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1 **South Tethyan passive margin paleoslope orientation inferred from soft-sediment deformation and**
2 **fault kinematic analysis: a case study from the Cretaceous of Borj Cedria area, Tunisia**

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10 **Abstract**

11 The Cretaceous outcrops of Borj Cedria-Bou Kournine area belongs to the NE-trending Atlas system
12 of northern Tunisia. This area exposes sub-meridian folds associated with numerous N- to NW-
13 trending major fault systems. This study together with previous surveys reveals that this N-trending
14 folding is believed to be related to the inversion of the Jurassic and Early Cretaceous pre-existing
15 fault zones and generated in response to the late compressive deformations. In addition, the study
16 area provides evidence of soft-sediment deformations by good exposures of Cretaceous-aged slump
17 sheets. Slump folds are usually associated with several meso-scale syn-sedimentary normal faulting
18 together with frequent reworked blocs and occasional conglomeratic horizons. All these features
19 indicate sedimentation on irregular seafloor topography. The aim of the present study is to
20 investigate slump folds by applying techniques to reconstruct the contemporaneous slope gradient
21 which has triggered soft-sediment deformations. Moreover, the brittle deformation is quantified
22 using fault kinematic analysis together with the analysis of lithostratigraphic correlation and syn-
23 sedimentary structures. Considerable thickness variations of Cretaceous deposits are interpreted as
24 controlled by normal faulting activities. Likewise, fault kinematic analysis typifies a regional pure
25 extension that trends NNW during Barreman, NNE during Albian and probably NW during
26 Cenomanian time. Based on slump folds analysis, the inferred sub-marine paleoslope is believed to
27 have a northward dipping during Barremian and a NNE-dipping during Albian time. On the light of
28 the over-mentioned interpretations, it is believed that Cretaceous sedimentation of the study area is
29 highly controlled by major syn-depositional normal faults associated with intra basin growth faulting.
30 These fault systems seem to be related to the Southern Tethyan expansion of the rifted continental
31 passive margin.

32 **Keywords:** Slumping, Submarine paleoslope, Fault Kinematics analysis, Northern Tunisia, Cretaceous.

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37 **1. Introduction**

38 Slumping is one of the most common features that characterize gravity-driven structures, dealing
39 with unlithified sediments above an irregular basin floor. Slump folds seem to be the most significant
40 deformation reflecting downslope flow (Strachan and Alsop, 2006). These soft-sediment
41 deformations reflect the orientation of the palaeoslope. Many paleogeographic reconstitutions can
42 be recognized using the systematic and meaningful link between slump folds distribution and the
43 sub-marine paleoslope attitude above which they were initially triggered (Woodcock, 1979; Strachan
44 and Alsop, 2006; Debacker and De Meester, 2009; Alsop and Wenberger, 2020). After the pioneering
45 work of Jones (1940), many studies have investigated the soft-sediment deformations and described
46 a lot of statistical methods which have been applied in a number of settings to deduce the
47 paleoslope dip direction from slump features (Hansen, 1965, 1967; Woodcock, 1979; Bradley and
48 Hanson, 1998; Strachan and Alsop, 2006; Strachan, 2008; Debacker and De Meester, 2009; Debacker,
49 2012; Alsop and Marco, 2011, 2012a, b, 2013, 2014; Yong and al., 2013; Sharman et al., 2015).

50 Submarine mass-movement within the Cretaceous sequences of Borj Cedria provides a well-exposed
51 example of soft-sediment deformation patterns within slump sheet. The Cretaceous sub-marine
52 slumping of this area is related to the Southern Tethyan rifted continental margin evolution (Marie et
53 al., 1982; Turki, 1985; Martinez et al., 1990; Saadi, 1990). Thus, during the rifting stage, major growth
54 faulting is highlighted which is responsible for basin floor instability. Consequently, many slope
55 failures occur on top of which incoherent sediments move downwards due to their pure gravity
56 and/or seismic activity (Strachan and Alsop, 2006; Alsop et al., 2013; Sharman et al., 2015). A large
57 spectrum of mass transport deposits is described related to slope gradient degree (Strachan, 2006;
58 Alsop and Marco, 2011, 2012a, b; 2014; Sharman et al., 2015). The mechanisms of the gravity-driven
59 deformational features are still poorly known or even not well characterized in this area and the
60 basin architecture is classically studied only on the basis of stratigraphic and/or sedimentologic tools
61 (Bey et al., 2012; Amri et al., 2018).

62 This paper aims to explore a good number of structural features in order to drawback the Cretaceous
63 basin architecture. Therefore, the main goal is to determine the sub-marine paleoslope direction
64 from slump features on the basis of the genetic link between the original slope and slump fold
65 distribution. Lithostratigraphic correlations together with detailed syn-sedimentary structures
66 analysis are also used to infer the paleoslope direction. Furthermore, the brittle deformation, which
67 reflects the paleostress state, is quantified through the kinematic analysis of syn-sedimentary fault
68 populations.

69 **2. Geologic setting**

70 The study area belongs to the northeastern part of Tunisia, located close to the gulf of Tunis (Fig. 1).
71 Tunisia corresponds to the far northeastern part of the NE-trending Atlas belt structured by
72 continuous compressions between the African and Eurasian plates during Cenozoic time (e.g.,
73 Guiraud, 1998; Frizon De Lamotte et al., 2002; Stampfli et al., 2002). The Tunisian Atlas system
74 belongs to the eastern part of the Alpine belt of Africa known as the “Maghrebides Chain”. Except for
75 its far northern side which belongs to the Numidian thrust domain, the northern Tunisian Atlas is
76 commonly divided into two well-known structural entities (Fig. 1):

77 The Borj Cedria-Bou Kournine studied area is affiliated to the Zaghouan–Ressas thrust which
78 constitutes the southern front of the Tunisian Alpine province. This first unit is bounded by a reverse
79 inherited major fault. During Mesozoic times, this large-scale faulting forms a paleogeographic
80 borderline separating a relatively southward shallow marine platform from a northward deep marine
81 basin (Burolet, 1956, Morgan et al., 1998; Soua, 2016).

82 The second one corresponds to the major Teboursouk thrust entity which marks the northern front
83 of the Alpine domain. This second unit is composed of a large number of salt structures belonging to
84 the northeastern Maghreb salt province (Masrouhi et al., 2013; Jaillard et al., 2013a, b, 2017).

85 During the Mesozoic times, the Tunisian realm is subjected to a continuous geodynamic expansion of
86 the northern Atlas chain. Primarily, a Mesozoic rifting took over the Permian passive continental
87 margin of North Africa (Frizon de Lamotte et al., 2015) that extended to the Early Cretaceous
88 (Guiraud, 1998; Rosenbaum et al., 2002; Stampfli et al., 2002; Bouaziz et al. 2002; Soussi, 2003;
89 Guiraud et al. 2005; Gharbi et al., 2013). From the latest Cretaceous to the present, a compressional
90 tectonic stage is highlighted with shortening tectonic episodes interrupted by relative tectonic
91 quiescence periods (Guiraud and Bosworth, 1997; Frizon de Lamotte et al. 2002; Masrouhi et al.,
92 2008).

93 The rifting phase occurring during the Early Mesozoic time has resulted in Triassic mini-basins
94 dominated mainly by thick beds of evaporites, dolomites and clays reflecting epicontinental
95 depositional environment (Snoko et al., 1988; Kamoun et al., 2001; Soussi et al., 2017), overlaid by
96 Jurassic carbonate layers which were deposited during the Tethyan rifting (Soussi, 2003; Boughdiri et
97 al., 2007). From the Jurassic to early Cretaceous, major extensional tectonic events predominated in
98 relation with the breakup of the Central Atlantic (Snoko et al., 1988; Souquet et al., 1997; Soussi et
99 al., 2000; Boughdiri et al., 2007; Masrouhi and Koyi, 2012; Bahrouni et al., 2016; Dhahri and Boukadi,
100 2017, Naji et al., 2018a). This extensional episode is responsible for the dislocation of the continental
101 platform resulting in considerable synsedimentary normal faults creating tilted blocks basin
102 architecture. Accordingly, this basin configuration is characterized by irregular sea-floor topography,
103 responsible for thickness and/or facies variations, abundant slumps sheets within syntectonic early

104 Cretaceous sequences (Snoké et al., 1988; Guiraud et al. 2005; Soua et al., 2009; Gharbi et al., 2013;
105 Masrouhi et al., 2014b; Jaillard et al., 2013; 2017; Naji et al., 2018a, b). During early Cretaceous
106 times, this extensional tectonic regime was accompanied along this margin by hyperactive
107 halokinetic movements (Masrouhi et al., 2013; Dhahri and Boukadi, 2017, Jaillard et al., 2017;
108 Belkhiria et al., 2017). Furthermore, by locality, volcanic activity recognized by basaltic flows was
109 described as the result of rift-related magmatism. (Mattoussi Kort et al., 2009). These particular
110 features (both halokinetic and volcanic activities) characterize the Tethyan passive margin style
111 (Mattoussi Kort et al., 2009; Dhahri and Boukadi, 2017, Jaillard et al., 2017). In addition, the late
112 Aptian to the lower-middle Albian period is characterized by the most extensional event of the south
113 Tethyan margin in northern Tunisia (Souquet et al, 1997; Masrouhi et al., 2014b, Naji et al, 2018a, b;
114 Amri et al., 2020). A paleogeographic differentiation between platforms in central and southern
115 areas (Gharbi et al., 2013) and a deep trough in the northern area is implied (Burolet, 1956).
116 Moreover, during the same period, relevant Cretaceous halokinesis indicated thick and/or thin-
117 skinned tectonic extension (Slama et al., 2009; Masrouhi and Koyi, 2012; Amri et al., 2020). The early
118 to middle Albian is perceived to coincide with the final stage of Atlantic Ocean opening (Jaillard et al.,
119 2013a, b). The late Cretaceous corresponds to an extensional post-rift cycle characterized by shallow
120 marine carbonate and open marine shale sedimentation. Subsequently, the deposition during this
121 period is essentially controlled by the isostatic response of successive depocenters and/or major
122 faults disposition (Gharbi et al., 2013; Naji et al., 2018a, b). A compressional phase, subsequent to
123 the Mesozoic rifting, has started since the Senonian time (Maastrichtian?). It is related to
124 African/Eurasia plates' convergence, inducing the Tethys seaway closure and the positive inversion of
125 the basin (e.g. Chihi, 1995; Gharbi et al., 2015; Masrouhi et al., 2019; Guiraud and Bosworth, 1997).

126 **3. Dataset and approach**

127 To study the tectono-sedimentary pattern along the northeastern Tunisia (Borj Cedria case study)
128 and deduce related paleoslopes orientations during Cretaceous time, lithostratigraphic correlation,
129 geological mapping together with field data collection (slump folds, directional syn-sedimentary
130 structures and fault kinematic analysis) are carried out. Subsequently, paleoslope orientation from
131 slump folds and sedimentary structures dataset is deduced using Stereonet 9 plotting software
132 (Cardozo and Allmendinger, 2013; Allmendinger et al., 2013). Moreover, the fault kinematic analysis
133 and paleostress reconstructions are made using Win-Tensor computer software (Delvaux and
134 Sperner, 2003, Delvaux, 2016).

135 To start with, the fault kinematic analysis yields important information about the brittle deformation.
136 Such analysis provides a main description of the reduced stress tensor consisted of the related trends
137 of the three principal stress axes (σ_1 , σ_2 , σ_3) with the stress ratio (R). Three tectonic regimes

138 (extensional, strike-slip or compressional regime) are distinguished based on the vertical principal
139 stress. The relationship between the three stress orientations σ_1 , σ_2 and σ_3 is illustrated by the
140 stress ellipsoid and can be given by the stress ratio R ranging from 0 to 1 and denoted as following: R
141 $= (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (Angelier and Goguel, 1979; Sperner and Ratschbacher, 1993; Ritz and Tobaoda,
142 1993; Bellier and Zoback, 1995). Here, the study area exposes a large number of sealed normal faults
143 in which related fault displacement and type are recorded on fault mirrors. However, in some cases,
144 fault planes show different families of striae. In such conditions, the separation of generations (slip
145 vectors) is made by referring to structural arguments using relative chronology of the striations (i.e.,
146 crosscutting relationships) together with their relations with regional recognized tectonic phases.
147 Specifically, meso-scale sealed syn-sedimentary faults have been especially surveyed here, because
148 they directly provide the date of the tectonic event. Collected from Borj Cedria outcrops, the fault
149 datasets are processed to deduce the paleostress tensor on the basis of the "Right Dihedron
150 method" (Angelier and Mechler, 1977; Tranos, 2017) and/or the Optimum methods (Delvaux et al.,
151 2012). Moreover, It is important to note that all fault datasets need to be tilted back to their original
152 horizontal orientation in order to assume the initial stress tensors.

153 On the other hand, the ductile deformation is highlighted using slump folds investigation based on
154 the assumption that the distribution of slump deformations has been correlated to the orientation of
155 the underlying sub-marine slope (Fig. 2A). Jones (1940) was the first geoscientist who carries out this
156 perception through the Mean Axis Method (MAM) based on the affiliation between the mean slump
157 fold axis and the related paleoslope orientation (Fig. 2B). Later, geoscientists have been interested in
158 the study of soft-sediment deformations and they described different methods for deducing
159 paleoslope dip direction from slump folds (e.g. Hansen, 1965, 1967; Woodcock, 1979; Bradley and
160 Hanson, 1998; Alsop et al., 2001; Strachan and Alsop, 2006; Strachan, 2008; Debacker and Meester,
161 2009; Debacker, 2012; Yong et al., 2013; Alsop and Marco, 2011, 2012a, b, 2013, 2014; Sharman et
162 al., 2015). In the present study, the paleoslope analysis using slump folds is conducted on the basis of
163 two methods: the Mean Axis Method (MAM) and the Axial-Planar Method (APM) (Fig. 2B). The first
164 one (Mean Axis Method) originally developed by Jones (1939), and later reviewed by Woodcock
165 (1976b) who postulated that slump fold axis may develop at right angles to the downslope
166 orientation and recognized statistical arrangement perpendicular to the flow or slump sheet
167 trending. Thus, this first method suggests two hypothetical transport directions which are
168 diametrically opposed. Subsequently, the paleoslope dip direction is commonly selected by referring
169 to the regional known paleogeographic stress (Jones, 1939, Woodcock, 1976b), and/or on the basis
170 of the vergence of slump features (Woodcock, 1976b). Furthermore, it should also be noted that
171 slump folds measurements or at least the deduced paleoslope orientation need to be tilted back to
172 their original orientations in order to remove later tectonic deformations. Otherwise, this method

173 (MAM) has the advantage of being statistically powerful as a result of being based on average
174 properties of fold measurements. However, the main inconvenient of this method that it does not
175 work with downslope (Fig. 2C) where slump axes are trending in parallel or oblique to the flow
176 orientation (Woodcock, 1979; Strachan and Alsop, 2006; Alsop and Holdsworth, 2007). The second
177 method called the Axial-Planar Method (APM) uses the fold axial planes which provide significant
178 kinematic perception in the same way as slump axes (Woodcock, 1976a, 1976b; Woodcock, 1979;
179 Sharman et al., 2015). Subsequently, the poles to axial surfaces have tendency to range in a great
180 circle around the mean fold axis, and consequently the strike of the best-fit girdle to these poles
181 yields a bi-directional indication of slumps flow orientation (Woodcock, 1976b, Sharman et al., 2015).
182 Moreover, the imbrication of the mean axial plane respectively to the general slumps flow trending
183 may be used to deduce the original slope orientation (Woodcock, 1976b).

184 4. Tectono-sedimentary dataset

185 4.1. Lithostratigraphy of the study area and correlation of measured sections

186 The study area (Fig. 1) shows well-exposed outcrops of Mesozoic and Cenozoic series which are easily
187 recognizable and accessible. In this section, detailed Cretaceous lithostratigraphic description and
188 correlation between the study area and surrounding fields are made (Fig. 3) on the basis of the
189 current investigation with previous studies (e.g. Turki, 1985; Ouahchi et al., 1993; Morgan et al.,
190 1998).

191 The Barremian to Aptian successions exposed in northeastern Tunisia have an estimated thickness of
192 about 2500 meters in Jebel Oust which is considered as a potential reference section for the early
193 Cretaceous (Souquet et al., 1997). The early Cretaceous outcrops of northeastern Tunisia have been
194 usually characterized as “flyschoid deposits” which are mostly made of continuous alternation of
195 sandstone beds and shale layers deposited in a deep-water environment. The turbidite, carbonate
196 breccia and conglomeratic layers are often found that indicate syn-tectonic activities (Memmi, 1981,
197 1989; Souquet et al., 1997; Naji et al., 2018b).

198 In the study area, situated 30 km to the northeast of Jebel Oust, The Jurassic and lower Cretaceous
199 lithofacies include reefs and bioclastic limestone beds associated with syn-tectonic soft-sediment
200 deformations, intraformational breccias and debris flows (Cossey and Ehrlich, 1978; Marie et al.,
201 1982; Turki, 1985; Morgan et al., 1998). Several authors (Cossey and Ehrlich, 1978; Marie et al., 1982;
202 Turki, 1985; Soussi, 2003) have postulated the presence of submerged paleohigh developed in the
203 top the Bou Kournine-Ressas tilted block around the Jurassic-Cretaceous transition. During
204 Barremian-Albian period, this area corresponds to a reef platform domain and the depositional
205 environment is mainly marked by gravity tectonics (Marie et al., 1982; Turki, 1985; Martinez et al.,
206 1990). The geodynamic context of this period appears to be guided essentially by N45 and E-W

207 trending normal faulting (Turki, 1985). Furthermore, the preserved tectono-sedimentary markers
208 correspond to olistolithes, monogenic breccias and slumping sheets encountered in the Barremian
209 and Albian deposits of Borj Cedria area. The Cenomanian-Turonian sedimentation is characterized by
210 para-reef bioclastic limestone (Isis Member), deposited in an outer platform (Marie et al., 1982). To
211 the east, considerable thickening of the reef deposits is described, particularly in the Gulf of
212 Hammamet area (Sebei et al., 2019), before grading into clays with planktonic microfauna in the Cap-
213 Bon, characteristic of open sea (Marie et al., 1982). Moreover, the geodynamic context of the late
214 Cretaceous period exhibits the reactivation of inherited faults. Thus, Early Cretaceous E-W trending
215 faults seem to be reactivated as dextral-normal movement in the study area. The sedimentation is
216 controlled essentially by N40 and N140 trending syn-sedimentary normal faults separating subsiding
217 zones with high rate of sedimentation from paleohigh zones characterized by condensed late
218 Cretaceous series (Turki, 1985; Martinez et al., 1990).

219 The lithostratigraphic correlation established between Jebel Mekki in the South and Jebel Bou
220 Kournine-Borj Cedria in the North highlights significant northward thickening of Barremian-Santonian
221 series clearly showing tilted blocks geometry (Fig. 3). Then, Barremian sequences, composed of
222 marly-nodular limestone alternating with siliciclastic sandstone beds, shows a considerable thickness
223 increase from Jebel Mekki to Jebel El Khourrija (Fig. 3). On the one hand, this thickness variation is
224 believed to be linked to E-W-trending normal faults activities. On the other, the Barremian beds
225 exposed in Bou Kournine-Borj Cedria area and Jebel El Khourrija structure are equal in thickness. The
226 Barremian sequences of Bou Kournine-Borj Cedria show large number of syndepositional structures
227 with frequent slump folds generated by syn-tectonic extensional activity. In this area, the Aptian-
228 Albian deposits are composed of gray to black marls and alternating limestone and discrete
229 sandstone beds. These deposits include slump sheets and show a northward thickness increase.
230 During the late Cretaceous, the siliciclastic input became reduced and sedimentation was going to be
231 more uniform generally composed of marl and fine grained limestone beds. From Jebel Mekki to
232 Jebel Bou Kournine, a northward thickening of the late Cretaceous deposits has been perceived (Fig.
233 3).

234 **4.2. Analytical results illustrating the syndepositional faulting**

235 In the current study, field survey has been conducted to investigate fault kinematic analysis that
236 yields significant information about the paleostress tectonic regime. Our study area (Fig. 4A) exposes
237 multiple Cretaceous meso-scale syndepositional faults with well-preserved brittle tectonics
238 indicators (Fig. 4). Syndepositional striated faults are especially surveyed in order to deduce tectonic
239 regime during Barremian, Aptian and Cenomanian-Turonian intervals.

240 **4.2.1. Barremian tectonic regime**

241 The Barremian sequences display evidence for conglomerate-rich and slumped beds in addition to
242 frequent syn-sedimentary meso-scale normal faults (Fig. 4B and C). Therefore, numerous faults
243 datasets are collected from Barremian deposits and rotated to their primitive orientation in order to
244 restore their initial tectonic regime. As a result, the computed stress tensors corresponding to this
245 area reveals a mostly uniform stress field. In this regard, four sites are processed and provide a pure
246 extensional tectonic regime with a general WNW to NNW trending during this period. In more
247 details, back-tilted fault diagrams of three sites (Fig. 5, S1, S4 and S5) exhibit a stress tensor showing
248 a NNW-trending extensional tectonic regime. However, the analysis of fault population of the only
249 remaining site (Fig. 5, S3) illustrates extension that trends WNW-ESE.

250 **4.2.2. Aptian-Albian tectonic regime**

251 The study of Aptian-Albian deposits reveals frequent ~NW-SE and NE-SW trending meter-scale sealed
252 normal faults (Fig. 4D and E). The processed striated fault planes clearly provide that the
253 predominant paleostress regime in the study area shows a general NNE to NE-trending extension.
254 Five sites are consequently analyzed to deduce the Aptian-Albian paleostress regime. In details, four
255 sites (Fig. 5, S6, S78, S11 and S12) reveal a pure extensional tectonic regime with a stress tensor
256 characterized by NNE-trending. Whereas unfolded fault measurements of the remaining site (Fig. 5,
257 S13) illustrate similar pure extensional regime with NE-trending stress tensor.

258 **4.2.3. Cenomanian-Turonian tectonic regime**

259 The Cenomanian-Turonian outcrops show remarkable synsedimentary extensional features
260 (reworked blocks, nodules, olistolithes...etc.) associated with meso-scale sealed normal faulting (Fig.
261 4F). Due to poor quality of outcrops, inaccessibility and observation gaps, a small number of striated
262 faults datasets is collected. Despite this, an extensional tectonic regime with NNW-SSE trending is
263 highlighted (Fig. 5, S9).

264 **4.3. Analytical results illustrating the regional stress tensor**

265 A comprehensive investigation of regional stress field along Borj Cedria-Bou Kournine faulted area
266 was highlighted in the current study. Striations measured on fault planes are used to characterize the
267 regional stress regime. Therefore, graphical methods have been here used to separate
268 heterogeneous data sets and eliminate non-linear measurements.

269 The study area is believed to be controlled by a persistent extensional tectonics related to the
270 Cretaceous Tethyan rifting (Turki, 1988; Ouahchi et al., 1993; Morgan et al., 1998). Likewise, the
271 inversion of 12 Barremain-aged fault data inputs indicates clear NNW-extensional tectonic regime.

272 In details, the corresponding back-tilted faults diagram illustrates horizontal NNW-trending minimum
273 stress tensor σ_3 (03/342) and a stress ratio $R=0,50$. The σ_1 axis of this stress regime has high angle
274 trending WNW-ESE- (83/097), the intermediate σ_2 stress trends ENE-WSW and shows 06/252 stress

275 axis (Fig. 6). Furthermore, 14 striated fault mirrors collected throughout well-exposed Albian
276 sequences across the Bou Kournine-Borj Cedria area are processed. Subsequently, the unfolded
277 faults diagram illustrates clearly NNE-SSW extensional tectonic regime according to the following
278 parameters: a stress tensor shows a gently plunging NNE-trending minimum stress axis (02/030) and
279 WNW-trending near-horizontal intermediate stress axis (00/300). The maximum stress tensor
280 displays a high dip angle and SSW-trending σ_1 (88/199). This fault population indicates a stress ratio
281 $R=0.46$ (Fig. 6).

282 4.4. Slumps analysis results

283 In the study area, Barremian and Albian sequences give evidences for well-developed soft-sediment
284 deformation structures which are highly related to the expansion of the Southern Tethyan rifted
285 continental passive margin (Masrouhi et al., 2014b; jaillard et al., 2017; Naji et al. 2018a,b). The
286 slumping, particularly generated in pre-existing mud-rich deposits, is the most typical kind of gravity-
287 driven sediment transport processes that reflect the slope attitude and the basin-floor topography.

288 In the current study, 21 meso-scale slump folds are collected throughout the Barremian sandy
289 limestone strata of the Bou Kournine-Borj Cedria area (Fig. 7). The most observed slump folds
290 geometry is described as asymmetric folds with thinner long limbs and thicker short limbs. This
291 assessment gives a preliminary idea about the transport direction (Fig. 7D). "Mean Axis Method" and
292 "Axial Planar Method" are rigorously applied for the collected Barremian slumps folds. Consequently,
293 both techniques give close values within a general northward dipping sub-marine paleoslope. The
294 analysis of restored slump axis (MAM method) highlights $\sim N008$ -trending paleoslope, whereas the
295 back-tilted poles to axial planes (APM method) show comparable value of $\sim N002$ -dipping paleoslope
296 (Fig. 7G).

297 The Albian deposits similarly show soft-sediment slumps related to the Cretaceous extensional
298 tectonic that occurred in the north-eastern Tunisia (Naji et al., 2018a). Abundant decametric slump
299 folds associated with frequent re-sedimented blocks and calcareous nodules are described within
300 Albian green-black marls series alternating with marly nodular limestone beds (Fig. 8). These features
301 are considered to be derived from gravity flows along a submarine paleoslope. Therefore, a good
302 number of Albian slump folds are measured and computed using the two methods (MAM and APM)
303 and illustrate a general $\sim NNE$ -dipping sub-marine paleoslope. More precisely, the restored slump axis
304 method illustrates a paleoslope orientation of $\sim N26$ and the unfolded poles to axial planes give a
305 value of $\sim N34$ -trending (Fig. 8G). Consequently, along the study area, the deduced paleoslope
306 dipping provides a persistent irregular basin floor. Likewise, the inherited early Cretaceous $\sim E-W$
307 trending faults system seems to remain active during Albian period in conjunction with
308 syndimentary $\sim NNW$ to $\sim NW$ trending normal faulting.

309 **4.5. Analytical results illustrating paleocurrent direction**

310 The early Cretaceous flysch deposits of Borj-Cedria area provide evidence for abundant centimetric
311 to decimetric “olistostromes” reworked blocks (Fig. 9d) associated with syntectonic conglomeratic
312 horizons which testify to active normal growth faulting. In addition, early Barremian sequences
313 highlight numerous directional syn-sedimentary structures (Fig. 9a, b, c, e) indicating a shallow
314 marine deposition. A paleocurrent analysis is rigorously performed through the examination of these
315 different Barremian-aged sedimentary structures (particularly flute and groove marks). The inferred
316 rose diagram (Fig. 9f) shows the result of the analysis of 17 rotated measurements and illustrates a
317 clear northward paleocurrent orientation. The latter seems to be persistent across the entire area in
318 the Barremian times. The result is correlated to slump fold analysis and consequently confirms the
319 regional northward Barremian paleoslope orientation.

320 **5. Discussion**

321 The fold-and-thrust belt of the Northern Tunisia observed at the present-day is the result of complex
322 tectonic expansion of the northern African margin which began with the late Permian break up of
323 Pangea and ended with the Cenozoic Alpine orogeny.

324 **5.1. Mesozoic paleoslope reconstruction of Borj Cedria-Bou Kournine area**

325 The geodynamic evolution of the northern margin of Africa has been mainly guided by the extension,
326 the crustal stretching and thinning, as well as subsidence during the Mesozoic Tethyan rifting
327 (Boughdiri et al. 2007; Mattoussi Kort et al., 2009; Gharbi et al. 2013; Soussi et al. 2017; Naji et al.
328 2018a,b). During the Jurassic and early Cretaceous period, the dislocation of the continental platform
329 in relation with the opening of Central Atlantic (Fig. 10A, B, C) is responsible for the creation of major
330 synsedimentary normal fault systems developing tilted blocks basin architecture (Martinez et al.,
331 1991; Snoke et al., 1988, Souquet et al. 1997; Piqué et al., 2002; Guiraud et al., 2005; Boughdiri et al.
332 2007; Masrouhi and Koyi 2012; Masrouhi et al., 2013; Gharbi et al., 2013; Tlig et al., 2015, Naji et al.,
333 2018b). A similar Mesozoic structural configuration with correlative extensional structures is
334 recorded in the northern range of the Tethyan margin including the Adria microplate (Masse and
335 Borgomano, 1987; Bertok et al., 2012; Santantonio et al., 2013; Tavani et al., 2015).

336 In northern Tunisia, the Jurassic and earliest Cretaceous sedimentation was controlled by E-W
337 normal faulting, created in response to a general N–S extension (Bouaziz et al., 1999, Piqué et al.,
338 2002). The inherited faults oriented NE–SW, NW–SE and N–S, were also active over the same time
339 (Piqué et al., 2002). The Jurassic series are largely composed of thick mass-transport deposits
340 separated by turbidite sequences (Fig. 10D). Therefore, the Jurassic depositional environment is
341 mainly guided here by major E-W growth faulting activities that control a northward regional
342 paleoslope (Fig. 10A) above which multiple soft-sediment deformations were triggered (Cossey and

343 Ehrlich, 1978). In addition, early Cretaceous deposits, outcropping in northern Tunisia, show
344 increased thickness and locally facies variations. It also display numerous soft-sediment
345 deformations, slumping, reworked blocks and syntectonic growth strata that are believed to be
346 coeval with the southern Tethyan rifted continental passive margin geodynamic evolution (Gharbi et
347 al., 2013; Naji et al., 2018a,b). In this regard, the Barremian deposits across the Bou Kournine-Borj
348 Cedria area provide evidence for numerous meso-scale slump folds (Fig. 7) associated with frequent
349 metric sealed normal faults. The turbiditic layers associated with frequent sandstone beds, show
350 directional sedimentary structures including hummocky cross stratifications (HCS), flute casts, groove
351 marks...etc., (Fig. 9) are here highlighted. The deposition of HCS structures requires careful
352 consideration of the possible ways that storm waves (oscillatory current) and turbidity current
353 (unidirectional current) interact both in time and space. Consequently, the HCS trigger is highlighted
354 to occur in proximal setting where the gradient of the slope is slightly inclined (Lamb et al., 2008). In
355 distal setting where slope gradient increases, the lack of oscillatory current flow leads to flute and
356 groove marks generation which reflects a unidirectional flow (Lamb et al., 2008). Thus, the
357 compilation of all these over-mentioned observations suggests for sedimentation above an irregular
358 basin floor under an extensional tectonic regime. A clear syn-rift Barremian tectonic style is likewise
359 highlighted.

360 The fault kinematics obtained from the analysis of unfolded striated fault mirrors collected from the
361 Barremian strata of the study area, display evidence for clear regional NNW-trending extensional
362 tectonic regime during this period. In addition, the back-tilted stereoplot shows frequent NE, NNE
363 and WNW-trending Barremian faults (Fig. 6). Using slump fold analysis, the unfolded slump axis and
364 poles of axial planes (MAM and APM respectively) illustrate very close results with a general
365 ~northward dipping sub-marine paleoslope during Barremian time (Fig. 10B). The same result is
366 confirmed through the paleocurrent indicators datasets (Fig. 9). In order to explain the ~N-S trending
367 of syn-sedimentary normal faulting which is here contemporaneous with the northward facing
368 paleoslope during the Barremian, two assumptions are here proposed. The first one suggests an
369 inherited ~E-W major fault situated to the south of the study area (probably between Jebel Bou
370 Kournine and Jebel Ressass), created during the Jurassic-earliest Cretaceous times that controls a
371 regional northward dipping paleoslope. The second assumption suggests a possible southward
372 located diapiric intumescence responsible for the northward dipping paleoslope during the
373 Barremian time. In this way, the southward Jebel Ressass structure is considered to be a salt diapir
374 developed during Cretaceous period (Jammeli et al., 2011; Turki, 1985; Martinez et al., 1990). In this
375 case, the extensive slumping is believed to be the result of salt intrusion which has fractured and
376 oversteepened the slope leading to instability and failure of the basin floor (Alsop et al., 2001; Alsop
377 and Holdsworth, 2007).

378 The Aptian - Albian time interval has long been recognized as the most extreme extensional period
379 characterizing the South Tethyan margins including the major part of northern Tunisia platform
380 which was broken up by active halokinesis (Martinez et al., 1991; Snoke et al., 1988; Souquet et al.,
381 1997; Vila et al, 1998; Piqué et al., 2002; Gharbi et al., 2013; Masrouhi et al., 2013; Jaillard et al.,
382 2017). Likewise, due to intense extensional tectonics, several widespread salt structures are
383 documented as having grown during the Aptian–Albian period which is also perceived to have
384 deposited the thick and rapid sedimentation rates (Souquet et al., 1997; Vila et al, 1998; Masrouhi et
385 al., 2014b; Jaillard et al., 2017). Some salt structures probably dominated by raft tectonics on
386 submarine salt bodies, especially active during the Albian time (Vila et al, 1998). The early to middle
387 Albian extension was correlated with the final stage of Atlantic Ocean opening (Jaillard et al., 2013).
388 In northern Tunisia, the sedimentation becomes more and more homogeneous since the Aptian-
389 Albian which is mainly made of limestone beds alternating with marls (Fig. 10D). In addition, Aptian-
390 Albian sequences show significant thickness variation with frequent sealed decametric normal faults
391 associated with abundant slump sheets. In this context, fault kinematic is obtained from the analysis
392 of restored fault, display evidence for homogenous paleostress tensor with a general ~NE-trending
393 pure extension (Fig. 6). More specifically, the MAM and APM methods typify very comparable results
394 within a general ~NNE-dipping sub-marine Albian paleoslope orientation (Fig. 10C). Based on these
395 findings, the Aptian-Albian sedimentation seems to be mainly controlled by NW to NNW-trending
396 normal faults (Fig. 6), in agreement with previous results (Turki et al., 1988, Piqué et al., 2002). In
397 addition, the unfolded Cenomanian fault diagram illustrates NW-trending extensional tectonic
398 regime. From the Cenomanian to the Campanian, the pelagic to hemipelagic depositional
399 environments were widely distributed, guided mainly by the isostatic response of major fault
400 systems and/or depocenters, developed during an extensional period of post-rift stage (Gharbi et al.,
401 2013; El Amari et al., 2016; Naji et al, 2018a, b).

402 5.2. Present-day configuration of Borj Cedria-Bou Kournine area

403 The northern Atlas domain of Tunisia is characterized by numerous NE-trending Atlassic folds
404 (classically called the “Atlassic direction” in the literature) resulting from the major northwest-
405 trending Mid-Miocene tectonic compression (Ben Ayed, 1986; Chihi, 1995; Bouaziz et al., 2002;
406 Masrouhi et al., 2019; Khomsi et al., 2019). Although, the study area exposes sub-meridian fold belts
407 (Fig. 1). This N-S trending folding is highlighted in some other localities from northern Atlassic domain
408 of Tunisia including Jebel Naheli (Ben Ayed, 1986), Jebel Touila located in the Nebeur area
409 (Chikhaoui, 1988)...etc. In addition, two principal major fault populations are highlighted across the
410 study area (Fig. 1): (1) A N-S trending faults which divide the region into several blocks probably
411 created during the Barremian; (2) A NW-trending faults located in the southern and northern parts of
412 the field and which seem to control the sedimentation during the mid to late Cretaceous.

413 Subsequently, a stress field perturbation is observed to the right of N-S trending major faults and an
414 E-W contraction has acted during the general NW-trending Alpine Cenozoic compression as
415 previously mentioned by [Martinez et al., 1990](#). This assumption is based on numerous field
416 observations including shear planes striae, schistosity, bench on bench sliding, stylolitic peaks...etc. In
417 addition, NW-trending faults which delineate this area are responsible for movements toward the
418 south-east ([Turki, 1985](#); [Martinez et al., 1990](#)).

419 A second structural complexity of the study area lies in the fact that Jurassic limestones are thrust
420 in normal position over the Cretaceous deposits. The Jurassic series are now at 570 m of elevation
421 ([Fig. 10D](#)). Based on lithostratigraphic and structural affinities, it is believed that Jurassic deposits
422 have been elevated up here at least 1500 m above their original position. The thickness and facies
423 variations characterizing the Jurassic and Cretaceous series of the study area indicate that Mesozoic
424 sedimentation was controlled by active extensional setting. Subsequently, such variations have
425 guided the style and the position of the major subsequent thrusting ([Turki, 1988](#); [Martinez et al.,](#)
426 [1990](#); [Souquet et al. 1997](#); [Morgan et al. 1998](#)). In addition, previous studies of [Turki, 1985](#); [1988](#)
427 highlights the involvement of the Triassic evaporites in the main thrust fault. Therefore, all the
428 above-mentioned features are in favor of fault systems inversion model for the development of the
429 major faults of the study area as it was drawn on the cross section of the [Fig. 10D](#). This cross section
430 illustrates the present-day structural configuration of Borj Cedria-Bou Kournine area. It shows clearly
431 reverse pre-existing Jurassic and early Cretaceous normal faulting systems. The basement detached
432 fault within the Triassic deposits is believed to be the continuity of the present day major Zaghouan
433 thrust fault.

434 **6. Conclusion**

435 The Cretaceous outcrops of Bou Kournine-Borj Cedria area, Northern Tunisia, exhibit multiple soft-
436 sediment deformations related to major synsedimentary normal faulting that was responsible for
437 irregular basin geometry. This architecture is marked by variable paleoslope distribution in context of
438 the Tethyan rifted continental passive margin. Subsequently, the lithostratigraphic correlation
439 established in the current study illustrates a significant thickness variation of the Cretaceous series
440 due to both inherited and syn-depositional growth normal faulting activities. The results are
441 summarized as follows:

442 1) Fault kinematic analysis of Barremian striated planes typifies NNW-trending regional extensional
443 tectonic regime. 2) Slump folds together with directional sedimentary structures analysis testify a
444 general northward dipping sub-marine Barremian paleoslope. 3) During the Aptian-Albian period, the
445 study area seems to be controlled by NNE-trending regional extensional tectonic regime. 4) Using
446 slump fold analysis methods, an Albian ~NNE-dipping sub-marine paleoslope is depicted. 5) The N-

447 trending folding is believed to be related to the pre-existing fault zones and generated in response to
448 the late compressive deformations.

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733 **Figures captions**

734 **Figure 1:** Geological map of the study area (Slightly modified from [Turki, 1985](#)). The inset in the top
735 right shows the location of the study area in northeastern Tunisia.

736 **Figure 2:** Fold patterns in slump trigger. A) Model used to relate slump fold geometry to paleoslope
737 attitude (Slightly modified from [Woodcock, 1976b](#)). B) Equal area plot of hypothetical fold axis and
738 poles of axial planes disposition to explain the mean axis, the separation, and the axial plane
739 methods. The best fit girdle to axes and poles to axial planes of the slump sheet are rotated to their
740 horizontals. The inferred paleoslope plunges to south (modified from [Woodcock, 1979](#)). C) folding
741 inducing during layer-parallel shearing (a) and layer-normal shearing (b), see [Alsop and Marco, 2011](#)
742 for more detail, and, associated facing direction (for more detail see [Alsop and Marco, 2011, 2012a](#)).
743 D) Fold facing orientation in schematic simulations summarizing the relationships between slump
744 folds vergence, axial plane and up-ward or downward facing states (see [Alsop and Marco, 2012a](#)).

745 **Figure 3:** Lithostratigraphic correlation of Cretaceous series of Bou Kournine-Borj Cedria with
746 surrounding area (Jebel Mekki and Jebel El Khourija). The inset in the Midst shows the location of
747 measured sections in northeastern Tunisia.

748 **Figure 4:** Photographic plate illustrating significant tectono-sedimentary features in the study area.
749 A) Panoramic view looking to the north showing the outcropping Barremian-Turonian series. B) Field
750 photo showing abundant meso-scale normal faults, sometimes with horst and graben geometry in
751 the Barremian strata of Borj Cedria area. C) Small-scale normal fault preserved in the sandy
752 limestone Barremian strata of the same area. D) Field photo showing small-scale extensive
753 deformation preserved showing a sealed normal fault in the Aptian sequences of Bou Kournine-Borj
754 Cedria area. E) Small-scale normal fault preserved in the nodular Cenomanian limestone series of
755 Jebel Srara (Borj Cedria area). F) Field photo showing abundant small-scale normal faults drawing
756 horst and graben geometry in the nodular Cenomanian limestone strata of the same area.

757 **Figure 5:** Simplified geologic map (extracted from Fig. 1) with the back-tilted stress tensors of
758 Barremian, Aptian and Cenomanian-Turonian fault populations collected from the study area with
759 the use of the Win-Tensor program ([Delvaux, 2016](#)). Fault slip data are computed through
760 Dihedron method.

761 **Figure 6:** Lower hemisphere projection of back-tilted major fault data sets showing the regional
762 paleostress regime in the study area during Barremian and Albian times.

763 **Figure 7:** Structural data from slump folds with inferred paleoslope direction during Barremian in Bou
764 Kournine-Borj Cedria area. A, B, C, D, E, F) Field photos that show well-preserved Barremian slump
765 folds. G) Equal area projection of restored (back-tilted) slump axis (blue box) and poles to axial planes
766 (red box) with respectively MAM (blue arrow) and APM (red arrow) methods.

767 **Figure 8:** Structural data from slump folds with inferred paleoslope direction during Albian in Borj
768 Cedria-Bou Kournine area. A, B, C, D, E, F) Field photos that show well preserved decametric Albian
769 slump folds. G) Equal area projection of unfolded slump axis (blue box) and poles to axial planes (red
770 box) with respectively MAM (blue arrow) and APM (red arrow) methods.

771 **Figure 9:** Paleocurrent orientation from the study area inferred from directional syn-sedimentary
772 structures with: a) Hummocky cross stratifications (HCS) with flute casts (F) collected from Barremian
773 strata. b, c, d) Flute casts (F) and groove marks (G) collected from Hauterivian-Barremian strata. e)
774 Reworked blocks (R) in the Barremian deposits. F) Rose diagram illustrating the paleocurrent
775 direction inferred from different directional sedimentary data sets (Flute casts, groove marks. etc...).

776 **Figure 10:** Simplified present-day structural configuration of Borj Cedria-Bou Kournine area: A, B, C)
777 Paleogeographic reconstruction map of the western Tethyan domain during respectively Bathonian,
778 Hauterivian and Albian times (From [Stampfli and Hochard, 2009](#)) with inferred paleoslope
779 assessment (colored arrow). The blue rectangle indicates the paleogeographic position of Tunisia. D)
780 Simplified cross-section across Borj Cedria-Bou Kournine area (slightly modified from [Turki et al.,](#)
781 [1988](#)) showing the present-day structural configuration of this area together with the related
782 deposits (lithostratigraphic sections). The inset in the left shows the location of the study area in
783 northeastern Tunisia.

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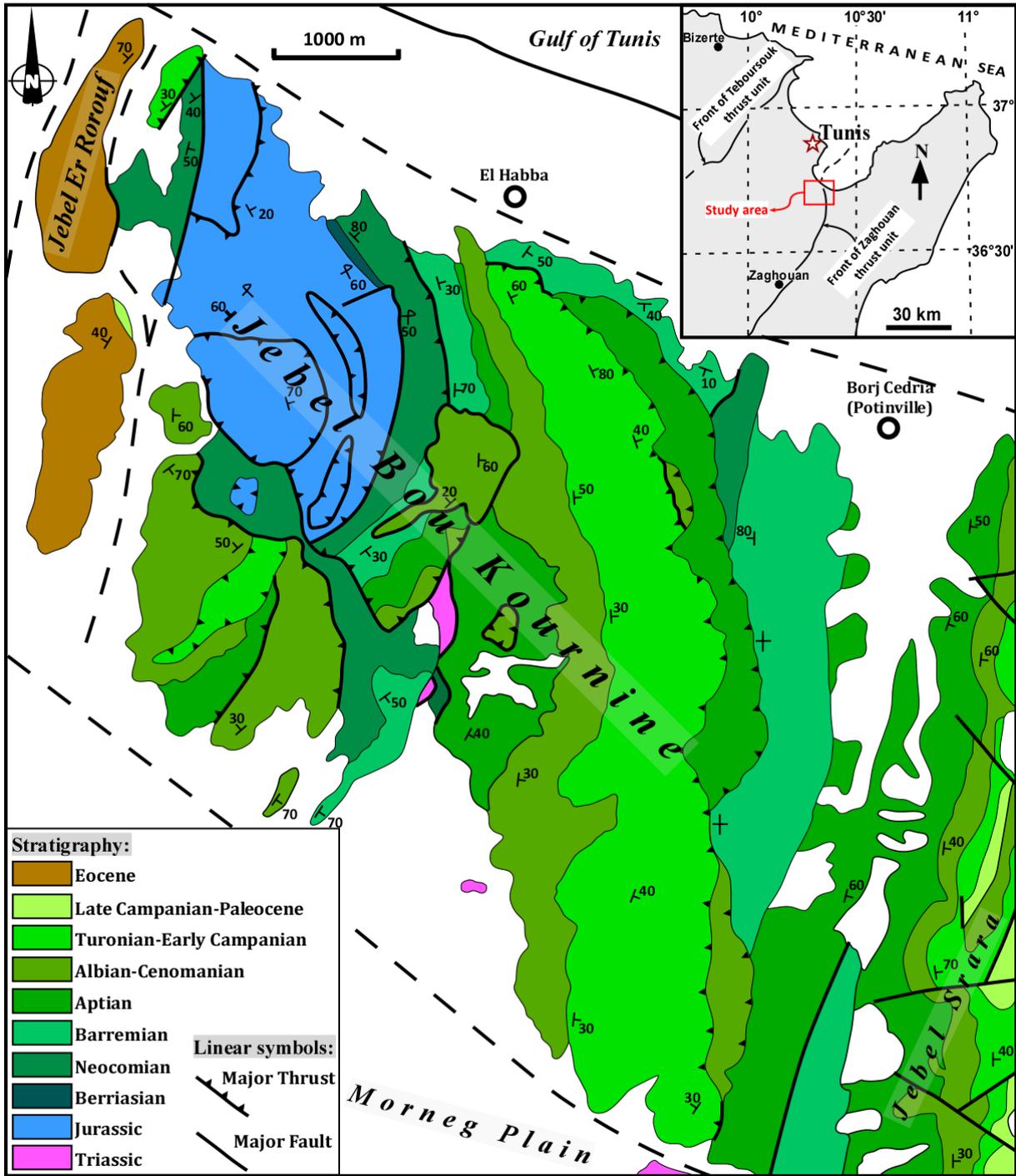
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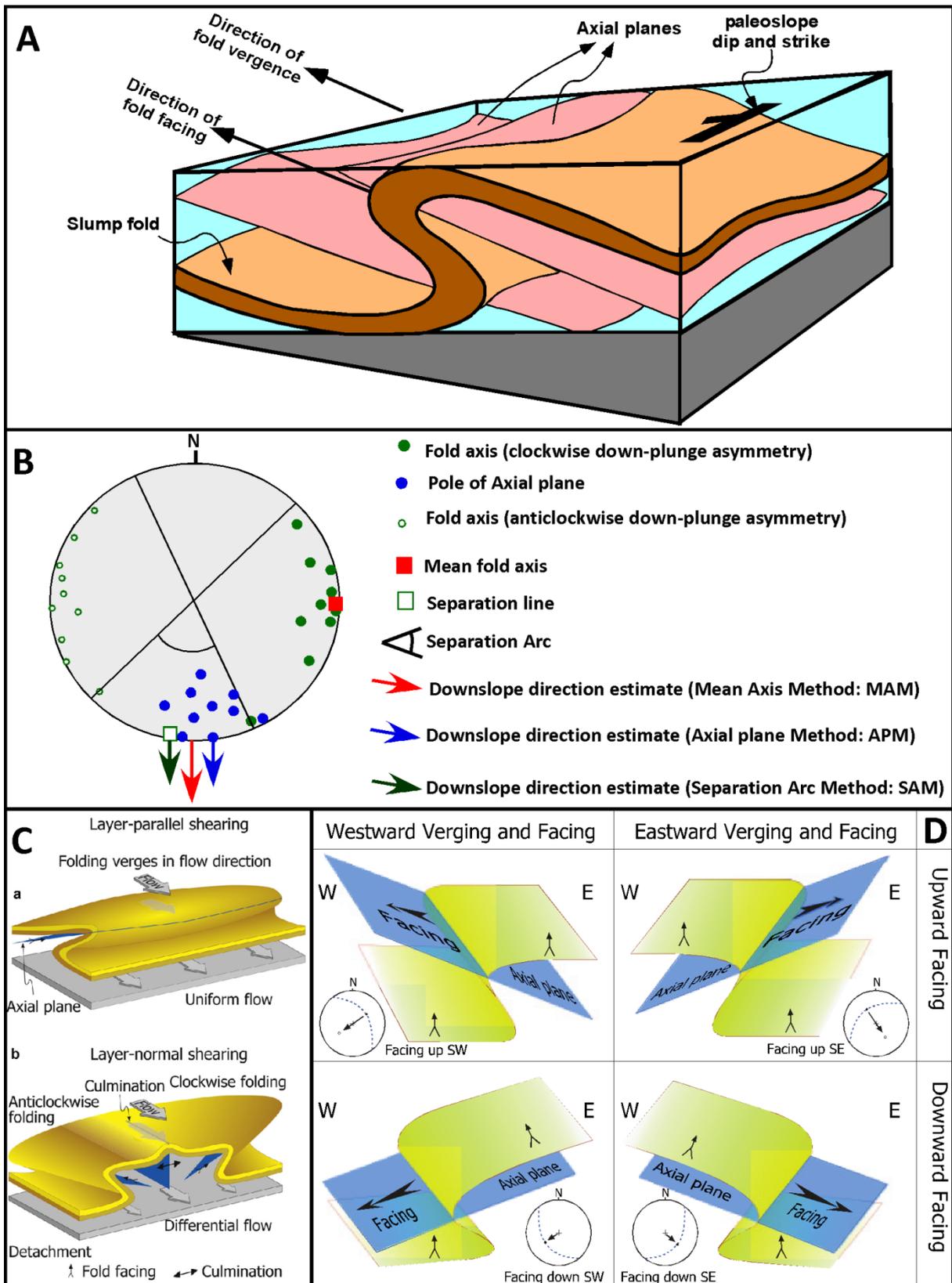
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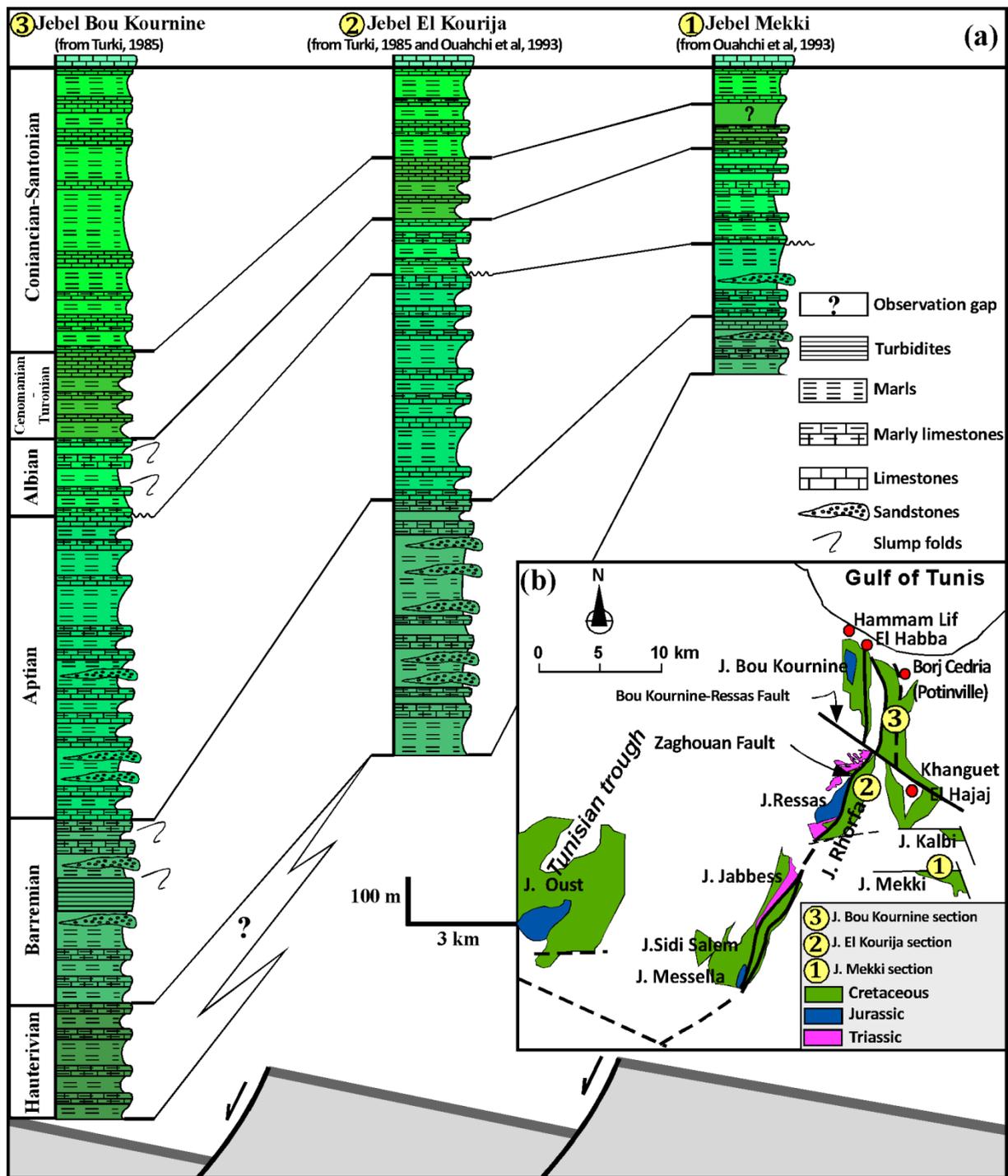
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793 Figure 1



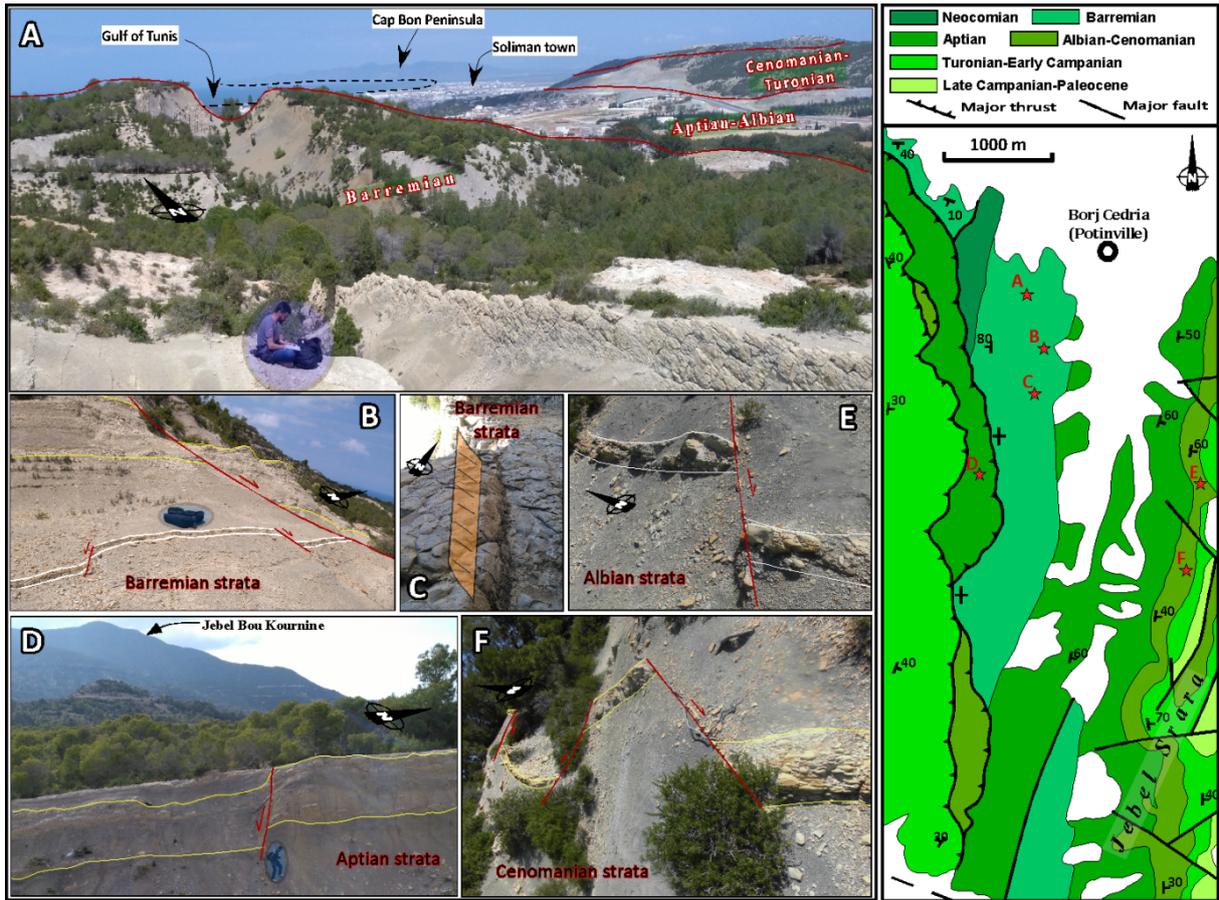
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795 **Figure 2**



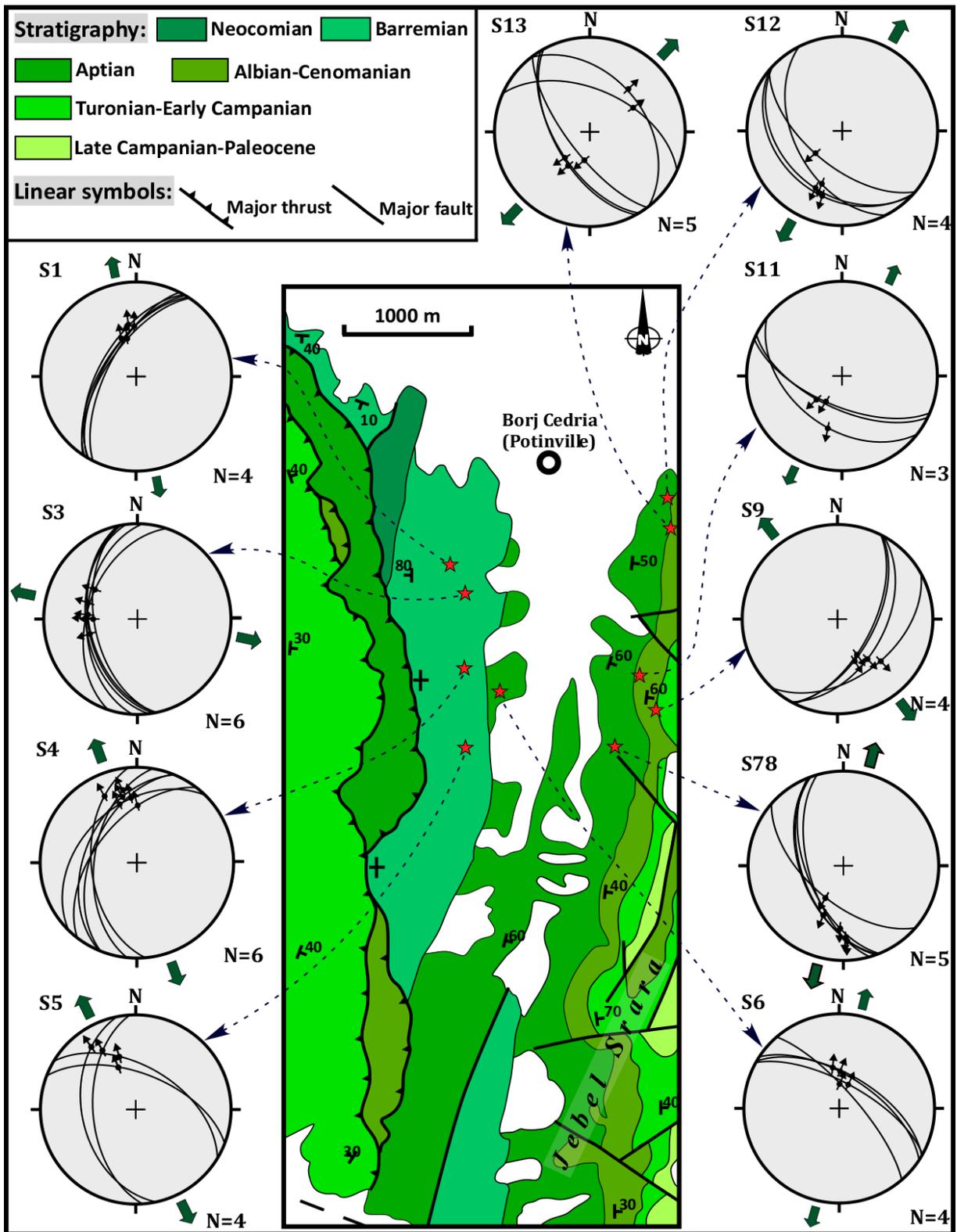
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797 Figure 3



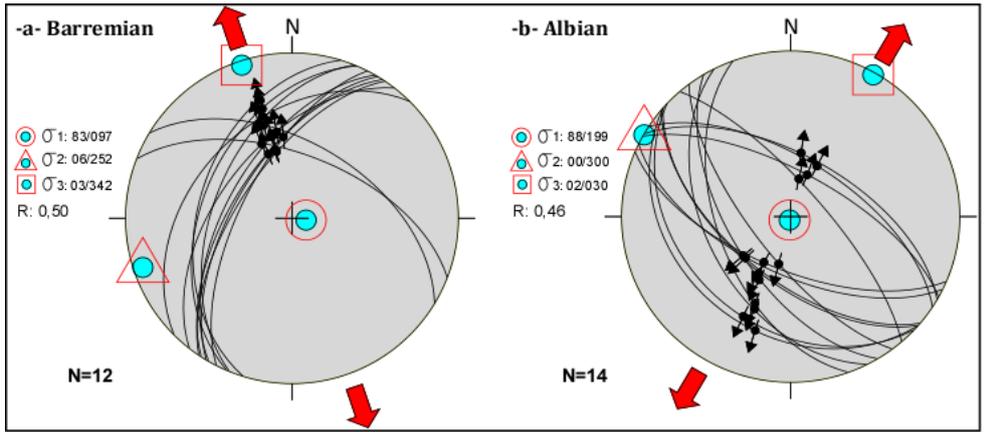
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799 Figure 4



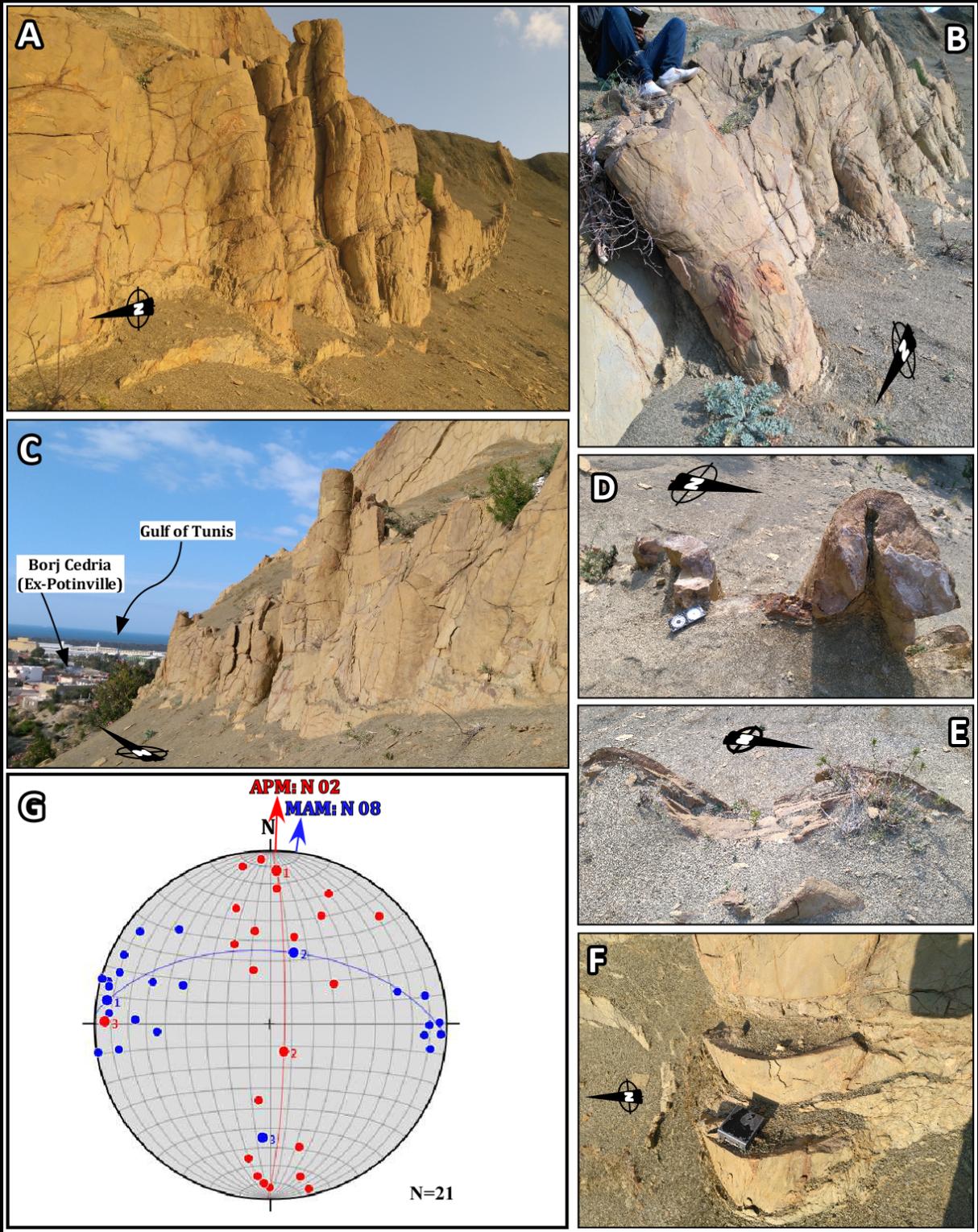
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801 Figure 5



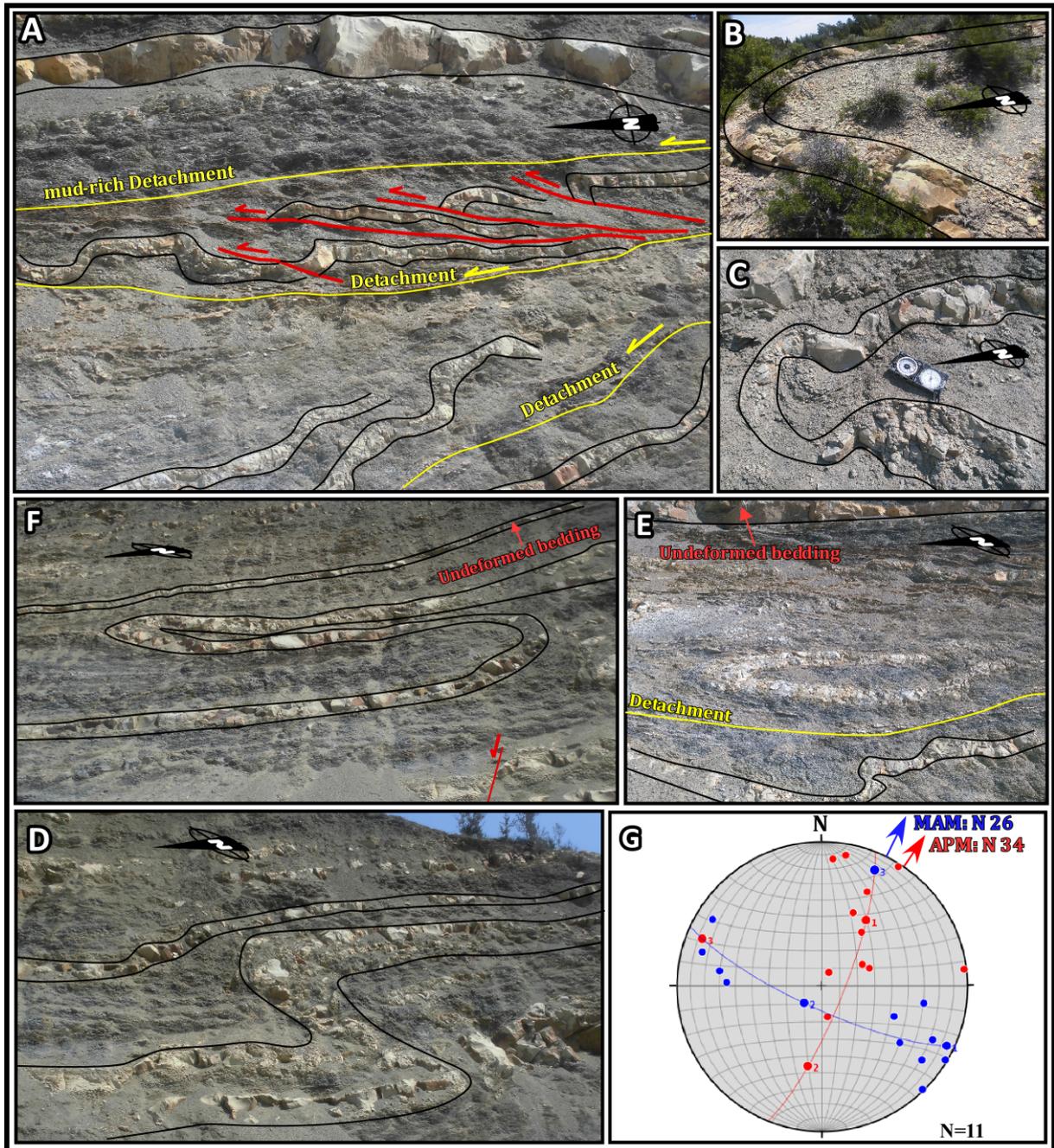
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803 **Figure 6**



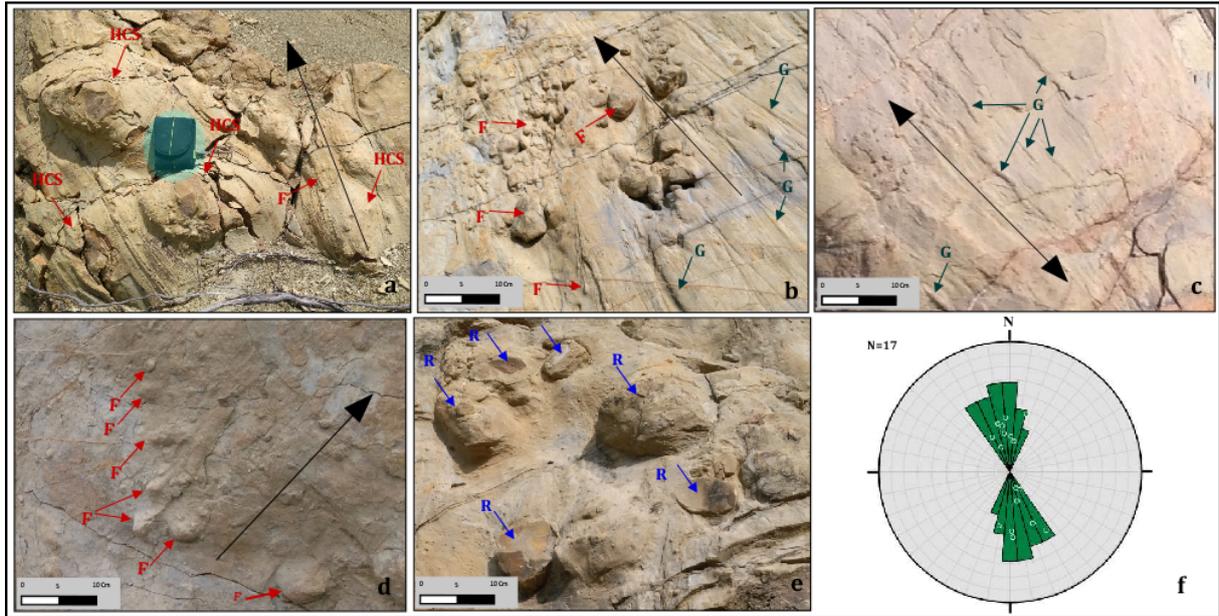
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805 Figure 7



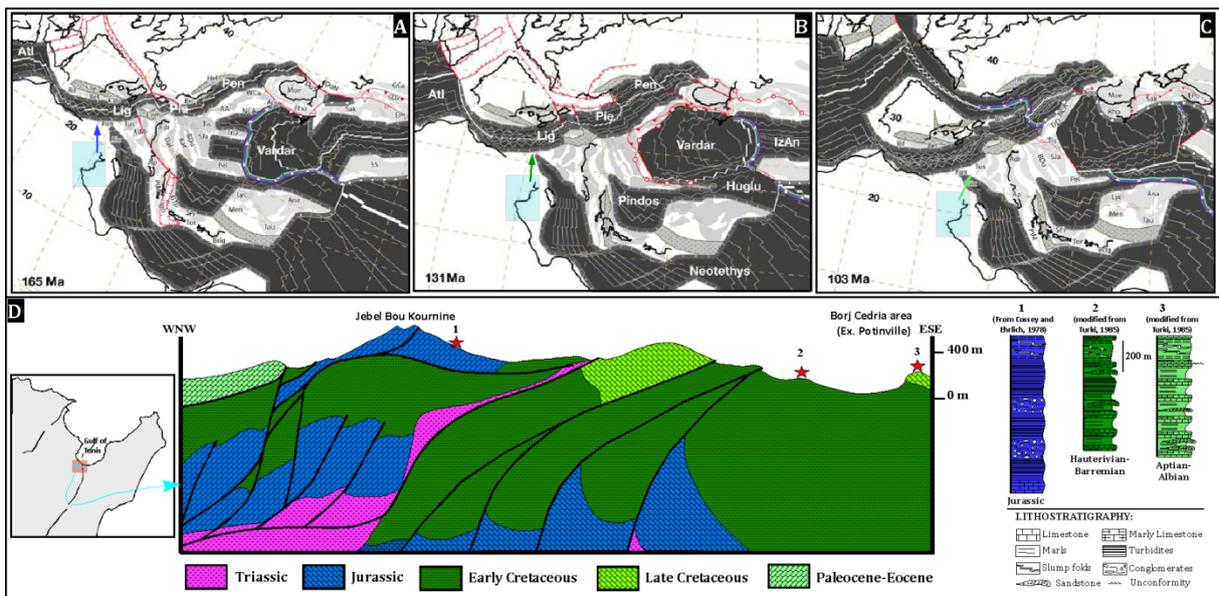
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809 **Figure 9**



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811 **Figure 10**