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Review of the deformation styles during the Cretaceous Tethyan period: inferred from slumps and fault Kinematics analysis along Northern Tunisia

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Abstract:

In northern Tunisia, the Cretaceous period is described as a spectacular episode of soft-sediment deformations exposed for several kilometers. These gravity-driven deformations are interpreted to be associated with the Tethyan passive margin rifting. Slump folds and fault kinematics are analyzed in order to characterize the structural style of Northern Tunisia basin' during the Cretaceous Tethyan period. As a result, Early Cretaceous sedimentation reflects a syn-rift stage mainly underlined by major basement faulting systems combined with other intra-basin growth normal faults. These faults are tilted northward creating a paleoslope (estimated here to be $\pm 3^\circ$) associated to abundant soft-sediment deformations. Major faults (probably listric) split the study area into various tectonic blocs. Meanwhile, the post-rift Coniacian-Maastrichtian rich-marly deposits seal all the inherited differentiations and were presumably driven by the isostatic response of various inherited major faults. Based on fault kinematic analysis, compressional events were not observed during the whole Cretaceous and the sedimentation mainly occurred under extensional tectonics during this period. Halokinetic movements and salt rise-up are active on the extensional structures essentially during the Mid-Cretaceous period allowing the creation of abundant large depocenters with numerous soft-sediment deformations. Thus, the Tunisian margin is described as an evaporite floored margin where significant part of the Mesozoic sedimentary cover underwent frequent gliding and spreading above the Triassic evaporite detachment layers, as described in several Atlantic-type passive margins. During the Cenozoic shortening, a fault inversion model is mainly accepted for the development of different thrust systems. Thus, a clear field relationship between various inherited structural entities and the present-day geographical repartition of faults and folds belts involves the role of the tectonic inheritance in style and the evolution of the northern Tunisia belt.

Keywords: Soft-sediment deformations, Paleoslope, Inherited faults, Cretaceous Tethyan rifting, Passive margin, Northern Tunisia.

1. Introduction:

The orogeny of the present-day belt of northern Tunisia is mainly derived from the polyphase geodynamic evolutionary history of the south Tethyan rifted passive margin realm (Bouaziz et al. 2002; Guiraud et al. 2005; De Lamotte et al. 2009; Khomsi et al. 2009; Khelil et al. 2021a; Naji et al. 2022b). The rift stage, which initiated approximately during the Late Permian to Early Triassic, is accelerated at the Triassic-Jurassic transition and continued during the Jurassic and Cretaceous by the passive margin basin's framework (Masrouhi and Koyi 2012; Tlig. 2015; Martín-Martín et al. 2017; Moragas et al. 2017; Naji et al. 2022b). During the Mesozoic Tethyan rifting, north Africa's margin was dominated by extensional tectonics, crustal stretching and thinning, accompanied by a high subsidence rate (Bouaziz et al. 2002; Boughdiri et al. 2007; Masrouhi and Koyi 2012; Gharbi et al. 2013; Soua 2015; El Amari et al. 2016; Soussi et al. 2017; Bejaoui et al. 2017; Jaillard et al. 2017; Naji et al. 2018a, 2022a, b; Khelil et al. 2021a, b). After this long extensional Tethyan period, a positive basin inversion was operated during the Late Cretaceous (Guiraud and Bosworth 1997; Dlala et al. 2002; Mabrouk et al. 2005; Masrouhi et al. 2008; Bey et al. 2012; Bejaoui et al. 2017; khelil et et al. 2021a). Within active and passive margin patterns, the main driving agent for triggering soft-sediment deformations is recognized to be the gravity-driven forces over an inclined submarine basin floor (Woodcock 1979; Mills 1983; Khafizov and Syngaevsky 2005; Shanmugam 2006a; Strachan and Alsop 2006; Owen and Moretti 2008; Alsop and Marco 2014; Kukla et al. 2018; Li et al. 2019; Rodrigues et al. 2021; Warsitzka et al. 2021). Moreover, mass transport deposits have been reported in seismic and outcrop studies in recent years (Færseth and Sætersmoen 2008; Posamentier and Martinsen 2011; Sharman et al. 2015; Basilone et al. 2016c). Likewise, the Cretaceous period, part of the Tethyan rifting (Soua 2012; Bey et al. 2012; Masrouhi et al. 2014b; Jaillard et al. 2017; Naji et al. 2018a, 2022a, b; Amami et al. 2021), is depicted in Tunisia as a spectacular episode of gravity-driven deposits. Slumping is perceived as the most common feature of soft-sediment deformations along the study area. Commonly, slump features are usually triggered by the gravity effect following the slope failure occurrence (Owen and Moretti 2008). Slump folds are qualified as deformational cells induced by the downslope motion of sediments that maintain their own cohesion on the scale of layering (Elliot and Williams 1988). Various mechanisms, including seismicity, may cause localized augmentations in pore fluid pressure and trigger slumping (Alsop and Marco 2011, 2012; Alsop and Weinberger 2020; Rodrigues et al. 2021). Several studies, which focused on soft-sediment slumping describe them as gravity-driven deformations that consistently infer slope orientation. Based on the pioneering relationship between slope attitude and slump folds distribution,

multiple techniques have been described by geoscientists (e.g. Hansen 1965, 1967; Woodcock 1979; Allen 1982; Mills 1983; Maltman 1984; Bradley and Hanson 1998; Alsop et al. 2001; Strachan and Alsop 2006; Strachan 2008; Debacker and Meester 2009; Alsop and Marco 2011, 2012, 2013, 2014; Debacker 2012; Yong et al. 2013; Sharman et al. 2015; Alsop and Weinberger 2020; Rodrigues et al. 2021). Therefore, slump folds analysis yields interesting conclusions about the structural and paleogeographic configurations of the study area (Woodcock 1979; Bradley and Hanson 1998; Strachan and Alsop 2006; Strachan 2008; Debacker and Meester 2009; Alsop and Marco 2011, 2012, 2013, 2014; Debacker 2012; Sharman et al. 2015; Alsop and Weinberger 2020; Rodrigues et al. 2021).

Accordingly, this study focuses on the tectono-sedimentary pattern of the northern Tunisia basin during the Cretaceous period. In order to bring back the Cretaceous basin paleogeography of the northern Tunisia Atlas, this work is based on the analysis of slump folds, which are well preserved for several kilometers across the study area associated with fault kinematics analysis. Therefore, this study added to the existing knowledge on the Tunisian margin evolution based on new datasets inferred from soft sediment deformation analysis.

2. Geological setting:

Tunisia pertains to the southern edge of the Tethyan paleomargin realm. It displays a complicated structural pattern due to the multiphase Tethyan margin's tectonic evolution. The structural history of the Northern African margin started with the rifting triggered by the breakup of Pangea operating since the Late Permian and followed by the Alpine orogenesis belt that prevailed during Cenozoic. This study focused on the northeastern part of the Atlas fold and thrust belt, which extends around over 2000 kilometers from the western Atlantic coasts of Morocco to the eastern Mediterranean coasts of Tunisia (Fig 1.a). The Atlas is the result of the African and Eurasian plate's collision, occurred during the Cenozoic Era. To the south, the Tunisia Atlas system is bounded by the African Saharan platform, which is not affected by Tertiary tectonic inversions. While, to the north, it is bounded by the Tellian domain, mainly, set up during the Middle to Late Miocene (Fig 1.b). The northern Atlas of Tunisia is characterized by two major NE-trending thrust systems: the Teboursouk and the Zaghouan-Ressas thrust unit fronts (Fig 1.b). These thrust systems resulted from the positive inversion of the Mesozoic extensional structures inherited from the earlier passive margin basin' configuration (e.g. Khomsi et al. 2009; Masrouhi et al. 2013; Jaillard et al. 2017; Naji et al. 2018a, b, 2022a, b; Masrouhi et al. 2019; Amri et al. 2020).

3. Synthesis of the Cretaceous lithostratigraphy of Northern Tunisia:

The Early Cretaceous Jebel Oust section, situated some kilometers to the North of Zaghouan (Fig 2.a), is described as a reference-type section along northern Tunisia (Ben Ferjani et al. 1990; Souquet et al. 1997;

Naji et al. 2018a, b, 2022b). This section exposed more than 2500 m of siliciclastic, carbonate and marly deposits. According to other studies (e.g. Masrouhi et al. 2013; Naji et al. 2018b; Melliti et al. 2019), a potential lithostratigraphic equivalent to this section is found in Jebel Boulahouadjeb, situated 50 km to the North of Jebel Oust anticline (Fig 2.a). Likewise, this locality exposes more than 1700 m-thick fossiliferous Early Cretaceous deposits. On the basis of several previous studies made along these sections (e.g. Ben Ferjani et al. 1990; Souquet et al. 1997; Masrouhi et al. 2013; Naji et al. 2018a, b; Melliti et al. 2019), a representative synthetic section of the Early Cretaceous was established. It is mainly composed of mixed deposits (Fig 2.b). In details, it starts with greenish muds associated with thin-bedded sandstone and siltstone, which are attributed to the Berriasian age. These sequences consistently include mud-flow and debris-flow associated to the top with carbonate-marls-dominated strata. Above, rest a large-thick pelitic unit consisting of turbidites marked by thin-bedded siliciclastic layers associated with slumped quartzites horizons and occasionally sliding blocks of various sizes (from centimeteric to metric scale blocks) corresponding to Valanginian deposits. The uppermost part of this unit is usually dominated by limestone–schistose marls alternations. This unit is largely surmounted by rich pyritic ammonite mudstones, which indicate the Lower Hauterivian, followed by aggrading mudstone-marls parasequences. On top, a lithostratigraphic unit includes marls succession with siliciclastic and carbonate tempestites and indicates to Late Hauterivian age. The Barremian series are composed of slumped sandstone beds and siliciclastic tempestites, surmounted by thick rich-ammonite nodular limestone bars followed by siliciclastic storm, which are topped by black-shale horizon. This unit is attributed to the Early Barremian age. The top of these sequences shows limestone-marls alternations, which reveal the Late Barremian age. The Aptian deposits are mainly marked by offshore nodular muds alternated with rich-belemnite schistose marls. Locally, these series include siliciclastic turbidites.

Accordingly, a synthetic lithostratigraphic section of Late Cretaceous (Fig 2.b) is established on the basis of several studies made along Jebel Rihane and Jebel Kechtilou, situated near the Bou Arada region (e.g. El Ouardi 1996; Masrouhi et al. 2013; Naji et al., 2018a, 2020). Late Cretaceous deposits are thick, well exposed and fossiliferous in these localities. This section shows that following the Aptian time, the sandstone deposition is very restricted in space, and the sedimentation becomes to be more uniform with homogenized facies commonly consisting of marl and fine-grained limestone beds. Albian deposits start with gray platy limestone beds with ammonites alternated with green marl, covered by dark gray marl interbedded by gray marly limestone. The top of this unit shows decametric bars made of platy limestones (a reference bar) usually attributed to the Uppermost Albian. The Cenomanian series show nodular limestone-marl alternations, covered by the platy organic-rich limestones beds of the Bahloul formation,

attributed to the uppermost Cenomanian–early Turonian. Above, rest thick sequences of monotone marl-limestone alternations surmounted by metric Inocerames-rich limestone strata, which indicate Coniacian deposition. The Santonian series are composed of large gray flaky marls with rare centimetric limestone beds followed by gray marls with white to gray clayey limestone beds that indicate the early Campanian. The late Campanian–early Maastrichtian Abiod formation is consistently marked by two white fine-grained limestone bars separated by limestone-marl alternations. This formation is covered by the marl-rich El Haria formation which includes the K/Pg boundary.

In northern Tunisia (Fig. 2.a), a series of major faults may represent major paleogeographic trends, which favored lateral flow of Triassic salt and uprising of domal structures (Fig. 2.c). Furthermore, halokinetic movements associated with major faulting controlled the sedimentary basin' infill, and notable thickness variations are highlighted along the northern Tunisian domain (e.g. Khomsi et al. 2009; Masrouhi et al. 2014b; Khelil et al. 2021a; Naji et al. 2022b; Amri et al. 2022).

4. Tectono-sedimentary dataset:

In northern Tunisia, the Cretaceous period is described as a spectacular episode of soft-sediment deformations which are exposed for several kilometers (Saadi 1990; Souquet et al. 1997; Bey et al. 2012; Soua 2012; Masrouhi et al. 2014b; Jaillard et al. 2017; Bachari et al. 2018; Naji et al. 2018a, b; 2022a, b). The most common and preserved structures are slump folds with various sizes ranging from centimetric scale to several meters along the study area. Several slump analysis techniques permit to infer paleoslope attitude (e.g. Hansen 1965, 1967; Woodcock 1979; Maltman 1984; Bradley and Hanson 1998; Alsop et al. 2001; Strachan and Alsop 2006; Strachan 2008; Debacker and Meester 2009; Debacker 2012; Alsop and Marco 2012, 2013, 2014; Sharman et al. 2015; Alsop and Weinberger 2020; Rodrigues et al. 2021). Therefore, a major first intent of the current study is to manipulate some advocated techniques designed to infer slope dipping from slump folds based on the pioneering relation between slump sheets and the original slope orientation (Fig 3.a.b). To do so, hundreds of slump fold structures are measured. In major cases, slump folds show fold hinges disposed at an angle of close to 90° to the transport direction and display monotonous vergence patterns. Therefore, the gravity-driven transport orientation is extrapolated here on the basis of two statistical methods: the Mean Axis Method (MAM) and the Axial-Planar Method (APM). Thus, these methods are accordingly based on the equal area stereographic projection of restored slump folds axis and poles to axial planes (Fig 3.c). Besides, these methods are assumed as the most appropriate to the study area where layer-parallel shearing is highly prevailed and a slight subsequent fold rotation was described. Otherwise, the present study highlights the brittle deformation is highlighted through fault kinematic analysis of numerous striated syn-sedimentary faults that offer significant

information about the paleostress regime state. The numerical proceeding of various fault measurements is compiled following the Right Dihedron method (Angelier and Mechler 1977; Tranos 2017). Therefore, in the laboratory, several software were used for the processing of different field datasets such as Win-Tensor (Delvaux and Sperner 2003), Stereonet 10 (Cardozo and Allmendinger 2013; Allmendinger et al. 2013), and canvas drawing software.

4.1. Early Cretaceous datasets analysis:

In northern Tunisia, early Cretaceous sedimentation is well exposed and characterized by mixed deposits mainly composed of siliciclastic, carbonate, clayey and marly sequences. In addition, deposition during this period includes frequent soft-sediment deformation structures associated with both large and small-scale syn-sedimentary faults (Fig 4.a). Therefore, along the major part of the study area, pronounced variations of the thickness and/or the facies of the early Cretaceous deposits are clearly highlighted (Masrouhi et al. 2013; Naji et al. 2018a, b, 2020). All these characteristics are in favor for sedimentation over a tilted basin floor. Thus, several slump folds measurements are performed. Using the above mentioned paleoslope determination methods (MAM and APM), the numerical processing of back-tilted slumps data indicates northward dipping of the basin floor (Fig 4.c). Otherwise, restored fault data sets demonstrate that early Cretaceous sedimentation is predominantly controlled by NE and NW-trending faulting. Fault kinematics of restored fault mirrors shows a pure regional NNW-trending extensional tectonic regime which is assumed to be predominant in the entire basin during this period (Fig 4.b).

4.2. Aptian-Albian datasets analysis:

Since the Aptian, the facies heterogeneity has become more and more reduced in space. The Aptian-Albian lithology is mainly composed of marl, limestone and marly limestone beds associated with rare siliciclastic deposits. Besides, the study area defines numerous outcropping salt structures which are perceived to be grown-up during this period (Masrouhi et al. 2013; Jaillard et al. 2017; Amri et al. 2020; 2022). In some localities, Aptian-Albian sedimentation includes reefs and bioclastic limestone beds (Saadi. 1990; Chihaoui et al. 2010; Ben Chaabane et al. 2018). Significant thickness changes, frequent slump sheets associated with reworked blocks and widespread syn-sedimentary faulting are also described during the same period (Fig 5.1a). Therefore, more than 50 striated fault planes are measured through Aptian-Albian deposits and then processed. The stereographic projection of back-tilted faulting shows that the sedimentation here was made up under the effect of WNW, NW, NNW and NE-trending faults (Fig 5.b). A pure extensional paleostress regime was shown wherein its parameters are; horizontal NE–SW (03/41) σ_3 , horizontal (06/042) NW-trending σ_2 , and high-angle plunging (86/180) N-S σ_1 . This fault population indicates a stress ratio $R = 0.6$ (Fig 5.b). This state of stress appears to be homogenous in most sites in the North of Tunisia.

Moreover, more than 60 slump folds are collected and manipulated. The restored slump axis (MAM method) and back-tilted poles to axial planes (APM method) confirm that Aptian-Albian deposition along the study area is made above a general northward dipping basin floor (Fig 5.c).

4.3. Cenomanian-Turonian datasets analysis:

During the Cenomanian-Turonian period, variable facies distribution is highlighted in Tunisia (Soua 2015). Therefore, the Saharan platform is characterized by littoral sedimentation, which changes into shelfal and probably lagoonal deposits along the southeastern Tunisia (Soua 2015). Whereas, central and northern Tunisia are marked by bathyal to deep marine black-shales (Soua 2015). In addition, a significant transgression prevailed during the early Cenomanian and culminated during the Cenomanian-Turonian transition (Soua 2015; Soua and Tribovillard 2007). This transgression was correlated with the highest levels of the global Phanerozoic Sea (Soua 2015; Soua and Tribovillard 2007). The sea flooded North Africa's platform and allowed it to evaporate and then to large neritic carbonate platforms to extend across the northern and northeastern African–Arabian Tethyan margins (Piqué et al. 2002; Guiraud et al. 2005). In northern Tunisia, Cenomanian-Turonian sequences are wholly formed by grey marl and marlstone alternated with fine-grained and/or nodular limestone beds. Commonly, these sequences include the thinly laminated fine-grained organic-rich limestone of the Bahloul formation which is attributed to the uppermost Cenomanian–early Turonian (Soua 2015; Bachari et al. 2018). Slumped horizons and olistoliths are well exposed during this period (Fig 6.a). In addition, syn-sedimentary extensive tectonic activities are clearly highlighted. Based on back-tilted slump folds measurements, a northward to NNW-dipping slope is here described (Fig 6.c). Using fault kinematic analysis, restored datasets, collected from several areas indicates that Cenomanian-Turonian sedimentation is mainly guided by ENE, NNE, NNW and WNW trending faulting (Fig 6.b). In addition, the stereographic projection typifies pure extensional tectonic regime which trends NNW during this period (Fig 6.b). The stress ratio $R=0,46$. This paleostress regime seems to be consistent in the main part of the study area.

4.4. Coniacian-Santonian datasets analysis:

In the study area, Coniacian–Santonian sedimentation of the Kef formation overlies conformably the aforementioned Cenomanian–Turonian deposits. The Kef formation started with large monotone marl-limestone series and was topped by metric Inocerames-rich limestone beds. These Coniacian-aged sequences are followed by flaky gray marls, which indicate the Santonian age. Hence, this thick marl-rich kef formation is described as having a character of post-rift deposits. Consequently, the Coniacian-Santonian sedimentation is believed to be controlled by the isostatic response of various major faults and/or depocenters (Gharbi et al. 2013; Naji et al. 2018b, 2022a, b). Coniacian-Santonian deposits show

considerable thickness changes due to syn-tectonic activities with clear field evidences. They show also growth strata geometry, and calcareous nodules associated to abundant mega-slump folds within open interlimb angle (Fig 7.a). The pre-tilted fault diagram of measured Coniacian-Santonian faults exhibits a main E-W, NE and NW-trending syn-sedimentary normal faulting (Fig 7.b). Thus, an extensional tectonic regime, which trends ENE-WSW is described. Its stress ratio is $R=0,35$ (Fig 7.b). The analysis of over 40 slump folds using the MAM and the APM methods demonstrates a coexisting slope mainly oriented to the NW during the same period (Fig 7.c).

4.5. Campanian-Maastrichtian datasets analysis:

In the northern Tunisia Atlas, the sedimentation continues with the late Campanian– early Maastrichtian Abiod formation, which shows commonly two white fine-grained limestone bars interfiled by chalky marls with interbedded marly limestones. The Abiod deposits are covered by El Haria rich-marl formation dated as late Maastrichtian-Paleocene. Campanian-Maastrichtian outcrops of northern Tunisia have been described as deep-water deposits (Buroillet 1956; Bey et al. 2012). Sedimentological analyses of the late Cretaceous-Early Eocene sequences in the Mateur–Beja area show that the Abiod formation was deposited in outer platform to basin environments situated under storm wave base (Belghouthi et al. 2019; 2020). Several studies carried out in various localities in northern Tunisia confirm that the Campanian series exhibits slope gravity deposits (notably including slumping and turbiditic sequences) associated to considerable extensional syn-sedimentary normal faulting activities (Guiraud and Bosworth 1997, 1999; Dlala et al. 2002; Mabrouk et al. 2005; Bey et al. 2012; Belghouthi et al. 2019; 2020). Through the current study, the Campanian-Maastrichtian deposits were studied in one site (the Oued Zitoun area situated to the North of the Mateur locality) where the Abiod formation is thick and well exposed. In details, Campanian deposits of Oued Zitoun area show abundant slump sheets and small-scale syn-sedimentary normal faults (Fig 8.a). The stereographic projection of pre-tilted faults shows that Campanian deposition was governed by N, NE and NW-trending faulting (Fig 8.b). Moreover, a tectonic extension oriented ENE-WSW is highlighted (Fig 8.b). On the basis of slumping analysis, the NNW dipping syn-depositional slope is interpreted during the same period (Fig 8.c).

5. Discussions:

5.1. Cretaceous geodynamic history of the northern Tunisia:

Northern Tunisia, part of the North African passive margin, undergone a regional extensional phase during Jurassic to Early Cretaceous period, in relation with the Tethyan and Atlantic “oceans” rifting (Fig. 9.a) (Souquet et al. 1997; Guiraud 1998; Piqué et al. 2002; Bouaziz et al. 2002; Guiraud et al. 2005; Boughdiri et al. 2007; De Lamotte et al. 2009; Soua 2012; Gharbi et al. 2013; El Amari et al. 2016; Jaillard et al. 2017;

Soussi et al. 2017; Naji et al. 2018b; Khelil et al. 2021a). Recent researches exhibit that the proliferation of the Central Atlantic occurs during the Jurassic-Early Cretaceous interval (Souquet et al. 1997; Soussi et al. 2000; Guiraud et al. 2005; Boughdiri et al. 2007; Masrouhi and Koyi 2012; Jaillard et al. 2013; Naji et al. 2022b), susceptible of a paleogeographic differentiation of the continental platform which is associated with volcanic and halokinetic activities in various settings (Mattoussi Kort et al. 2009; Masrouhi and Koyi 2012; Jaillard et al. 2017; Dhahri and Boukadi 2017). The Late Jurassic deposition is characterized by deep marine carbonates, including an “Ammoniticorosso” facies in the Tunisian Ridge, and open-marine radiolaritic facies along the northern Tunisia (Boughdiri et al. 2007; Soussi 2003). Subsequently, the extension seems to be accelerated and hyperactive subsidence prevailed during this episode which is correlated with the major extensional Tethyan tectonics (Soussi 2003) and/or the acceleration in the Central Atlantic opening (Guiraud et al. 2005). From the late Jurassic to the Barremian, the sedimentation in the major northern part of Africa was still mostly guided by ~E-W normal fault systems, presumably related to major basement discontinuities inherited from the Triassic period (Piqué et al. 2002; Khomsi et al. 2004; De Lamotte et al. 2009; Khelil et al. 2021b). Accordingly, the Jurassic rifting induced a general northward block-tilting geometry along northern Tunisia basin (Soussi 2003). During Early Cretaceous, the African continent was majorly under extensional tectonics and several rifts were developed along Africa and Arabia (Guiraud et al. 2005; Frizon de Lamotte et al. 2015; Jolivet et al. 2016). During the same period, Tunisia and Eastern Algeria received mixed sediments reaching more than 2500 m-thick in the Tunisian Atlas, precisely described in Jebel Oust depocenter, as illustrated in figure 2 (Guiraud et al. 2005; Ben Ferjani et al. 1990; Souquet et al. 1997; De Lamotte et al. 2009; Naji et al. 2018b). In Tunisia, considerable thickness and sometimes facies variations, gravity-driven deposits and syntectonic strata confirm that inherited ~E-W major faults remained active during Early Cretaceous (Snoké et al. 1988; Martinez et al. 1991; Piqué et al. 2002; De Lamotte et al. 2009; Naji et al. 2018b). These fault systems are responsible for paleo-highs characterized by reduced series associated with several stratigraphic gaps, and extended depocenters with a high accommodation rate (Soussi and Ben Ismail 2000; Bouaziz et al. 2002; Naji et al. 2018b; Khelil et al. 2021a). Therefore, the sedimentation along the northern Tunisia is clearly made above a fractured basin floor. Through slump sheets analysis, the basin’s slope is estimated to have a northward dipping. On the basis of faults’ stereographic projection, a pure extensional regime is described in northern Tunisia trending NNW-SSE. This paleostress regime is believed to be consistent in the entire area.

During the early Aptian (around 119–120 Ma), a rapid change in the Africa inter-plate stress state was recorded in which the extension direction was moved from ~N160 to NE–SW (Bouaziz et al. 2002; Guiraud et al. 2005; Turco et al. 2012; Berra and Angiolini 2014). Then, early-middle Albian times appear to be

described as the last episode of the Atlantic Ocean opening (Jaillard et al. 2013). Accordingly, Aptian–Albian epochs are believed to display the most extensional related-structures in the northern Tunisia, where the majority of salt structures seem to be hyperactive during this period (Martinez et al. 1991; Souquet et al. 1997; Masrouhi and Koyi 2012; Gharbi et al. 2013; Masrouhi et al. 2014a, b; Jaillard et al. 2017; Amri et al. 2020; Naji 2020; Amri et al. 2020; 2022; Khelil et al. 2021a). Moreover, continued extensional tilting is responsible for acute paleogeographic differentiation (Gharbi et al. 2013). Subsequently, the southern and central regions are characterized by platforms (Gharbi et al. 2013), whereas the northern areas are marked by deep basins with high rate of sedimentation, such as the Tunisian through (Burrolet 1956; Ben Ferjani et al. 1990; Souquet et al. 1997; Jaillard et al. 2017; Naji et al. 2018b), and the Selaoua through along the northeastern Algeria domain between Tebessa and Constantine (Fig. 9.c; Vila 1980; Guiraud et al. 2005). In northern Tunisia, the Aptian–Albian epochs show increased synsedimentary deformations coupled with thickness and sometimes facies variations of the sedimentary pile (Souquet et al. 1997; Gharbi et al. 2013; Masrouhi et al. 2014b; Jaillard et al. 2013; Naji et al. 2018a). Based on our datasets, Aptian-Albian sedimentary records of northern Tunisia was mainly controlled by WNW, NW and NNW synsedimentary fault systems. The kinematic analysis of back-tilted fault populations confirms the pure extensional NE-trending tectonic regime. The Aptian–Albian slope orientation inferred from slumps indicates ~N to NNW dipping. The slope orientation is incompatible with back-tilted Aptian–Albian synsedimentary faulting. Thus, the paleoslope is interpreted, here, as a result of the reactivation of inherited Early Cretaceous faulting and/or to salt activity.

During the Cenomanian, extensional tectonics remained active. This phase is responsible for tilted blocks geometry along the northern part of Africa plate, favorable for siliceous and organic-rich sedimentation characteristic of the late Cenomanian-early Turonian (Guiraud et al. 2005; Souza et al. 2009; Souza 2012). The Cenomanian-Turonian extensional tectonics are coincidentally correlated with the African-Eurasian plates' relative movements, the North-Atlantic opening in the west (Fig. 9.b) and the active rifting recorded along the basin of Sirt in the southeast (Guiraud et al. 2005; Souza et al. 2009; Frizon de Lamotte et al. 2011; Souza 2015). Moreover, during the early Cenomanian, an important transgression took place, which is culminated during the late Cenomanian-Turonian (Guiraud et al. 2005; Souza and Tribovillard 2007; Souza 2012). This major transgression coincided with the most elevated global Phanerozoic marine levels (Guiraud et al. 2005; Souza et al. 2009, Souza 2012). Then, the marine-water flooded the whole North Africa' platform which is marked by evaporitic deposition followed by large neritic carbonate platforms around the northern and northeastern African–Arabian Tethyan margins realms (Piqué et al. 2002; Guiraud et al. 2005). In northern Tunisia, Cenomanian-Turonian deposits expose numerous olistolith horizons testifying

for syn-tectonic activities (Soua 2012; Bachari et al. 2018; Naji et al. 2022b). Besides, these synsedimentary features are also highlighted by increased slumping. The fault kinematic analysis of several small-scale synsedimentary back-tilted faulting indicates that the Cenomanian-Turonian sedimentation was mainly guided by two principal fault systems which are: NW-SE and NE-SW trending faults, confirming previous interpretation of Soua et al. 2009. Furthermore, the stereographic projection of fault datasets exhibits extensional tectonic regime that trends NNW-SSE. The paleoslope inferred from restored Cenomanian-Turonian aged slump folds axis (MAM method) trends to the north. Meanwhile, the second method (APM method) indicates a NNW-dipping slope.

During the Late Cretaceous, Tunisia was described as a transtensive margin realm at least until the Maastrichtian (Dlala et al. 2002; Masrouhi et al. 2008; Bey et al. 2012; Gharbi et al. 2013; Naji et al. 2018b, 2022b; Amri et al. 2020). Other geoscientists have affirmed that the earliest tectonic compression reported by the Africa–Arabia plate during the Alpine phase was dated about approximately 85 Ma (known in the literature as the Santonian tectonic event). This compressional event is mainly related to the change in plates' motions resulting in an increase of convergence velocity (Guiraud and Bosworth. 1997; Piqué et al. 2002; Guiraud et al. 2005; Frizon de Lamotte et al. 2011). This tectonic event seems to be not registered everywhere from the Southern part of the Tethyan margin realm (Jolivet et al. 2016). Therefore, the central Mediterranean appears to be neglected from the impact of the convergence and being oppositely under a quite persistent extensional tectonics since the Triassic period (Frizon de Lamotte et al. 2011; Jolivet et al. 2016). In the whole northern Tunisia, Coniacian-Santonian times are described as a post-rift period characterized by pelagic sedimentation along the entire basin (Gharbi et al. 2013; Masrouhi et al. 2014b; Naji et al. 2018a, b, 2022b; Amri et al. 2020; Khelil et al. 2021a). The Coniacian-Santonian deposition here comes to seal all the pre-existing differentiations and was seemingly guided by the isostatic reaction of various inherited major faulting and/or depocenters (Gharbi et al. 2013; Naji et al. 2018b, 2022b). The fault kinematic analysis of pre-tilted Coniacian-Santonian faults collected from northwestern part of Tunisia (Le Kef-Siliana areas) shows ENE-trending extensional regime. Further, processed slump folds, collected mainly from the same area, indicate a general northwest gravity-driven orientation. This northwestward dipping Coniacian-Santonian slope is probably related to major inherited Early Cretaceous and Jurassic faulting (i.e. Zaghouan and Teboursouk faults).

Several authors confirm that extensional tectonics continued at least until Early Maastrichtian along the Tunisia margin (Bouaziz et al. 2002; Dlala et al. 2002; Mabrouk et al. 2005; Bey et al. 2012; Belghouthi et al. 2019; Naji et al. 2022b). Thus, The late Campanian-early Maastrichtian aged Abiod formation in northern Tunisia shows slumps and turbidites and even contourites horizons reflecting a clear

synsedimentary reworking of (hemi) pelagic carbonaceous deposits above a coexisting slope (Bey et al. 2012; Belghouthi et al. 2019; 2020). Besides, extensional tectonics during this episode are expressed in the field by frequent thickness and facies changes, abundant syn-sedimentary normal faults and abundant conglomeratic horizons (Dlala et al. 2002; Bey et al. 2012; Belghouthi et al. 2019; 2020). The stereographic projection of numerous faulting collected from Oued zitoun locality situated near the Mateur area (Northeast part of Tunisia in Fig 2.a) attests ENE-trending extensional regime which confirms the same result of Bey et al. 2012 in Ain Medheker structure (to the west of Enfidha locality in Fig 2.a). On the other hand, the pre-tilted slump fold axis and poles of axial planes (respectively MAM and APM methods) give very similar results with a ~NNW dipping slope during the Campanian. This result confirms the previous interpretation of Belghouthi et al. (2019) who studied the same section (Oued Zitoun locality) and described a NNW gravity-driven orientation.

5.2. Structural configuration of the northern Tunisia during Early to Late Cretaceous:

Taking into account the aforementioned results and other structural tools, a schematic bloc diagram illustrating the Cretaceous basin configuration, along the northwestern Tunisia is presented (Fig. 10). In details, the thicknesses of sequences and the salt tectonics are highlighted on the basis of the current study and previous works (Burollet 1956; Robaszynski et al. 1993; Memmi 1999; Soua et al. 2009; Masrouhi et al. 2014a, b). In addition, we use sections published in Naji et al. (2022b), which are marked along the 3D diagram (Sej-Bargou, Lorbeus, Bled Doghra, Zaafrana and Nebeur sections). The position of different major faults, delimiting various tectonic blocks are built on the base of several 1:50000 scaled geologic maps (Sainfeld et al. 1951; Sainfeld et al. 1953; Jauzein et al. 1961; Mahjoub 1992; Fakraoui et al. 1994; Fakraoui 1998; Mahjoub and Dali 2000) established by the Geological Survey of Tunisia. To the depth, the thickness of the crust and the continental lithosphere and the depth of the Moho discontinuity are all built on the basis of The European Geotraverse seismic model associated to other multiple previous investigations (Morelli and Nicolich. 1990; Research Group for Lithospheric Structure in Tunisia. 1992; Jallouli et al. 2013). In addition, the cross section is constructed based on the assumption that the ductile stretching of the lower crust appears much greater than the brittle extension of the upper crust (Bott 2006). The bloc diagram shows various tectonic blocs underlined by several major basement fault systems (probably listric) and generally tilted northward. The seaward-facing submarine basin' slope is estimated here to be $\pm 3^\circ$ to the north. These major faults are always combined with other intra-basin growth normal fault systems. Besides, from the domain of tilted blocks to the intra-basin growth faulting, the coexistence and the mobility of Triassic evaporites provide a superb decoupling level (Moragas et al. 2017; Jaillard et al. 2017). Then, halokinetic motions and salt rise-up are active on the extensional structures allowing the

establishment of abundant large depocenters with numerous soft-sediment deformations (Soua 2015; Naji 2020; Khelil et al. 2021a). Therefore, the major part of the Mesozoic sedimentary cover of northern Tunisia basin displays frequent gliding and spreading above the Triassic evaporitic decollement layers (evaporite floored margin), as reported in several Atlantic-type passive margin realms (Jaillard et al. 2017; Naji et al. 2022 b).

This study demonstrates that the North Tunisian basin Cretaceous history is entirely guided by extensional tectonics and that no compressional events are observed during this period. The observations above indicate a spatio-temporal variability in the intensity and the nature of deformations. Thus, we assume here that the syn-rift stage continues until Cenomanian-Turonian, whereas the Coniacian-Maastrichtian period is qualified to be a post-rift interval. In space, the proximal zone is mainly dominated by major normal faulting (graben and half-graben, depocenters...) compared to the distal zone, where salifereous intumescences are accentuated. In addition, the thickness of the sedimentary series shows a general northward increase related to accommodation growth up. However, the halokinetic activities are locally responsible for reducing the thickness of the sedimentary cover in the northern areas whereas the paleo-depth is growing up. Simultaneously, other structures (e.g. Guern Halfaya, Bled Doghra, and Nebeur area) were described as being marked by raft tectonic structures above submarine salt bodies (Vila et al. 1998; Masrouhi et al. 2014a). To the latter distal part of the margin (the toe of the margin), post-salt sedimentary cover glided toward the downslope above evaporate layers inducing squeezed diapiric occurs and contractional structures (thrusts and folds).

The Mesozoic extensional basin history of northern Tunisia interpreted in this study is supported by other interpretations made along surrounding areas. Therefore, to the south, along the Chad basin, the Early to Late Cretaceous times were interpreted as the main time of rift development (Genik 1992). The origin of this is attributed to the breakup of Gondwana and the start of separation between Africa and South America. It may equally be related to the Sudanese and Kenyan rifts, which also opened at this time, and evolved in response to India and Madagascar separating from Africa (Genik 1992). About 98 to 75 Ma, a late rifting stage was highlighted, accompanied by a marine transgression that reached this area from the Tethys via Mali and Algeria and from the South Atlantic to the south through the Benue trough (Genik 1992). Likewise, along the Aures Mountains in Algeria, the Atlasic trough opening results from a pure shear mechanism responding to an N-S or NW-SE extension (Piqué et al., 2002). To the East, the Sirte basin underwent an anticlockwise rotation of axis through time from NE-SW (Early Cretaceous) through N-S (Upper Cretaceous) to NW-SE (Paleocene and Eocene). This inversion is mainly related to the anticlockwise rotation of the African continent with respect to Eurasia. In addition, the internal differences in relative

motion between west and east Africa caused a clockwise change in the extension direction which in turn probably caused the anticlockwise rotation of the Sirte basin axis (Abdunaser and McCaffrey 2014).

5.3. Cenozoic shortening model of the northern Tunisia:

After the Mesozoic extensional episode in Tunisia, a Cenozoic shortening period appeared. Therefore, a positive tectonic inversion started during the uppermost Cretaceous (around the Maastrichtian time) following the convergence between Eurasia and Africa plates, which induced the progressive closure of the Tethyan realm (Guiraud et al. 2005; De Lamotte et al. 2009; Guiraud and Bosworth 1997; Bosworth et al. 1999; Masrouhi et al. 2008). Based on the previous geodynamic interpretations of the northern Atlasic range of Tunisia, geoscientists are widely admitted two major fault systems, which are the Teboursouk and the Zaghouan-Ressas thrust faults (Jauzein 1967; Morgan et al. 1998; De Lamotte et al. 2009; Khomsi et al. 2016). Several studies display evidence for frequent structural components, which are in favor of the fault inversion model for the geodynamic evolution of these two major thrust systems (Turki 1988; Martinez et al. 1990; Souquet et al. 1997; Morgan et al. 1998; Khomsi et al. 2009, 2016; 2019; Bejaoui et al. 2017; Amri et al. 2020; Gaidi et al. 2020; Naji et al. 2022a). In addition, field relationships between units and the present-day distribution of faults and folds obviously involve the role of the inherited structures in style and the growth of the north Tunisia fold and thrust belt (Turki 1988; Morgan et al. 1998; Khomsi et al. 2016; Bejaoui et al. 2017; Khelil et al. 2021a, b; Naji et al. 2022a; Amri et al. 2022). Recent works demonstrate that the shortening rate along northern Tunisia decreases from the west to the east (Gaidi et al. 2020). Besides, halokinetic features grown-up during the Mesozoic rifting, allowing the implication of the Triassic evaporites in major thrust systems during Cenozoic compressions (Khelil et al. 2021a, b; Naji et al. 2022a, b).

6. Conclusion:

Considering the results of field data, slope determination and fault kinematic analysis made through Cretaceous deposits of the Northern Atlasic domain of Tunisia, the following main conclusions can be highlighted:

- Early Cretaceous sedimentation (syn-rift stage) is underlined by major basement faulting systems (probably listric) combined with other intra-basin growth normal faults. These faults are tilted northward delimiting various tectonic blocs. The Coniacian-Maastrichtian deposits (post-rift stage) come to seal all the pre-existing differentiation and were probably conditioned by the isostatic response of different inherited major faults. Compressional events are not observed during the whole Cretaceous, and the sedimentation mainly occurred under extensional tectonics during this period.

- Halokinetic movements and salt rise-up are active on the extensional features during the Mid-Cretaceous period allowing the creation of abundant large depocenters with numerous soft-sediment deformations. Thus, the Tunisian margin is described as an evaporite floored margin where a major part of the Mesozoic sedimentary cover underwent frequent gliding and spreading above the Triassic evaporite decollement layers, as reported in several Atlantic-type passive margins.
- During the Cenozoic shortening period, a fault inversion model is mainly accepted for the development of different thrust systems. Thus, the relationship between various inherited structural units and the present-day position of major faults and folds is argued. This fact involves the role of inherited structures in the growth and the style of the North Tunisian fold-and-thrust belts. During the Cenozoic compressions, halokinetic structures, already developed during the Mesozoic Tethyan rifting, are reactivated, as the Triassic evaporites are incorporated in major thrust systems.

Conflict of interest statement:

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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Figures Captions :

Figure 1: [a] Descriptive structural sketch map of Northwestern Africa realm (From Frizon de Lamotte et al., 2011); [b] Simplified structural map of the north Tunisia' Atlasic domain illustrating the major fault systems and the different structural units.

Figure 2: (a) Simplified geologic map of northern Tunisia (from Bel Haj Ali et al. 1985); (b) Simplified lithostratigraphic column of the northern Tunisian Atlasic domain during Early Cretaceous (1) and Late Cretaceous (2); (c) Regional structural transect in northern Tunisia from the Tell domain in the northwest to the eastern Atlas foreland onshore of the gulf of Hammamet (from Khomsi et al., 2009).

Figure 3: Fold's patterns in slumping sheet. (a) Model used to relate slump fold geometry to slope attitude (after Alsop and Holdsworth, 2007); (b) Fold facing direction in schematic illustrations summarizing the relationships between folds vergence, axial plane and upward or downward facing states (after Alsop and Marco, 2012); (c) Equal area plot of hypothetical fold axis and poles of axial

planes distribution to illustrate the mean axis (MAM) and the axial plane (APM) methods. The cylindrical best fit girdle to axes and poles to axial planes of the slump sheet indicates a southward paleoslope orientation.

Figure 4: a. Field photos showing some important soft-sediment deformations and extensional structures within the Early Cretaceous deposits: a1) Reworked blocks (red arrows) associated to tension cracks (blue arrows) through Barremian deposits. a2) Small-scale synsedimentary normal fault. a3) Reworked block re-sedimented in the Barremian sequences. a4, a5, a6) Slump fold structures. b. Back-tilted stress tensors diagrams of Early Cretaceous fault populations. c. Equal area projection of back-tilted slump axis and poles to axial planes with respectively the inferred paleoslope orientation during Early Cretaceous.

Figure 5: a. Field photos showing some important soft-sediment deformations within the Aptian-Albian deposits: a1) Reworked blocs through organic-rich Albian marls. a2) Albian aged slumped strata. a3) Synsedimentary Aptian normal faults. b. Back-tilted stress tensors diagrams of Aptian-Albian fault populations. c. Equal area projection of back-tilted slump axis and poles to axial planes with respectively the inferred paleoslope orientation during Aptian-Albian.

Figure 6: a. Field photos showing some important soft-sediment deformations within the Cenomanian-Turonian deposits: a1) Slumped strata through the nodular limestone-marl alternations. a2) Slump fold associated to small-scale normal faults. a3) Inherited normal faulting inverted later by tertiary compressions. a4) Nodular limestones beds associated to olistolith block. a5) Slump fold structure. b. Back-tilted stress tensors diagrams of Cenomanian-Turonian fault populations. c. Equal area projection of back-tilted slump axis and poles to axial planes with respectively the inferred paleoslope orientation during Cenomanian-Turonian.

Figure 7: a. Field photos showing some important soft-sediment deformations within the Coniacian-Santonian deposits: a1) Slumped strata through the Coniacian nodular limestone-marl alternations. a2) Sealed normal faults affected the Coniacian sequences. a3) Fault surface shows well-preserved striations. a4) Calcareous nodules in the Santonian sequences genetically related to an irregular sea floor. b. Back-tilted stress tensors diagrams of Coniacian-Santonian fault populations. c. Equal area projection of back-tilted slump axis and poles to axial planes with respectively the inferred paleoslope orientation during Coniacian-Santonian.

Figure 8: a. Field photos showing some important soft-sediment deformations within the Campanian-Maastrichtian deposits: a1, a2) Slumped turbidites through the Late Campanian sequences (lower part of the Abiod Formation). a3, a4) Syn-sedimentary sealed small-scale normal faults affected the Campanian strata. a5) Well-preserved slump fold within the Early Campanian deposits (uppermost part of the Aleg Formation). b. Back-tilted stress tensors diagrams of Campanian-aged fault populations. c. Equal area projection of back-tilted slump axis and poles to axial planes with respectively the inferred paleoslope orientation during Campanian-Maastrichtian.

Figure 9: Large-scale reconstruction of the Tethys–Atlantic area: (a) Paleotectonic map of the Tethyan realm for the 140 Ma. (b) Paleotectonic map of the Tethyan realm for the 100 Ma. Maps are in orthographic projection. Close-up shows the evolution of the Iberian plate and the Ebro continental block. Colored background shows diffuse or ill-defined deformation (extension or transtension) in the continents, associated with the evolution of the Tethys (Paleoand Neotethys, purple) or the Atlantic (blue). Aq-Pyr: Aquitaine–Pyrenean Basin; BCB: Basque–Cantabrian Basin; Bet: Betics Basin; Cm: Cameros; EBR: Ebro; M: Maestrat; MI: Meliata; Pce: Provence Basin; V: Valaisan Basin; TZ: Tornquist Zone (from Angrand et al., 2020). (c) Paleogeographic reconstruction of the Early Aptian Tethyan realm (119 Ma) (from Hueter et al., 2019).

Figure 10: Schematic block diagram illustrating the northwestern Tunisia domain during Cretaceous (For location, see Fig. 2). It shows the structural configuration of the basin with widespread soft-sediment deformation onto north-facing submarine paleoslope related to the Tethyan margin expansion.

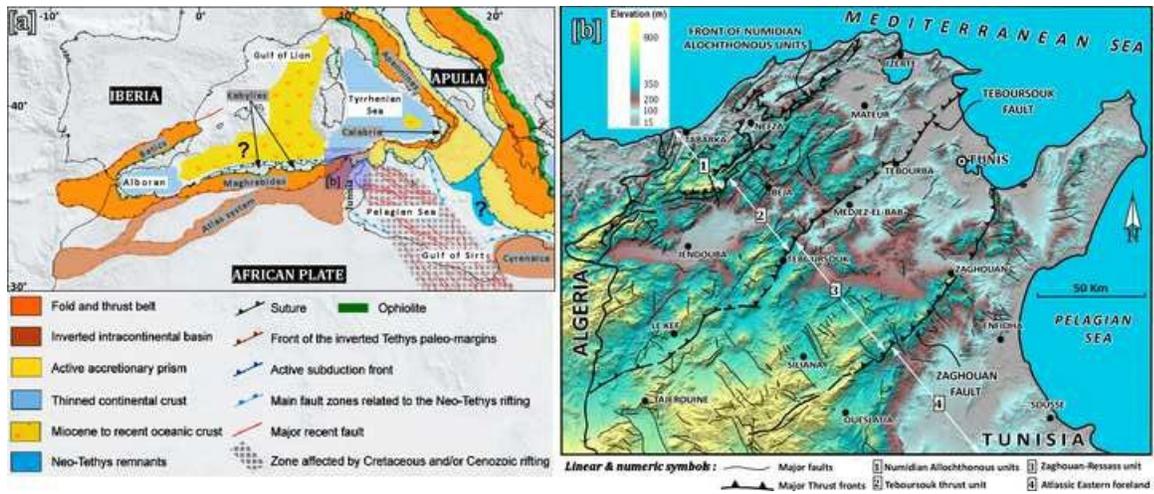


Fig. 1

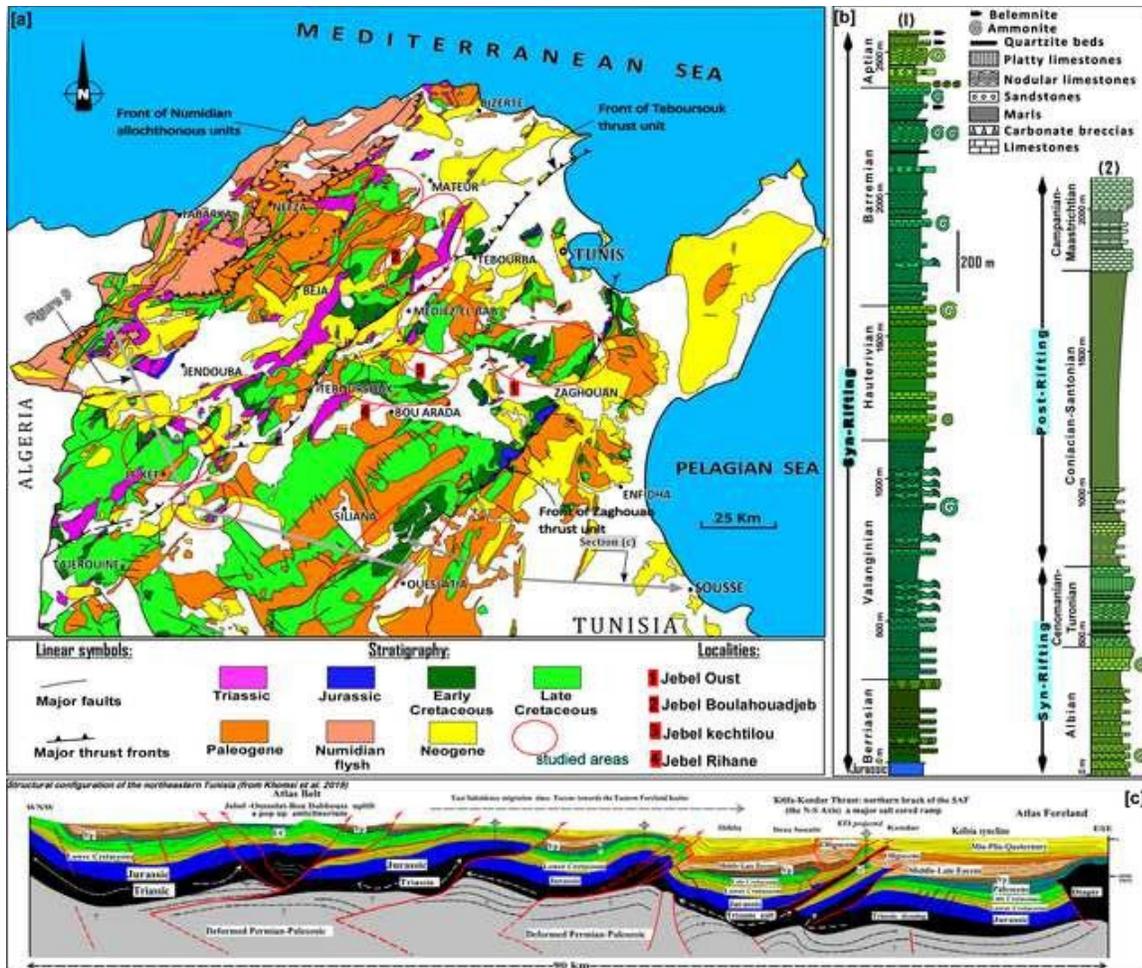


Fig. 2

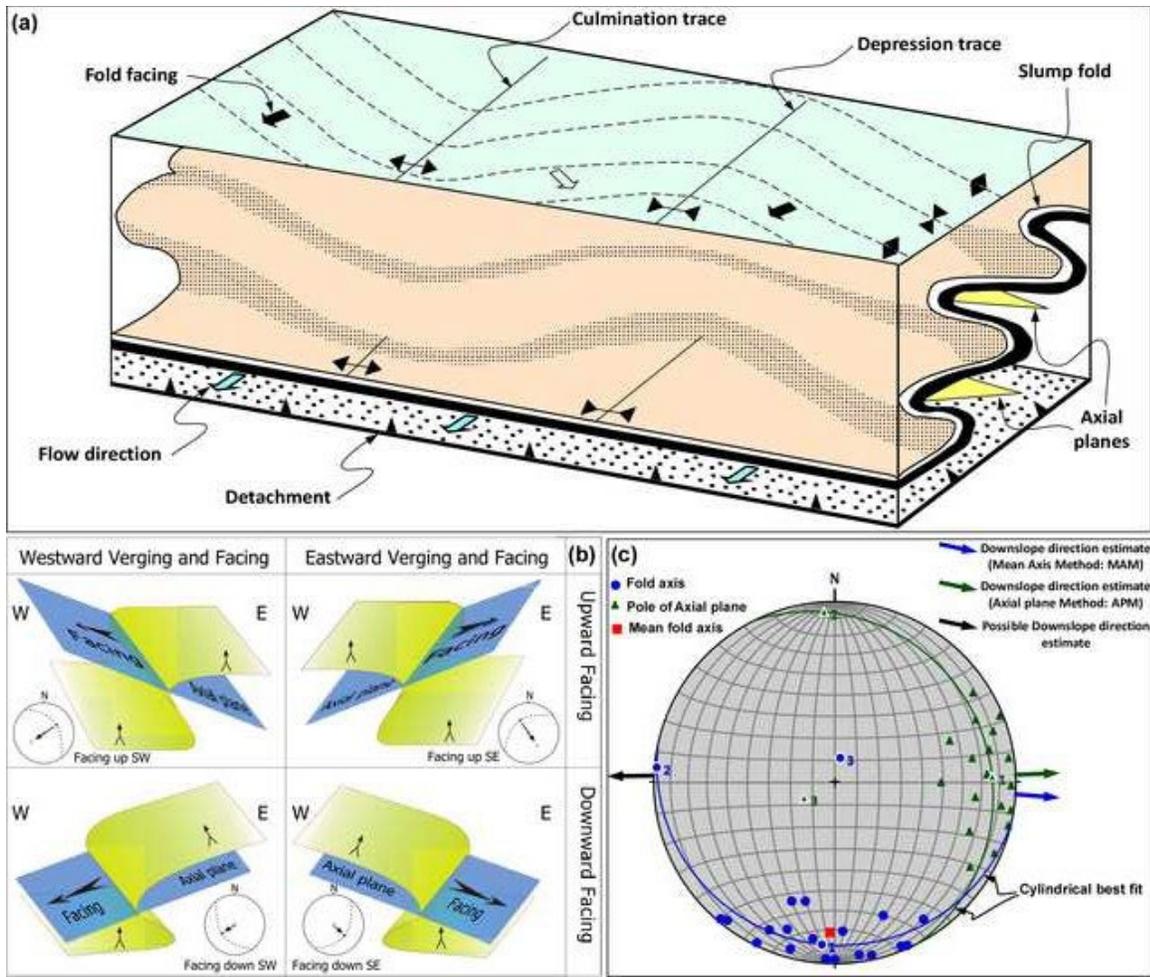


Fig. 3

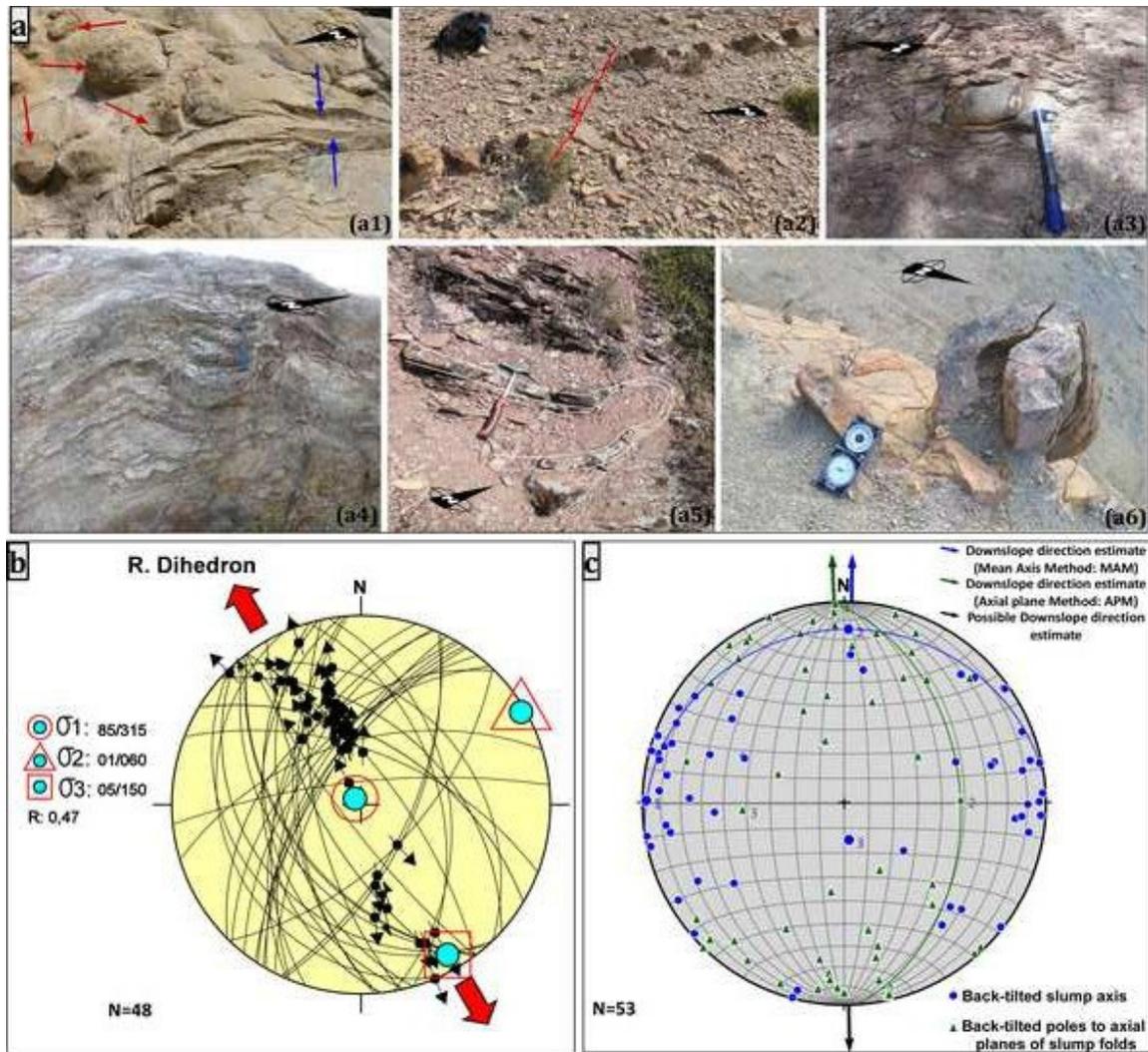


Fig. 4

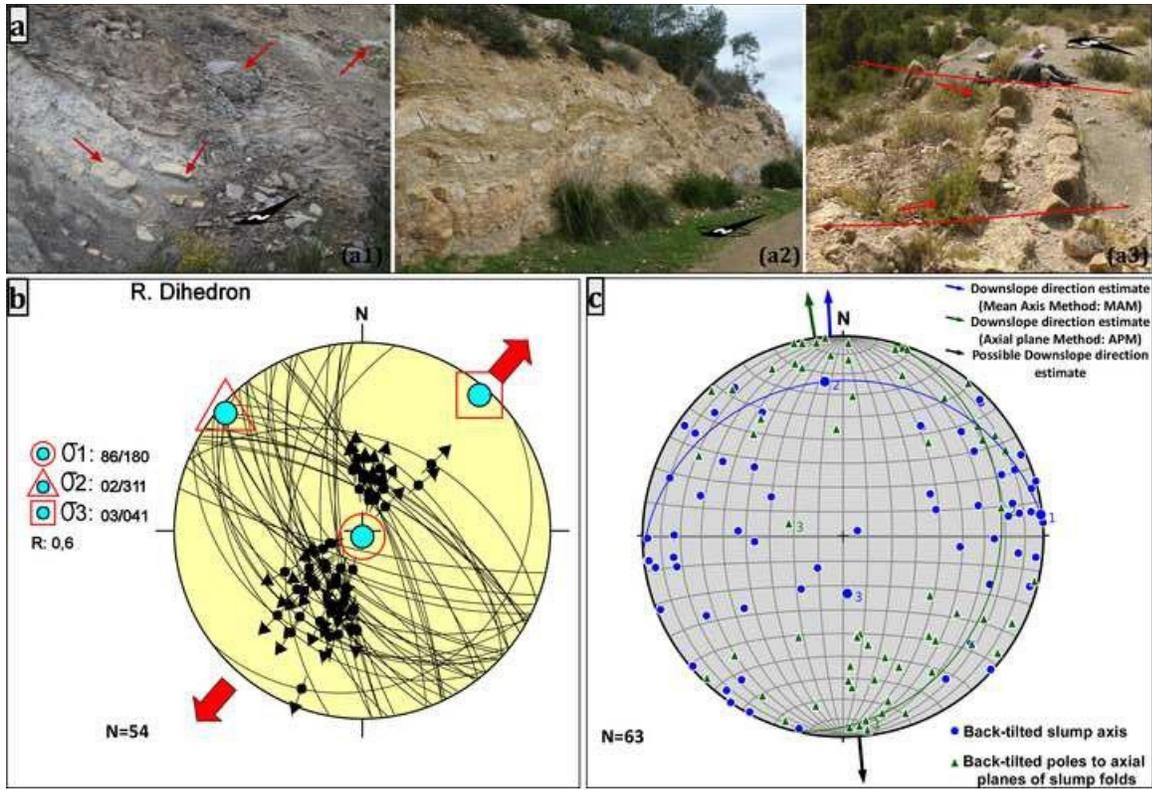


Fig. 5

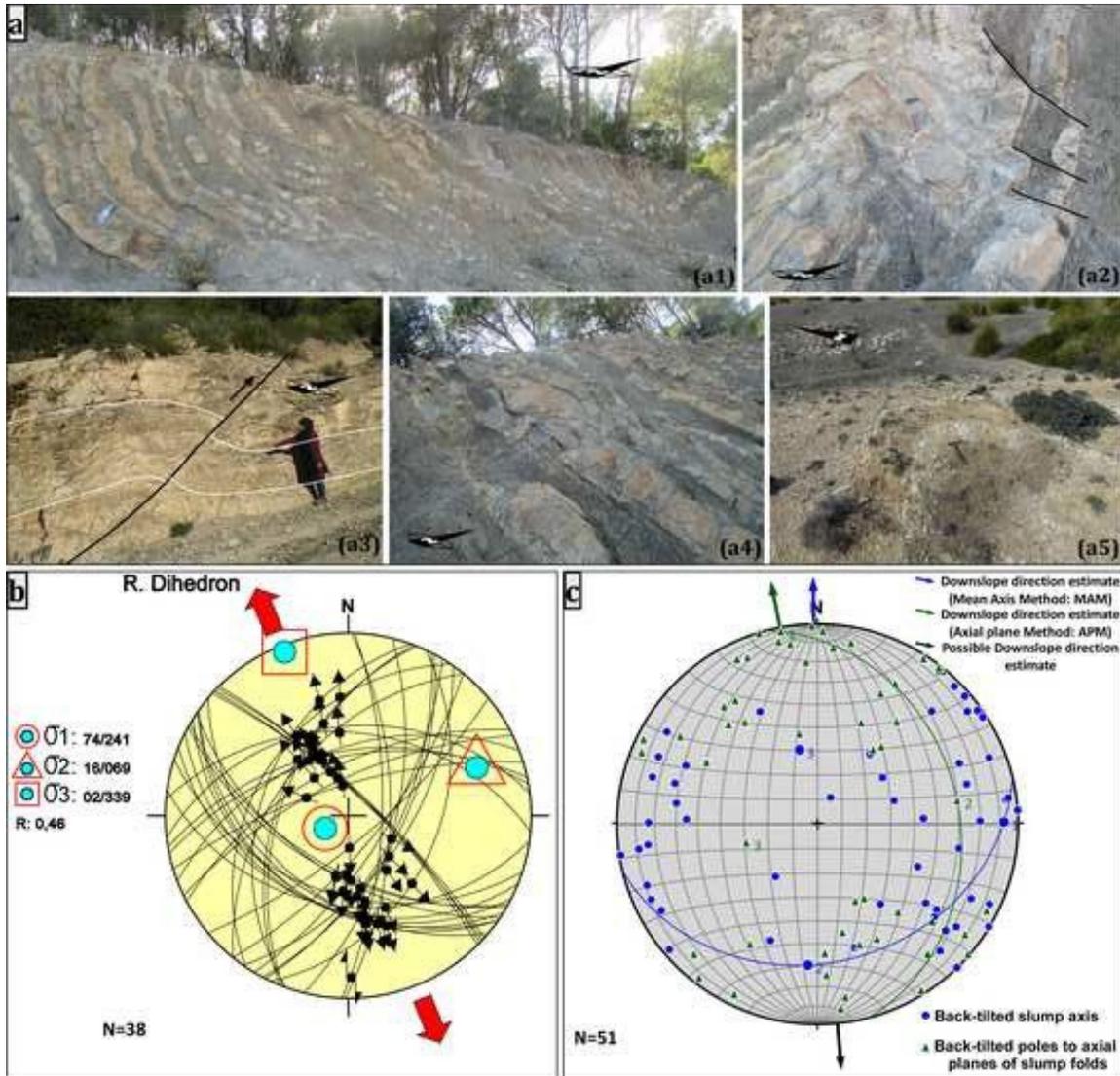


Fig. 6

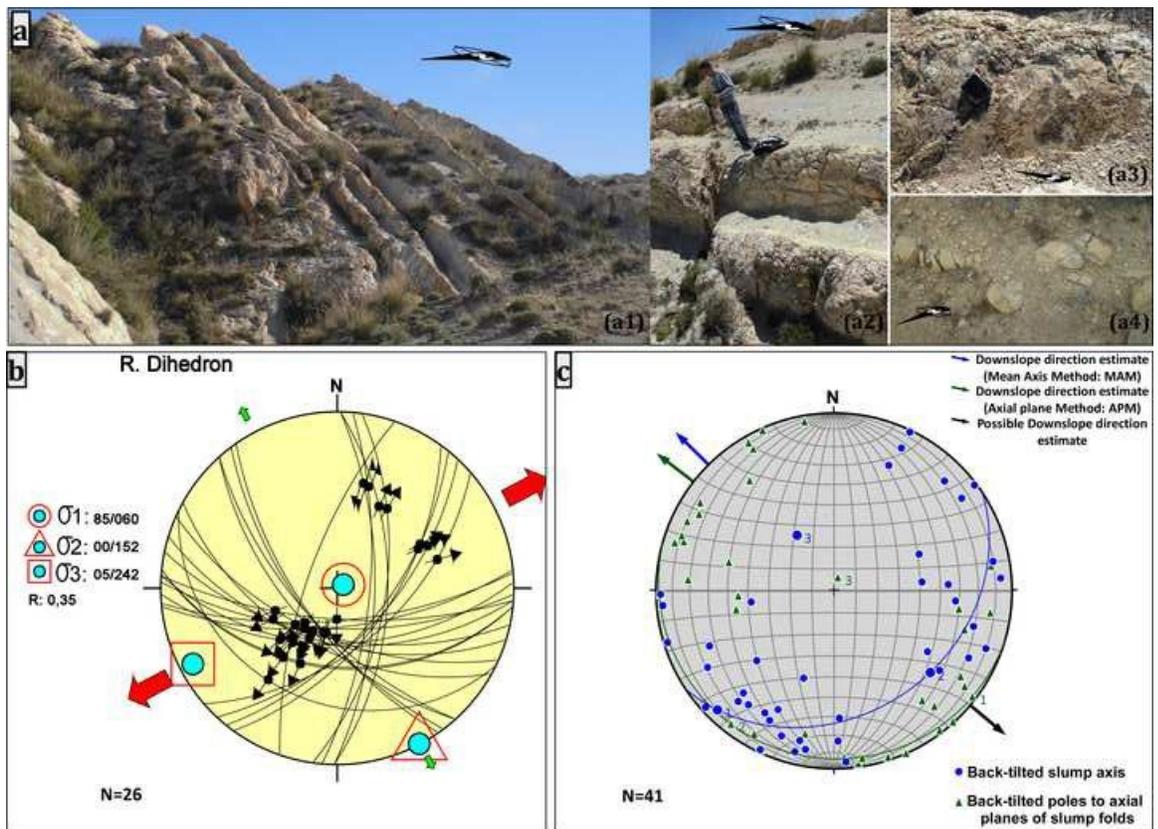


Fig. 7

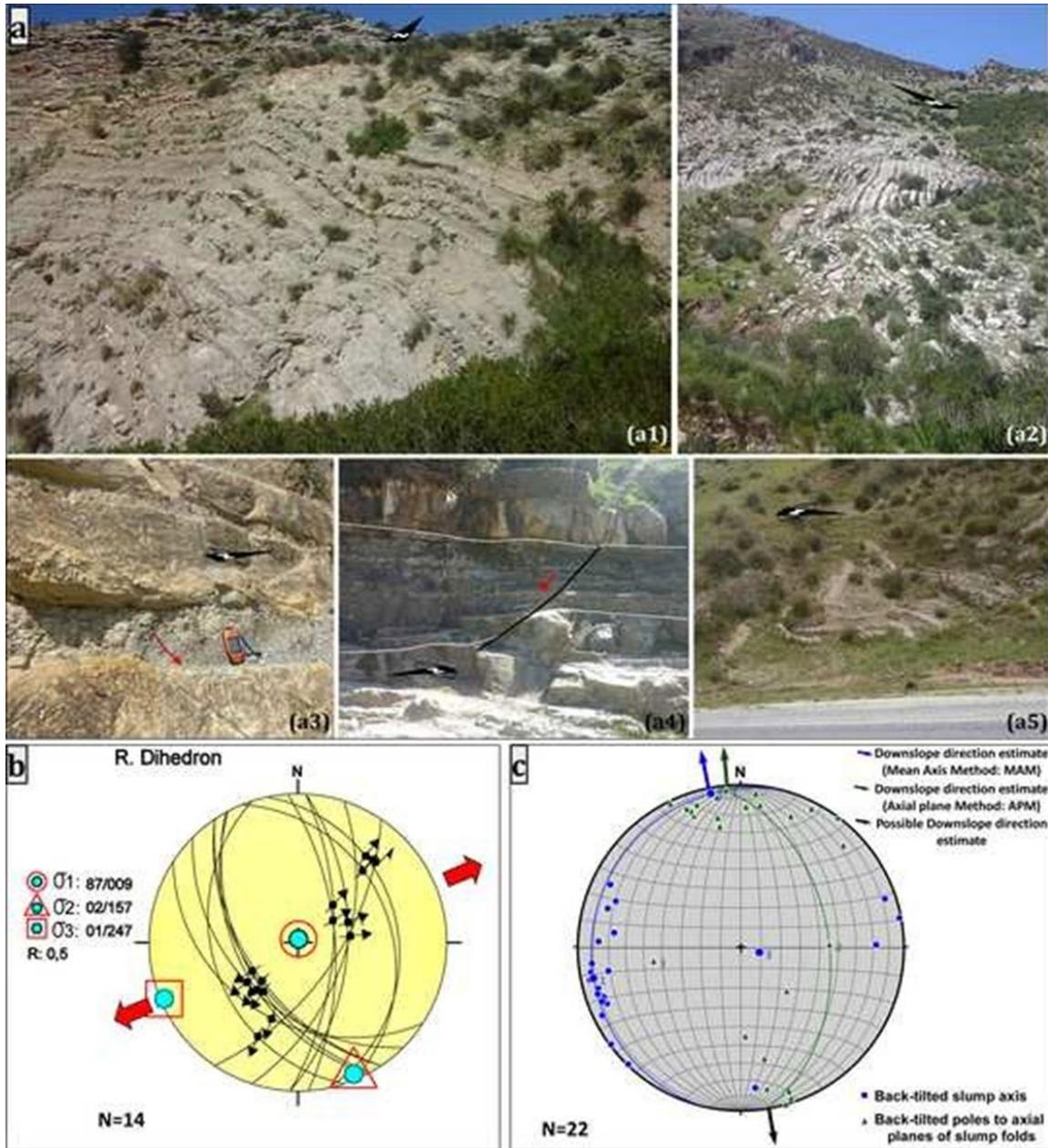


Fig. 8

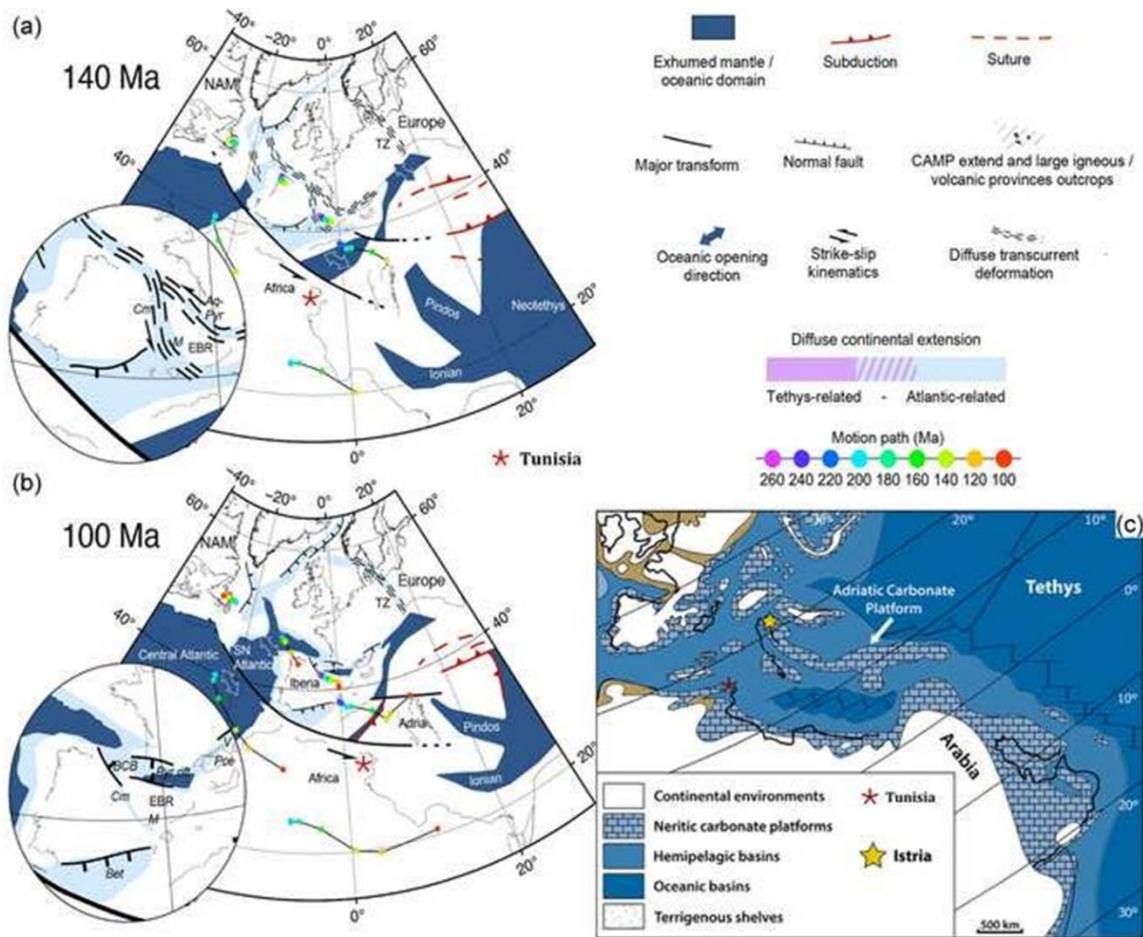


Fig. 9

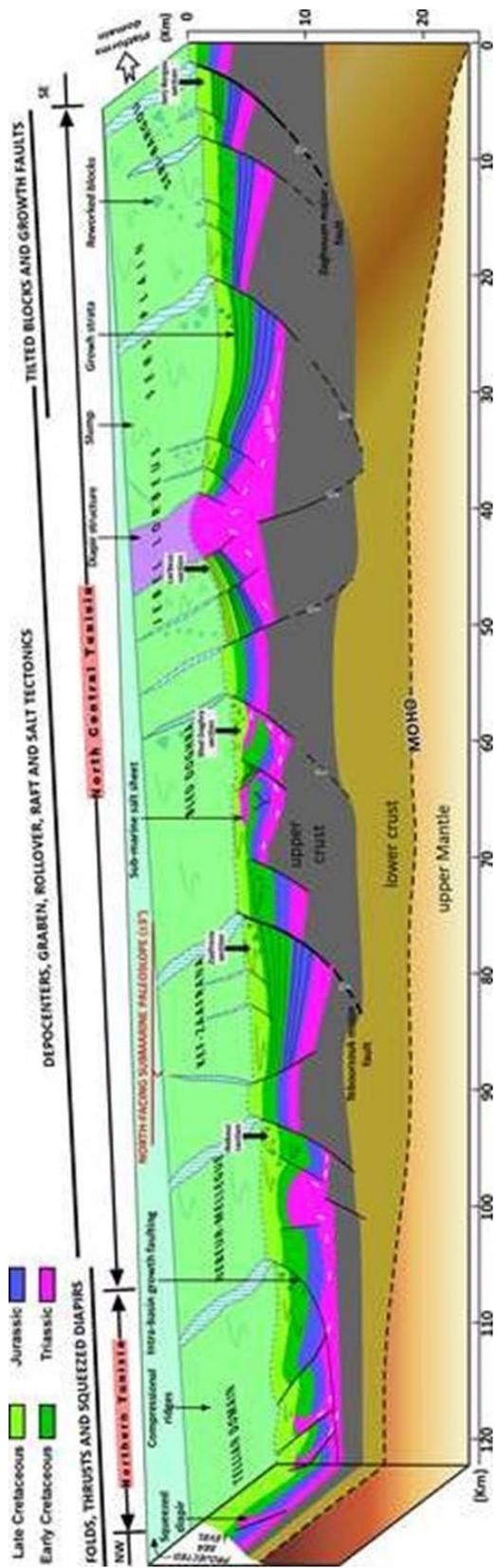


Fig. 10