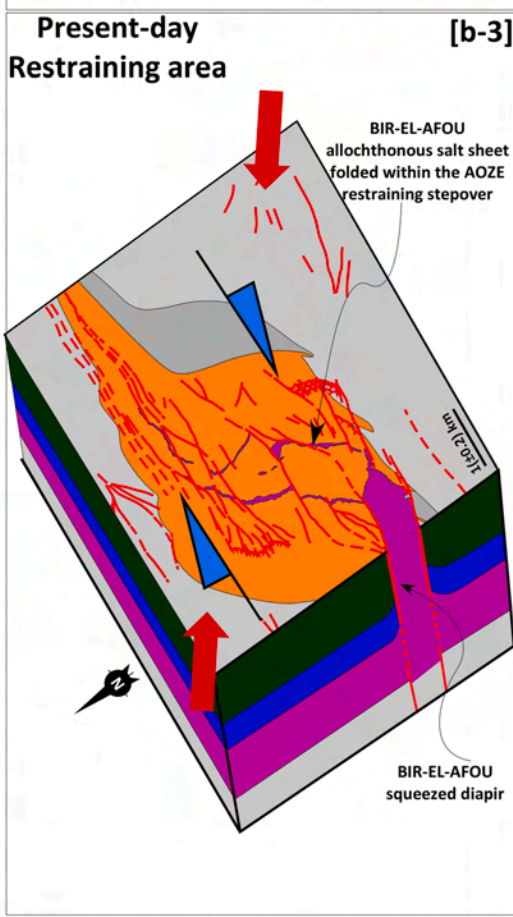
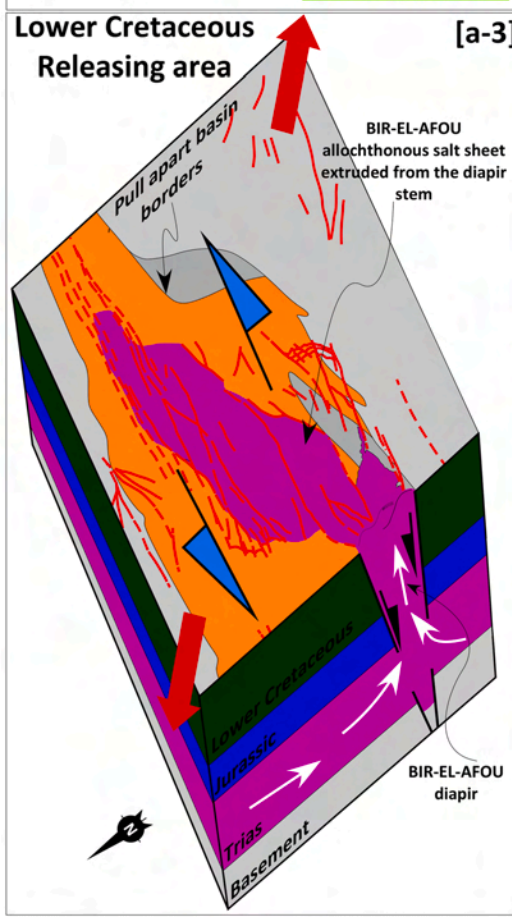
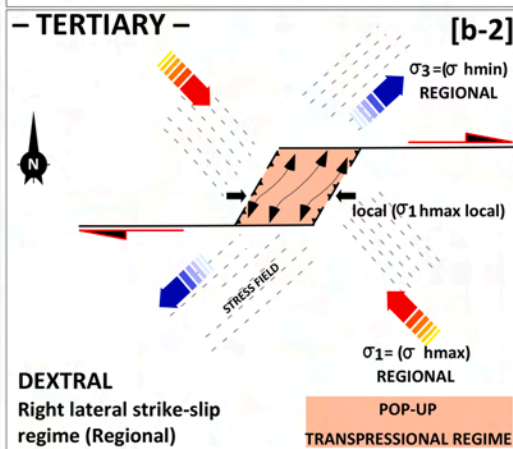
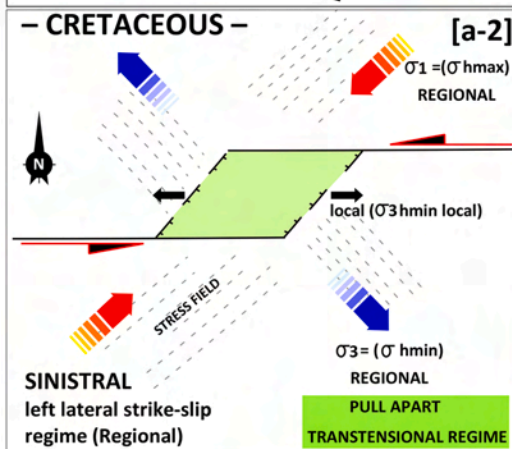
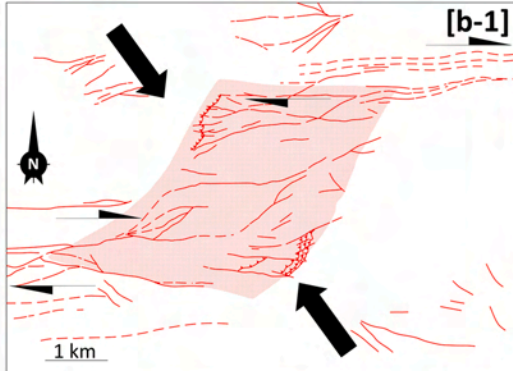
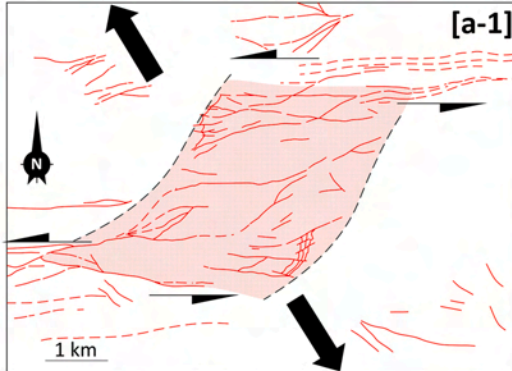












Mechanical relationship between strike-slip faulting and salt tectonics in the Northern Tunisian Atlas: the Bir-El-Afou salt structure

Highlights

- Salt diapir, associated with releasing stepover in response to strike-slip tectonics, is examined
- During the opening of the pull-apart, salt diapir took place in the corner of the basin
- 5-km-long salt sheet is formed as a result of salt extrusion from the diapir toward the basin
- The present-day squeezed diapir in a restraining stepover, is the result of the pull-part basin inversion

Mechanical relationship between strike-slip faulting and salt tectonics in the Northern Tunisian Atlas: the Bir-El-Afou salt structure

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conflict of interest

The Authors declare that there is no conflict of interest.