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1 **Structure and kinematics of an extensional growth fold, Hadahid Fault System, Suez Rift, Egypt**

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14  
15 **Abstract**

16  
17 Normal faulting drives extensional growth folding of the Earth's upper crust during continental  
18 extension, yet we know little of how fold geometry relates to the structural segmentation of the  
19 underlying fault. We use field data from the Hadahid Fault System, Suez Rift, Egypt to investigate the  
20 geometry and kinematics of a large (30 km long, up to 2.5 km displacement), exceptionally well-  
21 exposed normal fault system to test and develop models for extensional growth folding. The Hadahid  
22 Fault System comprises eight, up to 5 km long segments that are defined by unbreached or breached  
23 monoclines. These segments are soft-linked, hard-linked, or defined by a more subtle along-strike  
24 transition in overall structural style. High overlap:separation (O:S) ratios between its segments  
25 suggest the Hadahid Fault System comprises a single, now hard-linked structure at-depth. We  
26 demonstrate that a progressive loss of at-surface displacement along strike of the Hadahid Fault  
27 System results in surface-breaking faults and breached monoclines being replaced by unbreached  
28 monoclines developed above blind faults. However, shorter along-strike length-scale variations in  
29 structural style also occur, with unbreached monoclines developed between breached monoclines. The  
30 origin of this variability is unclear, but might reflect local variations in host rock material properties  
31 that drive short length-scale variations in fault propagation-to-slip ratio, and thus the timing and  
32 location of fold breaching. We show that folding is a key expression of the strain that accumulates in  
33 areas of continental extension, and argue that tectono-sedimentary models for rift development should  
34 capture the related structural complexity.

35  
36 **1. Introduction**

37

38           Stretching of the Earth's upper crust is invariably accommodated by the development of  
39 normal faults. Folds can also be locally important, with extensional growth folds (*sensu* Coleman et  
40 al., 2019) developing around the tips of propagating normal faults (Fig. 1) (e.g. Sterns, 1970; Patton,  
41 1984; Withjack et al., 1990; Schlische, 1994; Gawthorpe et al., 1997; Pascoe et al., 1999; Keller and  
42 Lynch, 2000; Maurin and Niviere, 2000; Corfield and Sharp, 2000; Sharp et al., 2000; Withjack &  
43 Callaway, 2000; Willsey et al., 2002; Gawthorpe et al., 2003; Jackson et al., 2006; Ford et al., 2007;  
44 Cardozo, 2008; Ferrill & Morris, 2008; El-Wahed et al., 2010; Ferrill et al., 2007; 2012; Wilson et al.,  
45 2013; Deckers, 2015; Tavani et al., 2013; 2015; 2018; Conneally et al. 2017). In two-dimensions,  
46 extensional growth folds define upward-widening monoclines (Fig. 1A-C) (e.g. Schlische, 1995;  
47 Gawthorpe et al., 1997; Janecke et al., 1998; Khalil and McClay, 2002; Willsey et al., 2002). In three-  
48 dimensions, extensional growth folds are typically characterised by a relatively smooth, along-strike  
49 transition from a breached monocline (i.e. a monocline cross-cut by a normal fault such that it is now  
50 defined by a footwall anticline-hangingwall syncline pair) to an unbreached monocline (Fig. 1D) (e.g.  
51 Gawthorpe et al., 1997; Lewis et al., 2015; Conneally et al., 2017).

52           It is well known, however, that normal faults, rather than being represented by a single,  
53 relatively planar surface, are commonly segmented, being composed of numerous soft- or hard-linked  
54 segments that bifurcate during propagation in both dip and strike directions (e.g. Childs et al., 2003;  
55 Walsh et al., 2002, 2003; van der Zee and Urai, 2005; Schöpfer et al., 2006, 2007; Long and Imber,  
56 2011; Giba et al., 2012; Jackson and Rotevatn, 2013; Fossen & Rotevatn, 2016; Freitag et al., 2017;  
57 Camanni et al., 2019). Because of this, fault tip lines can be highly irregular, reflecting spatial  
58 variations in host rock mechanical properties and related differences in propagation-to-slip ratio,  
59 and/or spatially selective reactivation of pre-existing structures (e.g. Baudon and Cartwright, 2008).  
60 We may therefore expect that extensional growth folds will reflect the geometric and kinematic  
61 complexity of their causal normal faults. These folds should essentially be more complex than  
62 predicted by current models, which are largely based on studies of relatively small, geometrically  
63 simple fault segments (e.g. Gawthorpe et al., 1997; Sharp et al., 2000; Corfield and Sharp, 2002;  
64 Lewis et al., 2015).

65           Understanding the structure and kinematics of extensional growth folds is important. These  
66 structures, which are widespread in some rifts (e.g. Gulf of Suez; Moustafa, 1987; Withjack et al.,  
67 1990; Gawthorpe et al., 1997; Sharp et al., 2000; Jackson et al., 2006; El-Wahed et al., 2010; Lewis et  
68 al., 2015), and well-developed adjacent to certain faults in others (e.g. offshore western Norway;  
69 Pascoe et al., 1999; Corfield and Sharp, 2000; Bell et al., 2014; Whipp et al., 2014), control basin  
70 geometry, sediment dispersal, and, ultimately, the syn-rift stratigraphic record of continental extension  
71 (see review by Coleman et al., 2019). It is also critical to understand the origin and style of fold-  
72 related extensional strains (so-called “continuous deformation”; Walsh & Watterson, 1989) when  
73 reconstructing the growth of normal faults (see also Childs et al., 2017 and Lăpădat al., 2017).  
74 Documenting the structure and kinematics of extensional growth folds is challenging given their size

75 (i.e. they can have amplitudes of several tens to hundreds of metres, widths of several kilometres, and  
76 strike extents of several tens of kilometres) and three-dimensional complexity. They are therefore  
77 much larger than the typical size of many field exposures, which commonly permit only a depth-  
78 limited perspective of fold structure and growth, at one specific along-strike location (see Patton et al.,  
79 1994 and Sharp et al., 2000 for exceptions). In contrast, high-quality, 3D seismic reflection data  
80 permit four-dimensional analysis of large extensional growth folds, although the impact of fault  
81 segmentation on fold geometry and kinematics has only very rarely been studied in detail (see  
82 Conneally et al., 2019). Here we use high-resolution field mapping (1:2000 and 1:5000 scale) to  
83 describe the geometric and kinematic development of the Hadahid Fault System, an exceptionally  
84 well-exposed, crustal-scale (30 km long, up to 2.5 km displacement) fault system located in the El-  
85 Qaa Fault Block, Suez Rift, Egypt (Figs 2 and 3). Our data allow us to test and develop models for the  
86 development of extensional growth folds.

87

## 88 **2. Geological Setting**

89

### 90 *2.1. Regional tectonic and structural framework*

91

92 The Neogene Suez Rift developed during Late-Oligocene to Early-Miocene (24-15.5 ma) rifting of  
93 the African and Arabian plates (e.g. Garfunkel and Bartov, 1977; Colletta et al., 1988; Lyberis, 1988;  
94 Patton et al., 1994; Bosworth and McClay, 2001). The NW-trending Suez Rift is 300 km long and up  
95 to 80 km wide, representing the northern arm of the failed intra-continental Red Sea rift system (inset  
96 in Fig. 2A). The Suez Rift consists of several large, broadly NW-SE-striking, normal fault systems  
97 that bound up to 50 km long and 10-20 km wide half-graben (Fig. 2) (e.g. Bosworth, 1995; Moustafa,  
98 1996; McClay et al., 1998; Bosworth and McClay, 2001).

99

### 100 *2.2. Structural evolution of the El Qaa Fault Block and Hadahid Fault System*

101

102 The El Qaa fault block is located on the Sinai margin of the Suez Rift. The fault block is defined by a  
103 40 km long by 25 km wide half-graben, which is bound to the east and west by NW-SE to NNW-  
104 SSE-striking, W-dipping, large displacement (up to 5 km) normal faults (e.g. Eastern Boundary and  
105 Coastal fault belts, and the Nezzazat, Sinai Massif, and Gebah faults; Figs 2-4) (*sensu* Sharp et al.,  
106 2000; see also Moustafa and El-Raey, 1993; Patton et al., 1994). This study focuses on the Hadahid  
107 Fault System, an intra-half-graben fault bounding the south-western margin of the Hadahid Fault  
108 Block (Fig. 3) (e.g. Moustafa and El-Raey, 1993). The Feiran Transfer Zone defines the northern limit  
109 of the Hadahid Fault System; here, displacement is transferred north-eastwards onto the Baba-Sidri  
110 Fault via several broadly NW-striking, SW-dipping, moderate displacement (<500 m) normal faults  
111 (Fig. 2) (e.g. Moustafa, 1992; Moustafa and El-Raey, 1993; Sharp et al., 2000). The Hadahid Fault

112 System is defined by several unbreached (Figs 3, and 4C, G, H and I) and breached (Figs 3, and 4A,  
113 B, D-F) forced folds (e.g. Patton, 1984; Withjack et al., 1990; Gawthorpe et al., 1997; Gupta et al.,  
114 1999; Sharp et al., 2000; Jackson et al., 2006; Lewis et al., 2015). The detailed structure and evolution  
115 of the Hadahid Fault System forms the focus of this study.

116

### 117 *2.3. Stratigraphic Framework*

118

119 The Suez Rift is underlain by Precambrian, ‘Pan African’ crystalline basement. The overlying  
120 sedimentary sequence is divided into three megasequences (Fig. 5). Megasequence One is *c.* 500 m  
121 thick and composed of Cambrian to Lower Cretaceous clastics (Nubian Sandstone). This succession is  
122 conformably overlain by Mesozoic, mixed carbonate-clastic, and Early Tertiary, carbonate-dominated  
123 rocks, which together comprise Megasequence Two (*c.* 650 m thick; Patton et al., 1994; Sharp et al.,  
124 2000). The competency contrast between mudstone-dominated intervals, such as the Duwi, Esna and  
125 Darat formations, and carbonate- and sandstone-dominated units in the upper part of Megasequence  
126 Two results in a strongly layered mechanical stratigraphy (Fig. 5); this exerts a strong control on the  
127 evolution of syn-rift structural styles, allowing decoupling and promoting extensional forced folding  
128 (*sensu* Coleman et al., 2019; see also Withjack et al., 1990; Sharp et al., 2000; Withjack & Callaway,  
129 2000; Jackson et al., 2006; Wilson et al., 2009; Lewis et al., 2015). Megasequence Three represents  
130 syn- to post-rift deposits associated with formation of the Suez Rift. The lower, Oligo-Miocene, syn-  
131 rift part of Megasequence Three consists of non-marine (Abu Zenima Formation; 24-21.5 ma), tidal-  
132 to-marginal marine (Nukhul Formation; 21.5-19.7 ma), and open marine (Rudeis Formation;  
133 19.7-15.5 ma) deposits (Gharandal Group) (Fig. 5). The upper, post-rift part of Megasequence Three  
134 is composed of clastic, carbonate and evaporite rocks (Ras Malaab Group) (e.g. Patton et al., 1994;  
135 Sharp et al., 2000). Due to a lack of hangingwall exposure, the full thickness of Megasequence Three  
136 in the El-Qaa fault block is unknown. However, Lewis et al. (2015) demonstrate that Abu Zenima,  
137 Nukhul and Rudeis formations are collectively at least 60 m thick.

138

### 139 *2.4. Timing of deformation on the Hadahid Fault System*

140

141 Although syn-rift growth strata are not preserved along its entire length, the following four  
142 observations by Lewis et al. (2015) place some constraints on the timing of deformation on the  
143 Hadahid Fault System: (i) early syn-rift strata of the Abu Zenima Formation (23.5-21 Ma; Fig. 5)  
144 onlap pre-rift strata (Mokattam Formation) along the Hadahid, and East and West Feiran monoclines  
145 (Figs 3A, and 4G and I), suggesting these structures initiated during the initial stages of rifting in the  
146 Late Oligocene; (ii) early syn-rift strata of the Abu Zenima Formation (23.5-21 Ma; Fig. 5) are locally  
147 preserved in syn-depositional faults dissecting the Hadahid, and East and West Feiran monoclines  
148 (not shown in the regional map in Fig. 3), suggesting these faults, which Lewis et al. (2015) infer

149 were kinematically linked to the forced folds on which they occur, initiated during the initial stages of  
150 rifting in the Late Oligocene; (iii) late pre-rift (Eocene) strata of the Thebes Formation are thrust over  
151 early syn-rift (23.5-21 Ma) strata along the Ratamat Segment (see below), suggesting fold tightening  
152 and deformation of the monocline middle limbs after rift initiation, perhaps during the Early Miocene;  
153 and (iv) syn-rift depocentres of the Abura Graben and Gebah Half-Graben, which are located at the  
154 southern end of the Hadahid Fault System and that contain syn-rift strata as young as 16.9 Myr (i.e.  
155 Abu Zenima, Nukhul, and Rudeis formation; Fig. 5), are cross-cut by the Hadahid Fault System,  
156 implying this structure was likely active post-Early Miocene.

157

### 158 **3. Structural style of the Hadahid Fault System**

159

160 We identify eight fault (i.e. Gebah and Abura, Hadahid Fault, Theghda, Abyad, and Ratamat fault  
161 segments), and three fold segments (i.e. Hadahid, and the East and West Feiran monoclines) along the  
162 Hadahid Fault System, based on abrupt along-strike changes in fault strike and/or structural style, for  
163 example from a breached to an unbreached monocline (Fig. 3B) (cf. Stewart & Taylor, 1996). For  
164 much of its length, the hangingwall of the Hadahid Fault System is not exposed, being buried beneath  
165 thick Quaternary deposits of the El-Qaa Plain. In these locations we cannot therefore constrain the  
166 location of the master fault responsible for generating the bulk of the observable strain, or the amount  
167 of displacement on the fault (Fig. 3A; see also Fig. 4A, B and D). For example, even where we  
168 observe a fault of appropriate scale (i.e. several hundreds of metres of throw), strike (e.g. ESE-WNW-  
169 to-SSE-NNW) and dip (i.e. broadly south-westwards), in broadly the correct structural position (i.e.  
170 immediately to the E or NE of the El-Qaa Plain), it remains unclear if this is the Hadahid Fault  
171 System 'master fault'. However, we use the following criteria to help constrain the position of the  
172 master fault: (i) where reverse faults occur, these likely lie in the hangingwall of the master fault, or  
173 on the hangingwall side of the up-dip projection of the master fault in cases where it is blind (cf. Fig.  
174 1); and (ii) growth fold (monocline) breaching typically results in preservation of steeply dipping (or  
175 overturned) beds within the fault zone or in the immediate hangingwall of the fault; as a result of this,  
176 footwall bedding increases in dip towards the fault, and where bedding dips steeply (i.e.  $>70^\circ$ ), the  
177 master fault is likely at- or near-surface.

178 Ignoring the fact that the position of the master fault is locally uncertain, the overall north-  
179 westward transition from breached to unbreached monoclines clearly defines a north-westward  
180 decrease in the ratio between discontinuous (i.e. fault offset-related) and continuous (i.e. fold-related),  
181 at-surface deformation (Figs 3 and 4A-I). One hypothesis links this along-strike change in structural  
182 style to the north-westwards propagation of the Hadahid Fault System from its branchline with the  
183 Gebah and Sinai Massif faults. In this model, extensional growth folds formed and were breached  
184 earlier in the SE than they were in the NW. The cessation of extension and the death of the Hadahid  
185 Fault System meant that unbreached extensional growth folds are preserved in the NW. We may refer

186 to this along-strike in structural style as being a so-called ‘propagation effect’. An alternative  
187 hypothesis is that the Hadahid Fault System nucleated broadly synchronously along its length and  
188 then propagated upwards, more quickly in the SE, which ultimately leading to north-westwards  
189 propagation of the fault system’s *surface trace*. We may refer to this along-strike in structural style as  
190 being a so-called ‘geometric effect’. Differentiating between these two hypotheses is impossible  
191 given: (i) our structural level of inspection is restricted to the Earth’s surface, thus we cannot  
192 demonstrate that fault-related displacement (i.e. discontinuous deformation) increases north-  
193 westwards at deeper structural levels (e.g. at the depth of top crystalline basement or top pre-rift; Fig.  
194 5); and (ii) discontinuous exposures of very poorly dated syn-rift deposits in the hangingwall of the  
195 Hadahid Fault System means we cannot establish the relative timing of faulting and folding along the  
196 structure; i.e. do the very earliest syn-rift growth strata become younger towards and thus document  
197 the north-westward initiation of folding and subsequent faulting, and hence north-westwards  
198 propagation of the fault system?

199 In this section we describe and interpret the structural style (i.e. plan-view and cross-sectional  
200 geometry) of the eight fault-fold segments of the Hadahid Fault System from south to north, following  
201 the inferred direction of displacement decrease along the structure. Where we infer the displacement  
202 of the master fault, it should be noted these values are based on stratigraphic cut-offs and do not  
203 include the ductile component of deformation (e.g. folding); displacement values are, therefore,  
204 minimum estimates of extensional strain (e.g. Walsh & Watterson, 1991).

205

### 206 3.1. Gebah Segment

207

208 The Gebah Segment is located at the southern end of the Hadahid Fault System and is defined by  
209 NNW-SSE- to WNW-ESE-striking, W-SW to W-dipping, c. 3.5 km long normal fault (Figs 3B, 6A  
210 and B). This segment splays off the Eastern Boundary Fault Belt, at the branchpoint between the  
211 Gebah and Sinai Massif segments (Figs 3B, 6A and 7). Along much of its length the immediate  
212 footwall of the Gebah Segment is defined by a c. 500 m wide anticline that is deformed by numerous  
213 normal faults (Figs 6A and 7). NE of this anticline, a 1-1.5 km wide, N-trending, syn-rift half-graben  
214 is developed, which is bound on its eastern margin by the Eastern Boundary Fault Belt (Gebah Half-  
215 Graben; Figs 5A, 6 and 7; Lewis et al., 2015).

216 Based on: (i) the sharp increase in topographic relief along the north-eastern margin of the El-  
217 Qaa Plain at its contact with exposed pre- and syn-rift rocks; and (ii) the presence of faulted and  
218 folded syn-rift strata in the Gebah Half-Graben, we infer that the master fault of the Hadahid Fault  
219 System is surface-breaching along the Gebah Segment. As such, we interpret that the anticline  
220 characters of the footwall of the Gebah Segment represents the footwall portion of a breached  
221 monocline; the related hangingwall syncline is buried beneath the El-Qaa Plain (cf. Fig. 1). Because

222 of this, we cannot constrain the displacement along this part of the Hadahid Fault System (Fig. 6A and  
223 B).

224

### 225 3.2. *Abura Segment*

226

227 The Abura Segment is defined by a WNW-ESE-striking, SW-dipping, *c.* 2 km long normal fault (Fig.  
228 6A and C). The structural style of the Abura segment is similar to that of the Gebah Segment, with  
229 syn-rift strata in its footwall defining a faulted footwall anticline. Because of this structural similarity,  
230 we also interpret that the Abura Segment defines a breached monocline, with the hangingwall  
231 syncline buried beneath the El-Qaa Plain. (Fig. 6A and B). Again, because of this, we cannot  
232 constrain the displacement along this part of the Hadahid Fault System (Fig. 6A and C).

233

### 234 3.3. *Theghda Segment*

235

236 The Theghda Segment is *c.* 4.5 long, trends WNW-to-NW, and is defined by strata that dip SSW  
237 (along its southern part) or WSW (northern part), and which define a *c.* 1.5 km-wide anticline (Figs  
238 8A and 9). Dominantly WSW-ESE-to-NW-SE-striking, SSW-to-SW-dipping, moderate-throw (up to  
239 100 m) normal faults are locally developed along the Theghda Segment.

240 Based on outcrop relationships and exposure levels, there are three possible interpretations for  
241 the location of the Hadahid Fault System master fault along the Theghda Segment. First, the master  
242 fault may be represented by the normal faults mapped to the NNE of the monocline middle limb. In  
243 this interpretation, Eocene strata exposed along the southern part of the segment lie in the faults  
244 hangingwall, and are eroded and thus absent further NW, whereas Cretaceous strata along the  
245 northern part of the segment lie in its footwall (Fig. 8B). Second, the master fault could be blind,  
246 underlying the monocline middle limb (i.e. the interpretation shown in Figs 4C and 8B). Finally, the  
247 master fault could lie SSW of the main outcrop belt, beneath the El-Qaa Plain; in this interpretation,  
248 Eocene and Cretaceous strata lie in the faults footwall, with Eocene strata absent along northern part  
249 of the segment due to erosion (interpretation not shown). In all three interpretations the eastern part of  
250 the master fault would lie directly along strike of where we map it along the Abura Segment (Fig.  
251 8A). Given that stratal dips increase towards and are at a maximum immediately adjacent to the El-  
252 Qaa Plain (Fig. 8B), we reject the first interpretation, as this would require a progressive *decrease* in  
253 stratal dips SSW of the faults juxtaposing Eocene and Cretaceous strata (Fig. 8). We therefore favour  
254 the second or third interpretation; the former suggests an along-strike decrease in displacement on the  
255 fault, such that its tips plunges towards and is blind in the WNW, whereas the latter envisages the  
256 fault is surface-breaking (but just not observable).

257

### 258 3.4. *Abyad Segment*

259

260 The Abyad Segment has a similar overall structural style and is of similar scale to that of the adjacent  
261 Theghda Segment, being *c.* 4 km long and trending NW, and characterised by SW-dipping strata that  
262 define an up to *c.* 1 km-wide anticline (Fig. 10). Numerous NW-SE-striking, predominantly SW-  
263 dipping, low-throw (up to 50 m) normal faults are present along the Abyad Segment, defining an up to  
264 *c.* 500 m-wide zone of intense deformation. These faults bound rotated blocks of the Matulla  
265 Formation, within which mudstones layers are highly attenuated (Fig. 11A). 5-30 m wide, fault-  
266 bounded blocks of intensely fractured Sudr Chalk occur within the fault zone (Fig. 14).

267 We again suggest there are three possible interpretations for the position of the master fault in  
268 this location. For reasons outlined above, we again favour an interpretation that: (i) the master fault is  
269 blind, underlying the monocline middle limb (i.e. the interpretation shown in Fig. 10B); in this  
270 interpretation, the zone of relatively low-throw normal faults could represent the upper tip of the  
271 master fault, which in this case would lie just below the level of exposure (cf. Fig. 1B); or (ii) the  
272 master fault is surface-breaking, but lies SSW of the main outcrop belt, beneath the El-Qaa Plain.

273

### 274 *3.5. Ratamat Segment*

275

276 The *c.* 3 km long, NNW-to-N-trending Ratamat Segment displays a broadly similar geometry to the  
277 Abyad and Theghda segments, being defined by SW-to-W-dipping strata that define a *c.* 1 km-wide  
278 anticline that is deformed by low-throw normal faults towards its southern end (Fig. 12A and B).  
279 These faults bound blocks of the Matulla Formation, within which mudstone layers are highly  
280 attenuated (Fig. 13A). Heavily fractured blocks of Sudr Chalk are also present between closely spaced  
281 faults. The Ratamat Segment differs to the Abyad and Theghda segments in that reverse faults are  
282 well-developed along its central and northern parts. Along its central part, a NNW-SSE-striking thrust  
283 places steep to locally-overturned Thebes Formation carbonates on top of overturned, mixed  
284 carbonate-clastics of the Darat and Mokattam formations (Figs 12A and B, and 13B). Further north,  
285 two E-dipping, N-S-striking, *c.* 1 km long thrusts occur, placing overturned pre-rift strata onto steep-  
286 dipping to overturned syn-rift strata (Figs 12A and C, and 13C).

287 Observations from numerical and physical models (Fig. 1A and B), and from other natural  
288 examples of extensional growth folds (e.g. Sharp et al., 2000; Jackson et al., 2006; Coleman et al.,  
289 2019) (see also Fig. 1C), suggest that the reverse faults lie in the immediate hangingwall of the master  
290 fault. As such, we interpret that the Hadahid Fault System master fault lies east of these reverse faults  
291 (interpretation shown in Fig. 12). Locally, however, the master fault may be blind, as suggested by the  
292 intact monocline defining the middle of the Ratamat Segment. Even here, reverse faults locally offset  
293 the monocline limb, suggesting the upper tip of the master fault is near-surface (interpretation shown  
294 in Fig. 12B; see also Fig. 1A).

295

296 3.6. *Hadahid Monocline*

297

298 The Hadahid Monocline is a 5 km long, NW-SE striking, SW-facing, unbreached monocline, the  
299 middle limb of which increase in dip from NW to SE (from 40° to locally overturned) (Fig. 14).  
300 Overall, the dip of the monoclines middle limb (<65°) immediately adjacent to the El-Qaa Plain is less  
301 than that observed on segments to the SE. In the SE, where the monocline middle limb dips more  
302 steeply (>65°), several NW-SE-striking, moderately (30-50°) NE-dipping reverse faults place steeply-  
303 dipping-to-locally overturned pre-rift strata on overturned syn-rift strata (Fig. 14A and B). These  
304 structures are geometrically similar to those observed along the Ratamat Segment, suggesting that,  
305 like the central part of that structure, the upper tip of the master fault is near-surface and is, at its  
306 southern end at least, represented by the zone of at-surface, relatively low-throw normal faults  
307 described above. Immediately to the NW of the zone of reverse faults, where it dips more gently, the  
308 monocline middle limb is undeformed; further to the NW, where it passes into the Hadahid Fault  
309 Segment, normal faults become more common (see below) (Fig. 14A and C). Along the entire length  
310 of the Hadahid Monocline, syn-rift sandstones onlap pre-rift carbonates across a low-angle, angular  
311 unconformity (*c.* 10° angular discordance) (Figs 14A and C, 15 and 17) (see Lewis et al., 2015).

312

313 3.7. *Hadahid Fault Segment*

314

315 The Hadahid Fault Segment is *c.* 5.5 km long, strikes N-S, and is defined by a breached, W-facing  
316 monocline (Figs 16 and 17) that is deformed by several N-S-to-NW-SE-striking, steeply (70-80°) and  
317 broadly W-dipping, 0.5-2 km long normal faults that have a maximum throw of *c.* 300 m (Figs 16 and  
318 17). The Hadahid Fault Segment is one of the few places where the hangingwall of the Hadahid Fault  
319 System is relatively well exposed; here we see relatively steeply (*c.* 60°) W-dipping strata at the  
320 segment centre, with these pre-rift strata onlapped by syn-rift strata across a low-angle (*c.* 10° angular  
321 discordance) unconformity (Figs 16 and 17). We infer the Hadahid Fault Segment is represented by  
322 the faults that breach the related monocline east of the position where syn-rift strata onlap it.  
323 Accordingly, we interpret this monocline is a breached extensional growth fold (Figs 16 and 17; cf.  
324 Fig. 1A and C).

325

326 3.8. *Feiran Monoclines*

327

328 The Feiran Monoclines are represented by two NW-SE striking, SW-facing, up to 4.5 km monoclines  
329 that overlap by *c.* 1.75 km and are separated across-strike by 1-5 km (the West Feiran and East Feiran  
330 monoclines; Figs 2, 3, 18 and 19). The West Feiran monocline plunges north-westwards and is  
331 breached at its southern end by a steeply (*c.* 70°) SW-dipping fault that tips out just north of Wadi  
332 Feiran; this fault represents the northern end of the Hadahid Fault Segment (Fig. 18A). The East

333 Feiran monocline also plunges to the NW, with stratal dips on the middle limb decreasing along-strike  
334 from *c.* 35° to *c.* 10° WSW (Fig. 18A). Variably striking, relatively small (up to 1.2 km long and with  
335 up to 60 m displacement) normal faults deform the monocline middle limb (Fig. 18A). Pre-rift rocks  
336 defining the East and West Feiran monoclines are overlapped by syn-rift deposits across an angular  
337 unconformity defined by a 5-10° dip discordance (Figs 18 and 19) (see Lewis et al., 2015).

338

#### 339 **4. Discussion**

340

341 Current geometrical models for extensional growth folds predict a relatively smooth, along-strike  
342 transition from a breached monocline to an unbreached monocline, the latter being developed above  
343 the smoothly plunging, upper tip-line of the underlying (and laterally related) normal fault (e.g.  
344 Gawthorpe et al., 1997; Gawthorpe & Leeder, 2000; Cardozo, 2008; Coleman et al., 2019). The  
345 Hadahid Fault System displays many of the geometrical characteristics captured in this model. For  
346 example, the inferred north-westward decrease in bulk displacement on the fault system is associated  
347 with an overall change in structural style, from breached monoclines in the SE (e.g. Gebah Segment)  
348 to unbreached monoclines in the NW (e.g. Feiran monoclines). However, we show that, in detail, the  
349 along-strike transition in structural style is more discontinuous, with unbreached monoclines (i.e.  
350 Hadahid Monocline) being flanked by breached or unbreached monoclines (i.e. Ratamat and Hadahid  
351 segments) (Figs 3 and 14). Individual segments of the Hadahid Fault System are also flanked (and  
352 defined) by segment boundaries that are; (i) unbreached at the structural level of exposure (e.g.  
353 between the West and East Feiran monoclines; Figs 3 and 18); (ii) breached and defined by a  
354 pronounced bend in the fault-fold trace (e.g. between the Hadahid Monocline and Ratamat segments;  
355 Figs 3 and 14; and between the Ratamat and Abyad segment; Figs 3 and 12); or (iii) are defined by a  
356 more subtle transition in overall structural style (e.g. between the Theghda and Abyad segments; Figs  
357 3 and 10). Unbreached segment boundaries are characterised by relatively small (*c.* 2 km) across-  
358 strike separations and large (*c.* 3 km) along-strike overlaps; these segments are thus defined by high  
359 overlap:separation (O:S) ratios (*sensu* Whipp et al., 2017) (Figs 3 and 18). In the case of breached  
360 segment boundaries, the strike-normal step in the faults plan-view trace is similarly small (i.e.  
361 maximum 500 m) relative to the length of the bounding segments (typically at least 4 km) (Figs 3, 10  
362 and 12). We tentatively suggest that the high O:S ratios between unlinked segments of the Hadahid  
363 Fault System, as well as the narrow width of breached relays, together suggest the structure is defined  
364 by a single, hard-linked structure at-depth, which splays upwards into and is thus defined by, several  
365 segments at shallower depths (Fig. 20). Similar geometries are observed in 3D seismic reflection data  
366 from the Taranaki Basin, offshore New Zealand, where Conneally et al. (2017) describe segmented  
367 fault-fold systems, separated by relays at relatively shallow structural depths, above and related to  
368 upward progradation of a single, *c.* 8 km-long. basement-involved normal fault, (i.e. their fig. 8).

369           Where data quality and quantity permit three-dimensional mapping of extensional growth  
370 folds and causal faults (e.g. Corfield and Sharp, 2000; Ford et al., 2007), the relatively short length-  
371 scale (<5 km) variations in structural style we described from the central part of the Hadahid Fault  
372 System are absent. The reason for this is unclear, and may reflect the fact that the Hadahid Fault  
373 System was associated with non-uniform upward propagation of its upper tip, superimposed on the  
374 overall north-westwards propagation of the fault. Non-uniform propagation could be controlled by  
375 short length-scale variations in the mechanical properties of the faulted host rock and associated  
376 changes in the propagation-to-slip ratio (Hardy and McClay, 1999; Finch et al., 2004; Hardy and  
377 Finch, 2006). A consequence of this would be that, above portions of the fault tip that were  
378 propagating relatively rapidly, monoclines would be breached, with intact monoclines being preserved  
379 along-strike in locations where, at least locally, tip propagation was relatively slow. Such variability  
380 may therefore be absent in subsurface examples due to: (i) seismic data resolution being insufficient  
381 to resolve relatively low-displacement structures that locally breach seemingly unbreached  
382 monoclines (e.g. Lewis et al., 2013); and/or (ii) because the faulted and folded host rock is relatively  
383 lithologically and thus mechanically homogeneous. For example, in the Taranaki Basin example of  
384 Conneally et al. (2017), the fault grew in a relatively homogenous, mudstone-dominated succession.  
385 Irrespective of what controls the short length-scale structural variability seen along the Hadahid Fault  
386 System, our study supports the notion that including the ductile component of deformation (i.e.  
387 folding) is key when defining the geometry and assessing the kinematics of segmented normal fault  
388 systems (e.g. Walsh & Watterson, 1991).

389           Where unbreached monoclines are preserved, or where the steep-dipping limbs of breached  
390 monoclines are exposed in the fault system hangingwall, most commonly towards the centre of the  
391 Hadahid Fault System, reverse faults are relatively well-developed. It is likely these structures are not  
392 developed to the NW due to the lower total bulk strains (i.e. faulting and folding); to the SE, these  
393 structures may be developed, but are simply not exposed, being buried beneath hangingwall strata due  
394 to higher strains and, therefore, larger discrete, fault-related displacements. Thrusts are rarely  
395 described from seismic reflection datasets, but are common in exposed forced folds in the Suez Rift  
396 (Withjack et al., 1990; Gawthorpe et al., 1997; Sharp et al., 2000; Jackson et al., 2006). The apparent  
397 lack of thrusts in seismic reflection datasets may simply reflect the fact that many thrusts have low  
398 displacements (<100 m), are steeply dipping (>50°), and are thus unlikely to be imaged in seismic  
399 reflection datasets (although see Fig. 1C for an exception).

400

## 401 **7. Conclusions**

402

403           We used field data from the Hadahid Fault System, Suez Rift, Egypt to investigate the geometry and  
404 kinematic development of an exceptionally well-exposed normal fault system. We showed that this 30  
405 km long fault system, which has up to 2.5 km of displacement, comprises eight, up to 5 km long

406 segments that are defined by unbreached or breached, hard- or soft-linked monoclines. The high  
407 overlap:separation (O:S) ratios between the constituent segments of the Hadahid Fault System suggest  
408 it passes upwards from a single, through-going structure at-depth, into a more strongly segmented  
409 feature at shallower depths. We infer that the along-strike transition from breached to unbreached  
410 monoclines records a progressive loss of displacement along the Hadahid Fault System at deeper  
411 structural levels and may suggest that the surface trace of the fault propagated north-westwards. We  
412 document short (<4 km) length-scale variations from unbreached to breached monoclines, which may  
413 reflect variations in the fault propagation-to-slip ratio, and the timing and location of growth fold  
414 breaching, perhaps linked to local variations in host rock material properties. We conclude that  
415 growth folding is a key expression of continental rift-related strain, and that tectono-sedimentary  
416 models for rift basin development must incorporate related structures.

417

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419

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429

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689

## 690 **Figure captions**

691

692 **Figure 1:** (A) Physical analogue (clay) model showing the kinematic and structural development of  
693 an extensional growth fold (*sensu* Coleman et al., 2019) and associated secondary structures  
694 (modified from Withjack et al., 1990). Note the eventual development of a through-going ‘master’  
695 fault in Stage II; this fault breaches the overlying extensional growth fold, which during Stage I is  
696 characterised by a basinward-facing, unbreached monocline. Reverse faults are shown in red. (b)  
697 Result of a trishear-based model, showing the kinematic and structural development of an extensional  
698 forced fold (modified from Jackson et al., 2006) (based on the kinematic model of Allmendinger,  
699 1998; see also Hardy & McClay, 1999). Note again the presence of steep-dipping reverse faults in the

700 immediate (proto-)hangingwall of the through-going master fault. (c) 2D profile from a 3D seismic  
701 reflection volume from the Northern North Sea, showing the final structure of a breached extensional  
702 fault-propagation fold. Note the development of reserve faults in the immediate hangingwall of the  
703 now through-going master fault. (d) Block diagram showing the change in structural style along-strike  
704 of a simple, isolated normal fault segment associated with extensional growth folding.

705

706 **Figure 2:** (A) Simplified geologic map of the El Qaa Fault Block (modified from Moustafa, 1993 and  
707 Sharp et al., 2000). B-SF=Baba-Sidri Fault; NF=Nezzazat Fault; CFB=Coastal Fault Belt;  
708 FTZ=Feiran Transfer Zone; EBFB=Eastern Boundary Fault Belt; HFS=Hadahid Fault System;  
709 GF=Gebah Fault; SMF=Sinai Massif Fault; HFB=Hadahid Fault Block. Inset map shows the regional  
710 plate tectonic setting of the Gulf of Suez Rift. Dark-grey shading indicates area containing structures  
711 and stratigraphic units related to Oligo-Miocene rifting. (B) Geoseismic section across the central dip  
712 province of the Gulf of Suez Rift (modified from Patton et al., 1994). Location of the section is shown  
713 in (A).

714

715 **Figure 3:** (A) Simplified geologic map of the Hadahid Fault Block (see Fig. 2A for location) (based  
716 on Moustafa, 1993 and new mapping undertaken as part of this study). The locations of cross-section  
717 in Fig. 4 are indicated. (B) Simplified geological map highlighting the constituent segments of the  
718 Hadahid Fault System.

719

720 **Figure 4:** Cross-sections through the Hadahid Fault Block from south to north, based on the mapping  
721 of Moustafa (1993) and Sharp et al. (2000), and mapping undertaken as part of this study. Locations  
722 of the cross-sections are shown in Fig. 3A. Vertical exaggeration=2. Colour key to stratigraphic units  
723 is shown in Fig. 3A. The mapped and inferred location of the Hadahid Fault System is shown (see text  
724 for full discussion). Note that all topographic profiles shown here and in other figures are constructed  
725 using 30 m ASTM DEM data (vertical exaggeration= $\times 2$ ). The geometry of the hangingwall of the  
726 Hadahid Fault System, especially on the southern segments, is largely unconstrained due to burial; it  
727 is inferred based on the measured thickness of the pre-rift succession (Fig. 3), and geometries  
728 predicted by physical and numerical models, and observed in natural examples of extensional growth  
729 folds (Fig. 1).

730

731 **Figure 5:** Composite stratigraphic section of the Hammam Faraun and El-Qaa fault blocks (modified  
732 from Moustafa, 1987). Mudstone-dominated units represent major layer-parallel slip horizons and are  
733 indicated by opposing black arrows. Bed thickness is based on measurements across the Hadahid  
734 Fault Block, with the recorded ranges being comparable to those reported by Moustafa and El-Raey  
735 (1993). The thickness of Megasequence One is taken from the Hammam Faraun Fault Block (Sharp et  
736 al., 2000), as the base of this interval is not exposed in the Hadahid Fault Block. Ages of key

737 stratigraphic surfaces bounding early syn-rift units are also indicated (Bentham et al., 1996; Krebs et  
738 al., 1997).

739

740 **Figure 6:** (A) Field map of the southern end of the Hadahid Fault System, showing the Gebah and  
741 Abura segments. Colour key to stratigraphic units is shown in Fig. 3A. Red dots indicate the  
742 approximate boundaries between the identified segments. Lower hemisphere projection stereonet  
743 summarise the dip and dip direction of pre- and syn-rift bedding (A-G; location shown on map). The  
744 location of the photographs shown in Figs 7, 11 and 13, and the cross-sections shown in (B) and (C),  
745 are indicated. (B) Down-plunge cross-section across the Gebah Segment. (C) Down-plunge cross-  
746 section across the Abura Segment.

747

748 **Figure 7:** Photograph looking northwards along the Sinai Massif and Gebah faults, showing the  
749 branchpoint with the Gebah Segment of the Hadahid Fault System. The location of the photo is shown  
750 in Fig. 6A.

751

752 **Figure 8:** (A) Field map of the Theghda Segment of the Hadahid Fault System. Colour key to  
753 stratigraphic units is shown in Fig. 3A. Red dots indicate the approximate boundaries between the  
754 identified segments. Lower hemisphere projection stereonet summarise the dip and dip direction of  
755 pre- and syn-rift bedding (A-D; location shown on map). Rose diagrams show the trend of fractures in  
756 pre-rift strata on the middle limb of the Thebes Formation-cored monocline. The location of the  
757 photograph shown in Fig. 9 and the cross-section shown in (B) are indicated. (B) Down-plunge cross-  
758 section across the Theghda Segment.

759

760 **Figure 9:** Photograph looking ESE, along strike of the Theghda Segment. The location of the photo  
761 location is shown in Fig. 8A.

762

763 **Figure 10:** (A) Field map of the Abyad Segment of the Hadahid Fault System. Colour key to  
764 stratigraphic units is shown in Fig. 3A. Red dots indicate the approximate boundaries between the  
765 identified segments. Lower hemisphere projection stereonet summarise the dip and dip direction of  
766 pre- and syn-rift bedding (A-G; location shown on map). Rose diagrams show the trend of fractures in  
767 pre-rift strata on the middle limb of the Thebes Formation-cored monocline. The location of the  
768 photograph shown in Fig. 11 and the cross-section shown in (B) are indicated. (B) Down-plunge  
769 cross-section across the Abyad Segment.

770

771 **Figure 11:** Photograph showing the structure of a 'secondary' normal fault zone associated with the  
772 Hadahid Fault System. The location of the photograph is shown in Fig. 10A.

773

774 **Figure 12:** (A) Field map of the Ratamat Segment of the Hadahid Fault System. Colour key to  
775 stratigraphic units is shown in Fig. 3A. Red dots indicate the approximate boundaries between the  
776 identified segments. Lower hemisphere projection stereonet summarise the dip and dip direction of  
777 pre- and syn-rift bedding (A-G; location shown on map). Rose diagrams show the trend of fractures in  
778 pre-rift strata. The location of the photograph shown in Fig. 13 and the cross-sections shown in (B)  
779 and (C) are indicated. (B) Down-plunge cross-section across the central part of the Ratamat Segment.  
780 (C) Down-plunge cross-section across the northern part of the Ratamat Segment.

781

782 **Figure 13:** (A) Photograph showing the structure of a ‘secondary’ normal fault zone associated with  
783 the Hadahid Fault System. (B) Photograph looking obliquely (to the NW) at the southern end of the  
784 Ratamat Segment of the Hadahid Fault System. The monocline limb is deformed by reverse faults  
785 which thrust older pre-rift over younger pre-rift strata (i.e. right-hand reverse fault), or pre- over syn-  
786 rift strata (i.e. left-hand reverse fault). (C) Photograph looking obliquely (to the S) at the northern end  
787 of the Ratamat Segment. The Hadahid Fault System master fault is surface-breaching, and is inferred  
788 to lie to the E of the network of reverse faults that dissected the strongly rotated middle limb of a  
789 precursor monocline. The reverse fault-bound block of pre-rift Thebes Formation is thrust onto  
790 overturned syn-rift strata. Locations of the photos are shown in Figure 12A.

791

792 **Figure 14:** (A) Field map of the Hadahid Monocline and Hadahid fault (see also Fig. 16) segments of  
793 the Hadahid Fault System. Colour key to stratigraphic units is shown in Fig. 3A. Red dots indicate the  
794 approximate boundaries between the identified segments. Lower hemisphere projection stereonets  
795 summarise the dip and dip direction of pre- and syn-rift bedding (A-G; location shown on map). Rose  
796 diagrams show the trend of fractures in pre-rift strata. The location of the photograph shown in Fig. 15  
797 and the cross-sections shown in (B) and (C) are indicated. (B) Down-plunge cross-section across the  
798 central part of the Hadahid Monocline Segment. (C) Down-plunge cross-section across the south-  
799 central part of the Hadahid Monocline Segment. (D) Down-plunge cross-section across the southern  
800 part of the Hadahid Fault Segment.

801

802 **Figure 15:** Photograph looking northwards along the Hadahid Monocline Segment. Note the angular  
803 discordance of *c.* 10° between the pre-rift (Mokattam Formation) and overlying syn-rift strata (Nukhul  
804 Formation) (see Lewis et al., 2015). Location of the photo is shown in Figure 14A

805

806 **Figure 16:** (A) Field map of the Hadahid Fault Segment of the Hadahid Fault System. Colour key to  
807 stratigraphic units is shown in Fig. 3A. Red dots indicate the approximate boundaries between the  
808 identified segments. Lower hemisphere projection stereonet summarise the dip and dip direction of  
809 pre- and syn-rift bedding (A-G; location shown on map). Rose diagrams show the trend of fractures in

810 pre-rift strata. The location of the photograph shown in Fig. 17 and the cross-sections shown in (B)  
811 are indicated. (B) Down-plunge cross-section across the central part of the Hadahid Fault Segment.

812

813 **Figure 17:** Photograph looking westwards along the Hadahid Fault Segment. Note the angular  
814 discordance of *c.* 10° between the pre-rift (Mokattam Formation) and overlying syn-rift strata (Nukhul  
815 Formation) (see Lewis et al., 2015). Location of the photo is shown in Figure 16A.

816

817 **Figure 18:** (A) Field map of the Feiran monoclines segment of the Hadahid Fault System. Colour key  
818 to stratigraphic units is shown in Fig. 3A. Red dots indicate the approximate boundaries between the  
819 identified segments. Lower hemisphere projection stereonet summarise the dip and dip direction of  
820 pre- and syn-rift bedding (A-G; location shown on map). Rose diagrams show the trend of fractures in  
821 pre-rift strata. The location of the photograph shown in Fig. 19 and the cross-sections shown in (B)  
822 are indicated. (B) Down-plunge cross-section across the West Feiran Monocline.

823

824 **Figure 19:** Photograph looking northwards along the middle limb of the East Feiran Monocline  
825 Segment. Location of the photo is shown in Figure 18.

826

827 **Figure 20.** Schematic diagram summarising some of the key observations from the Hadahid Fault  
828 System and outlining key structural elements of segmented normal fault-fault propagation fold  
829 systems. Fault A is defined by an irregular upper tip-line elevation, superimposed on a net right-to-left  
830 decrease in elevation and net fault displacement (i.e. the Hadahid Fault System); Fault B is defined by  
831 an more smoothly decreasingly fault displacement and elevation of the upper tip-line. Footwall  
832 anticline-hangingwall syncline pairs, which represent breached fault-propagation folds (monoclines)  
833 and that flank the breaching faults, are not shown for clarity.

Fig. 1

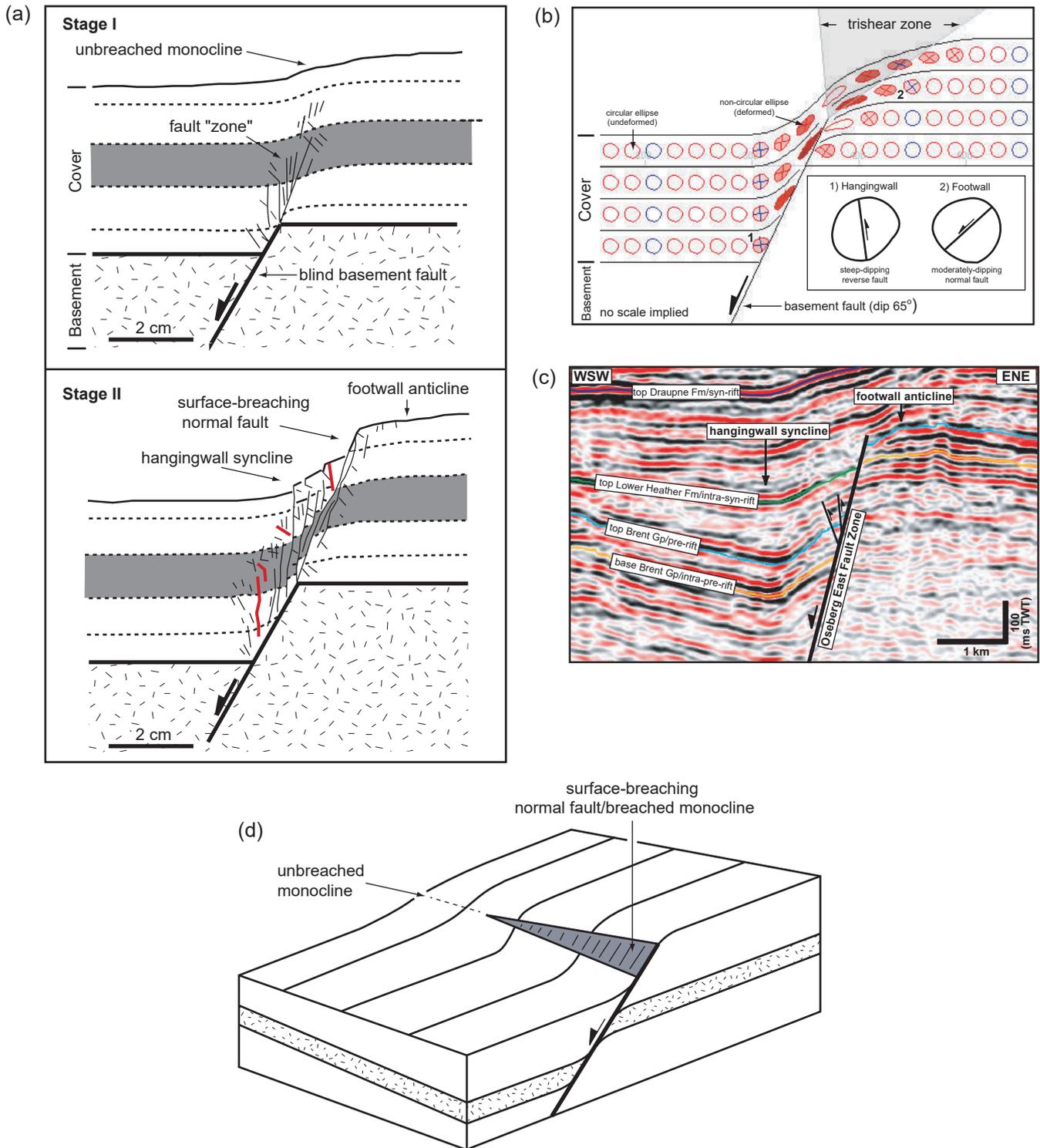


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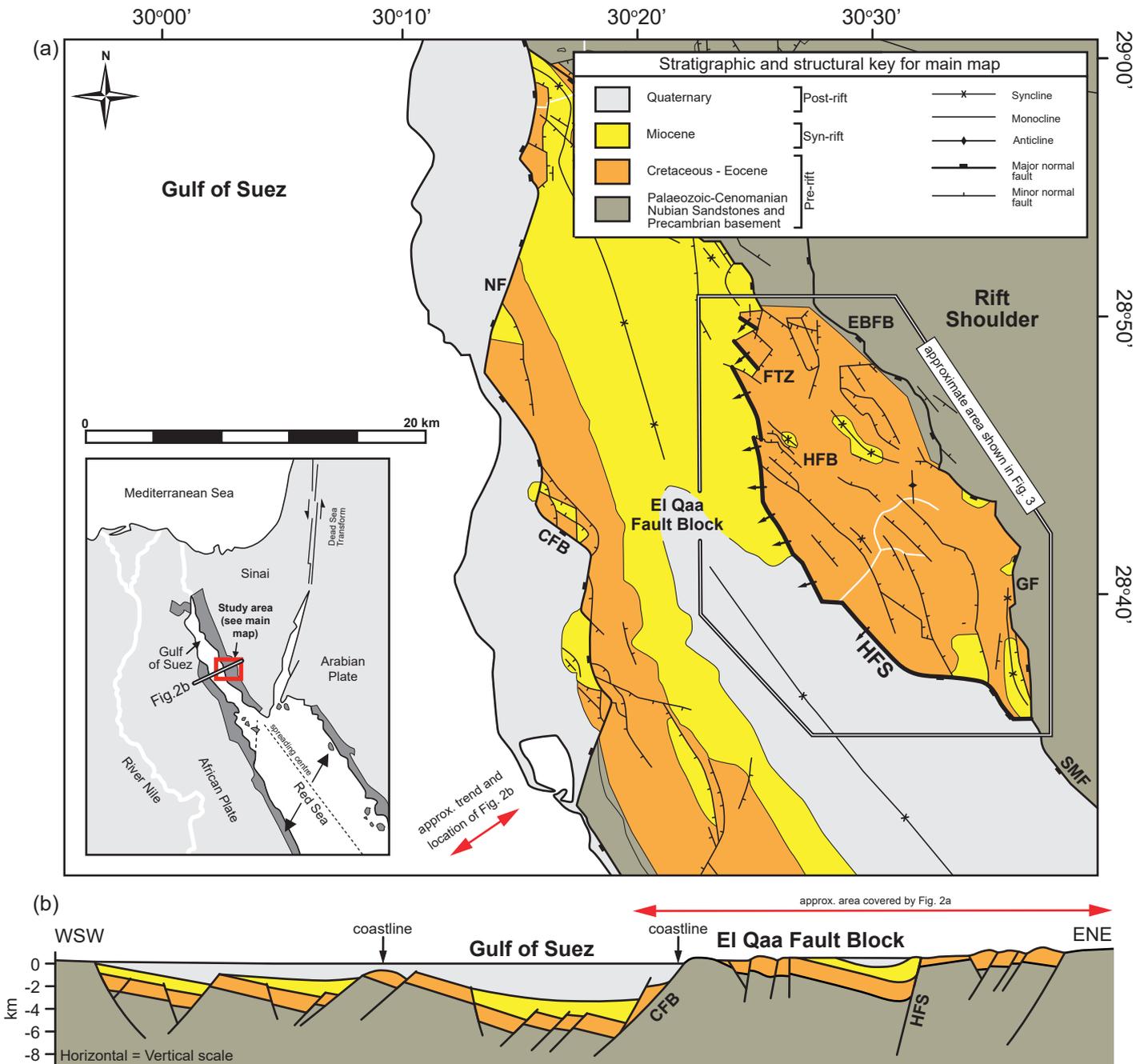




Fig. 4

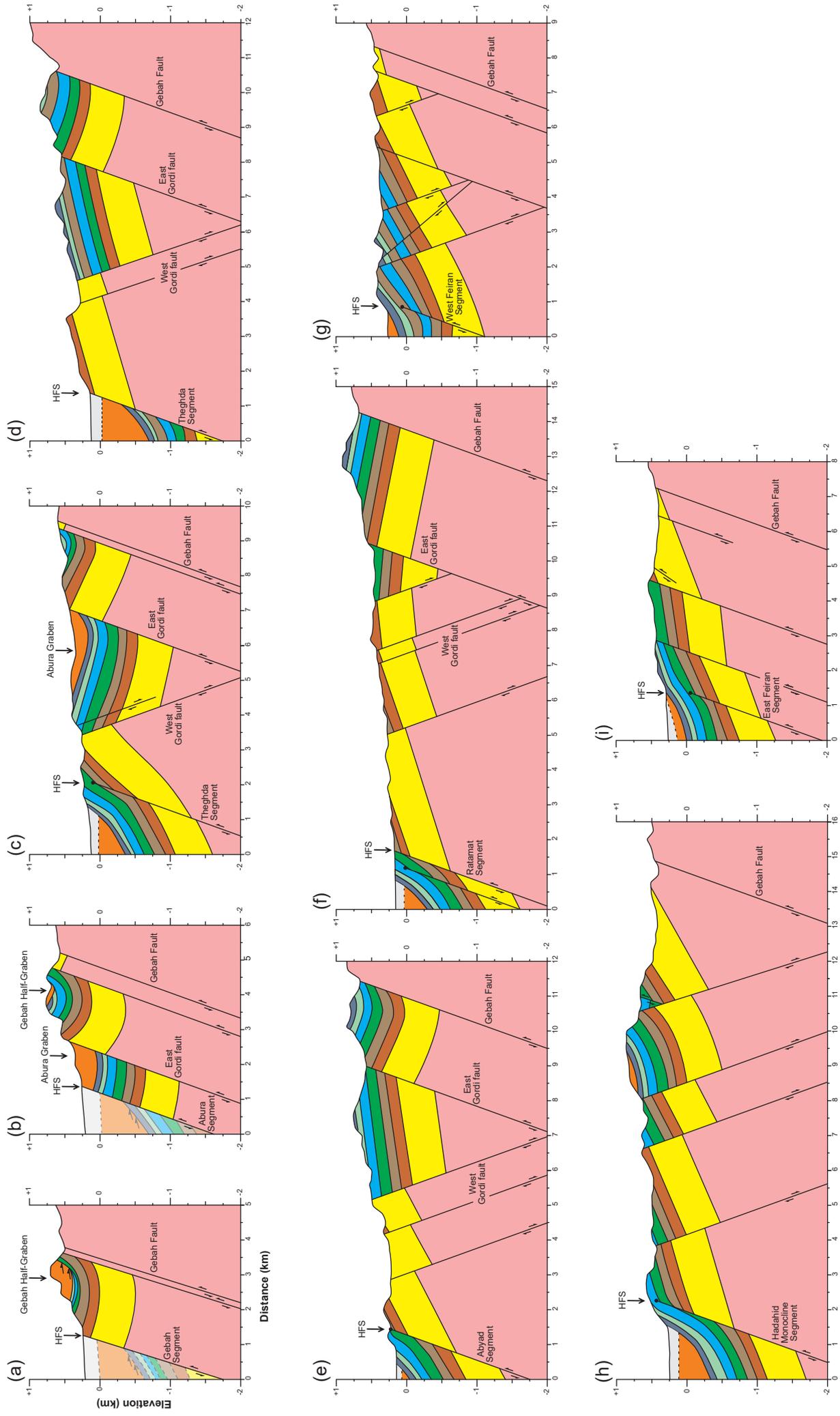


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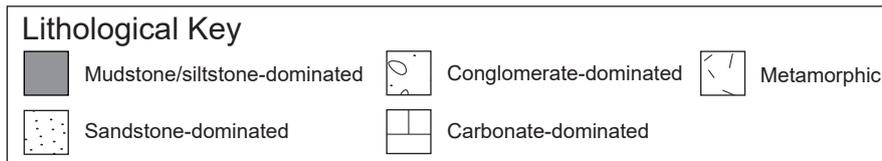
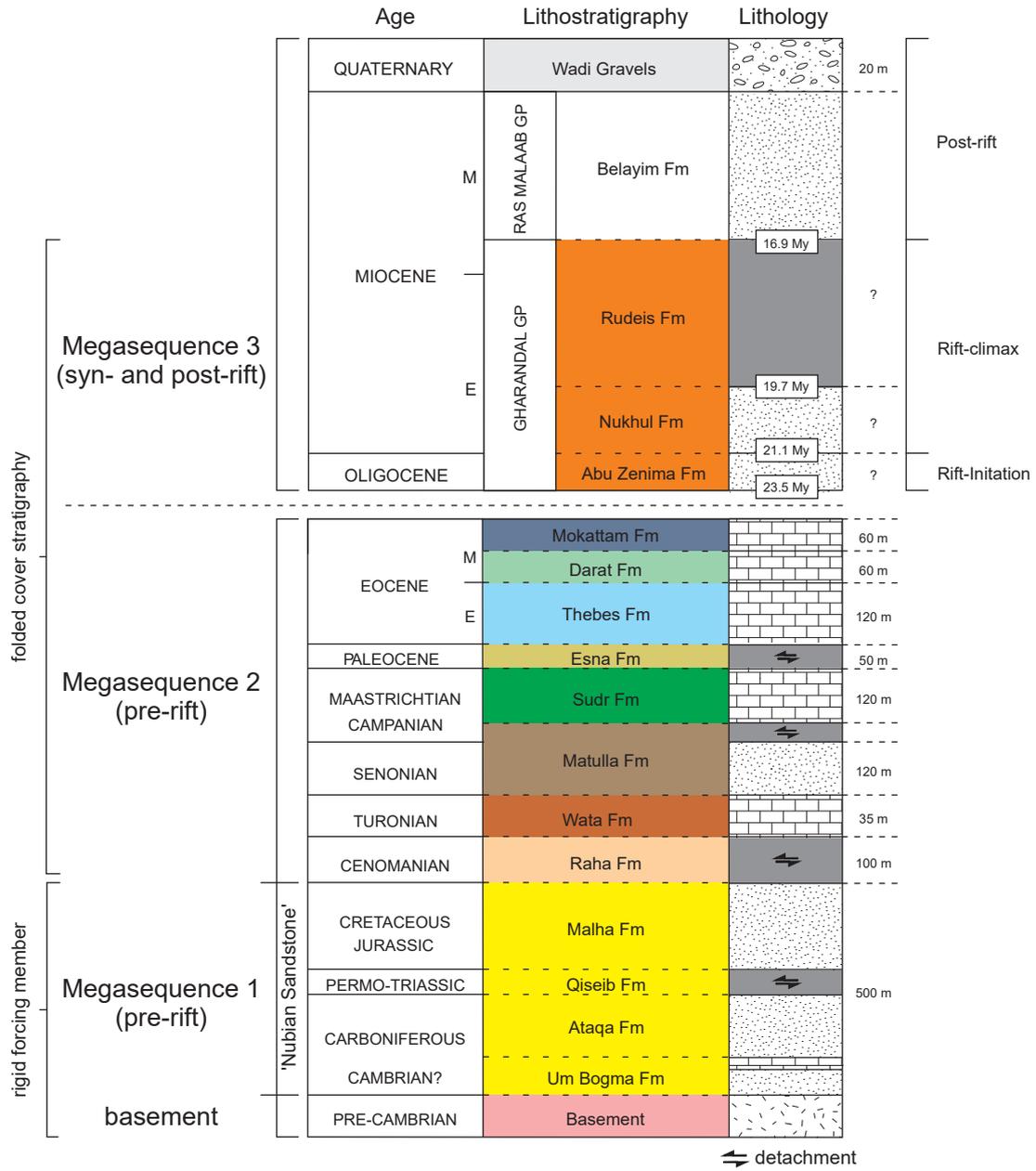


Fig. 6

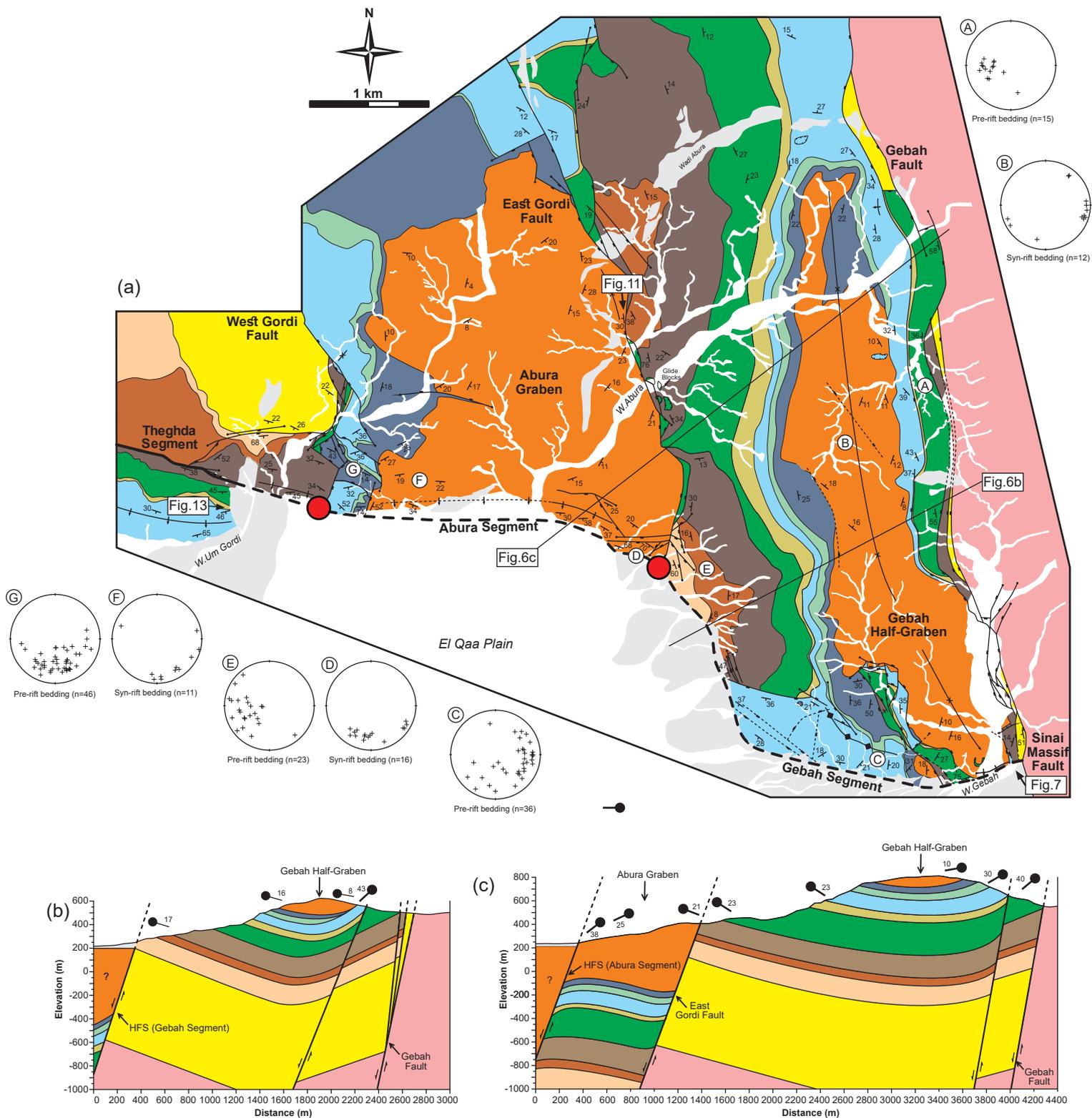


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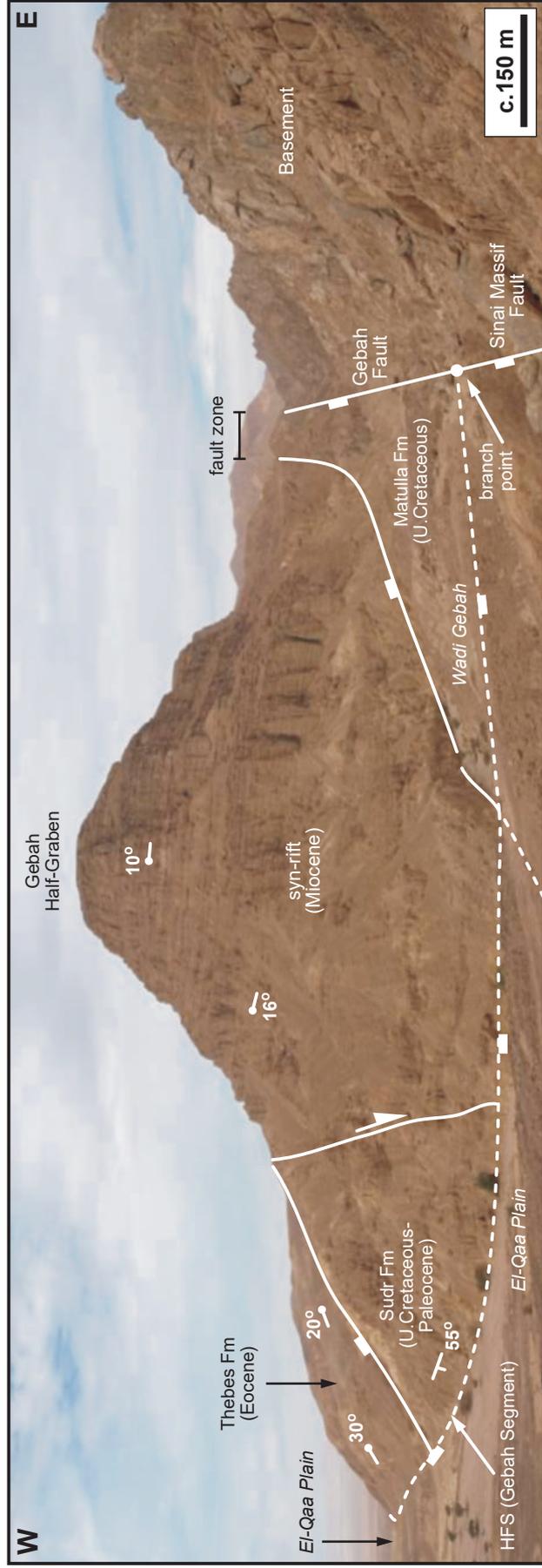


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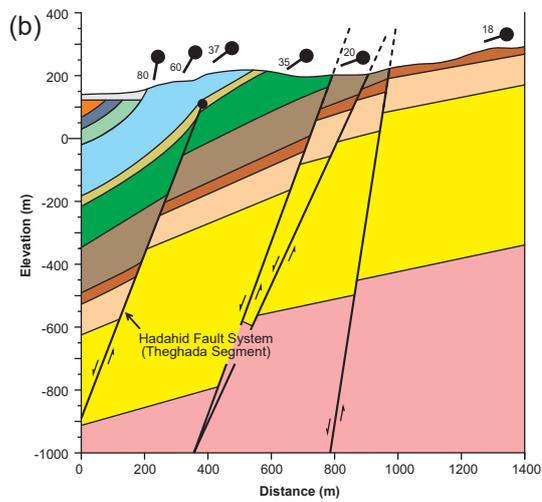
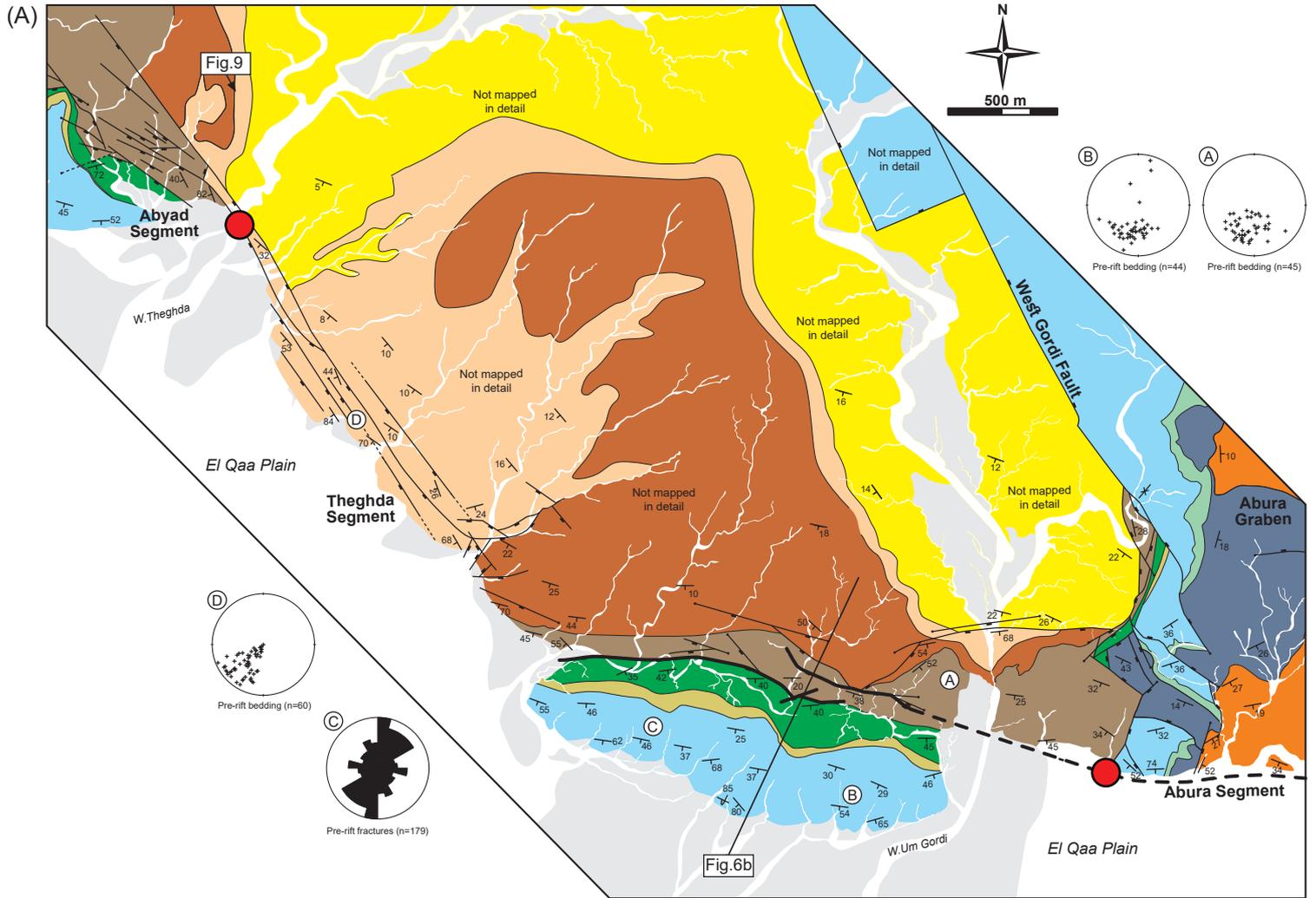


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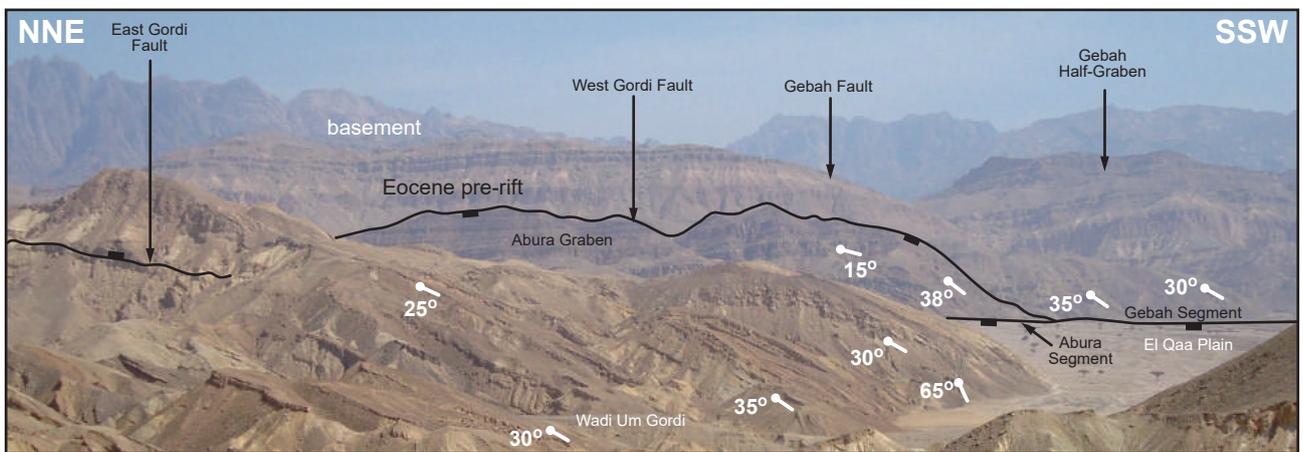


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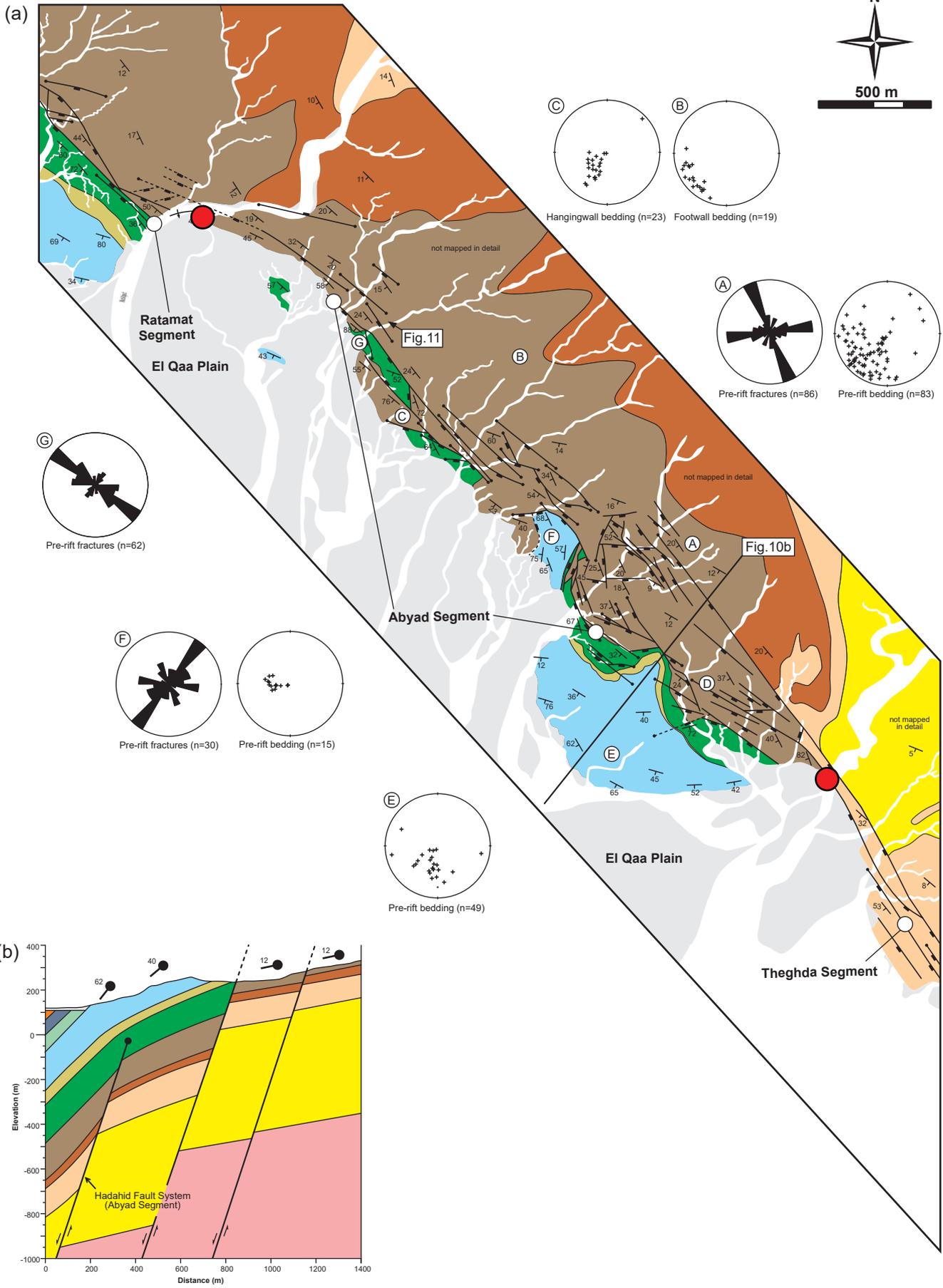


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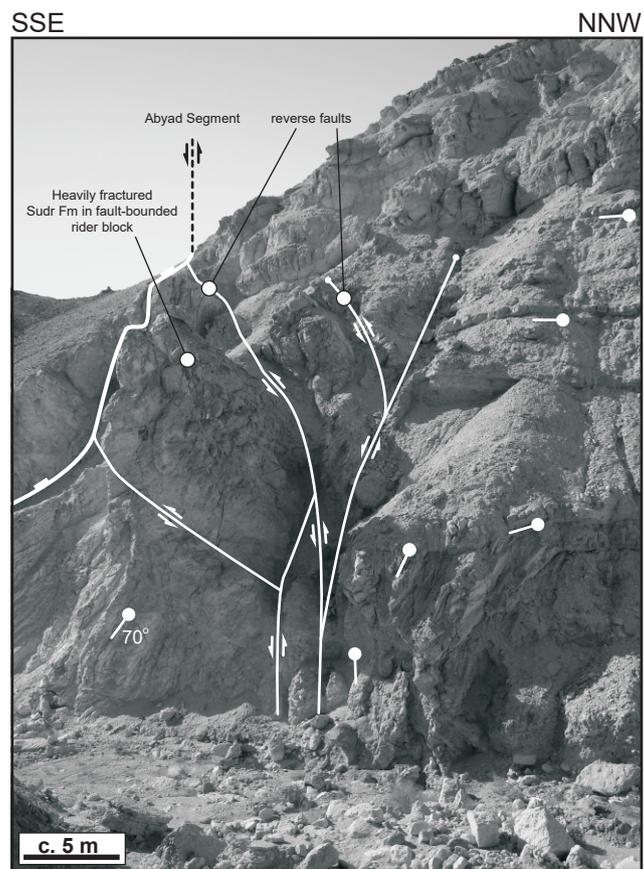
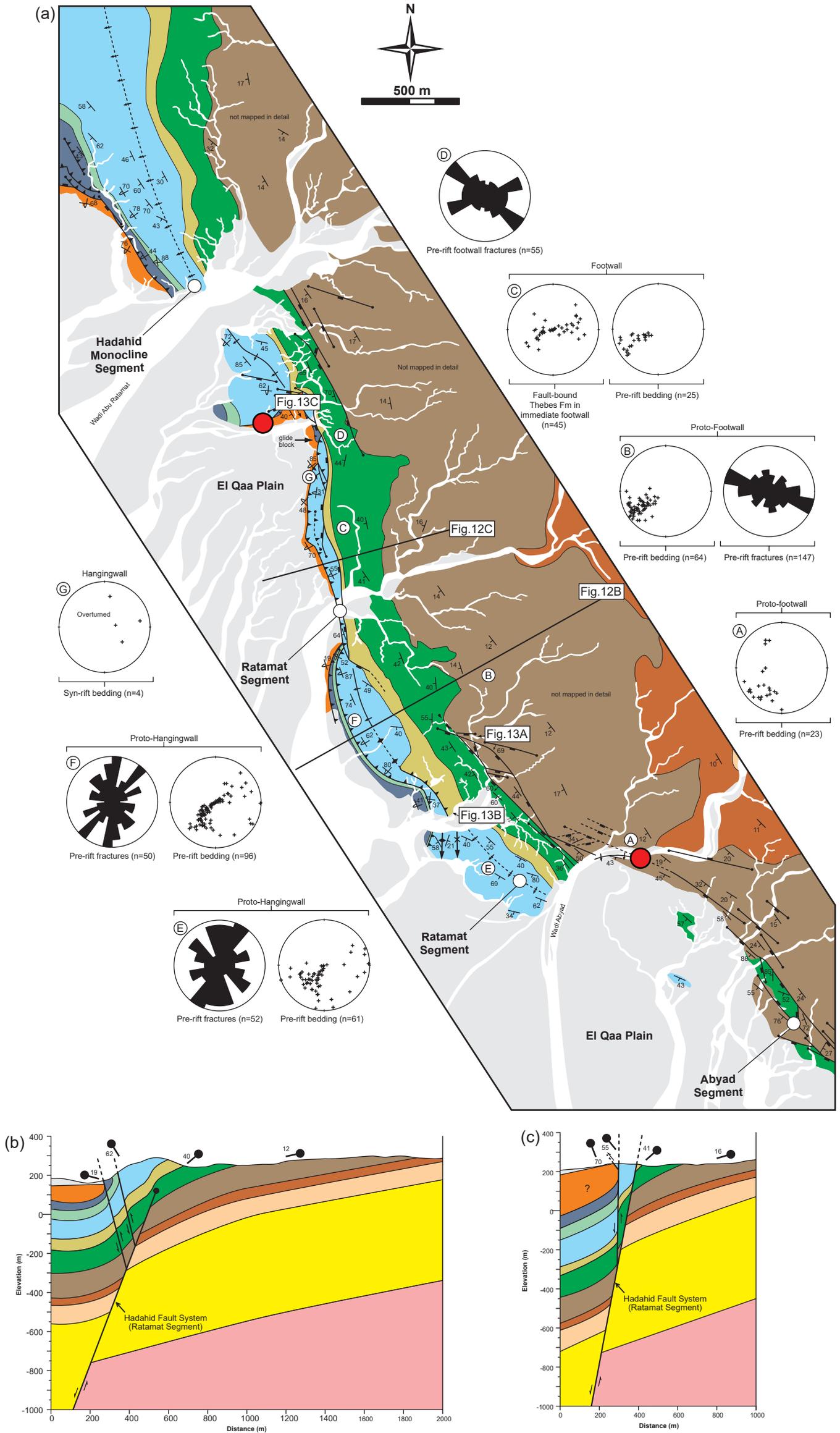


Fig.12



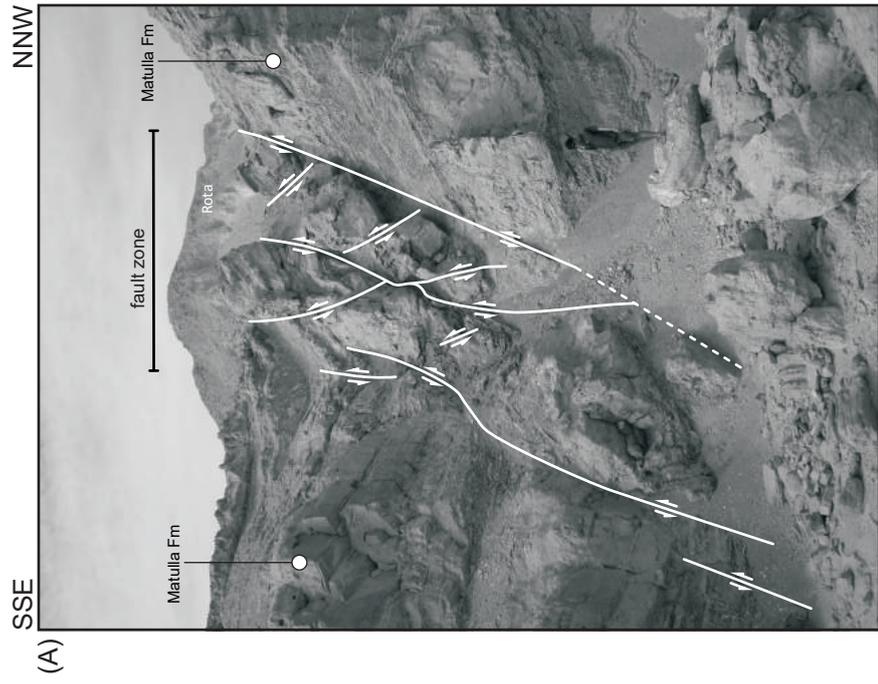
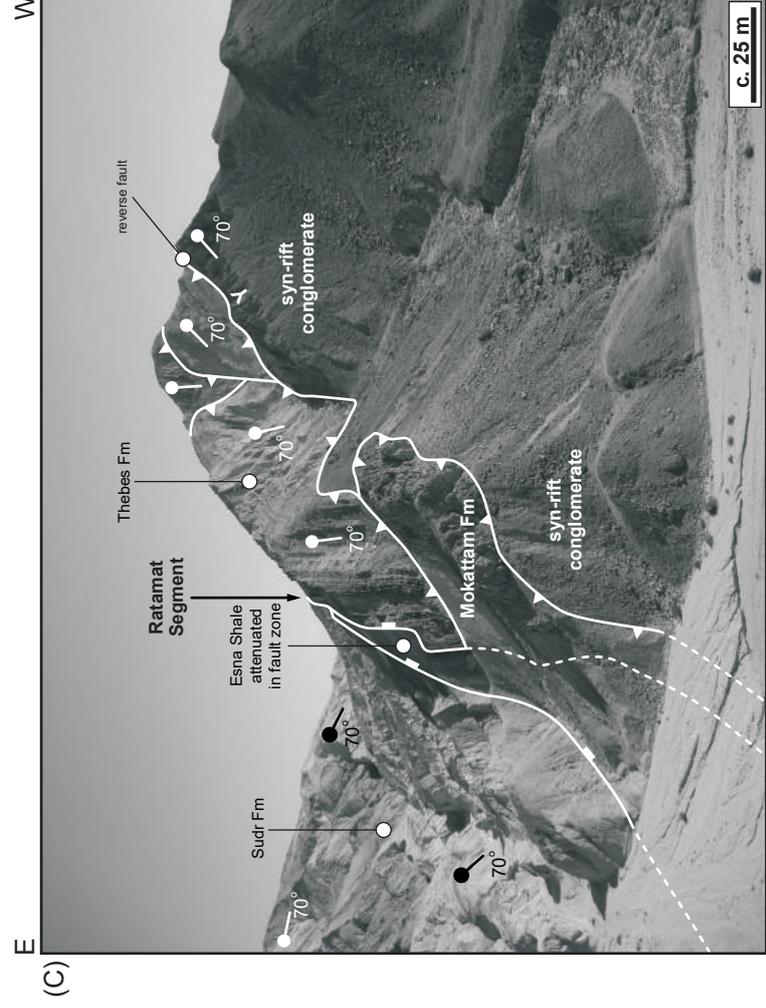


Fig.13

c. 25 m

Fig. 14

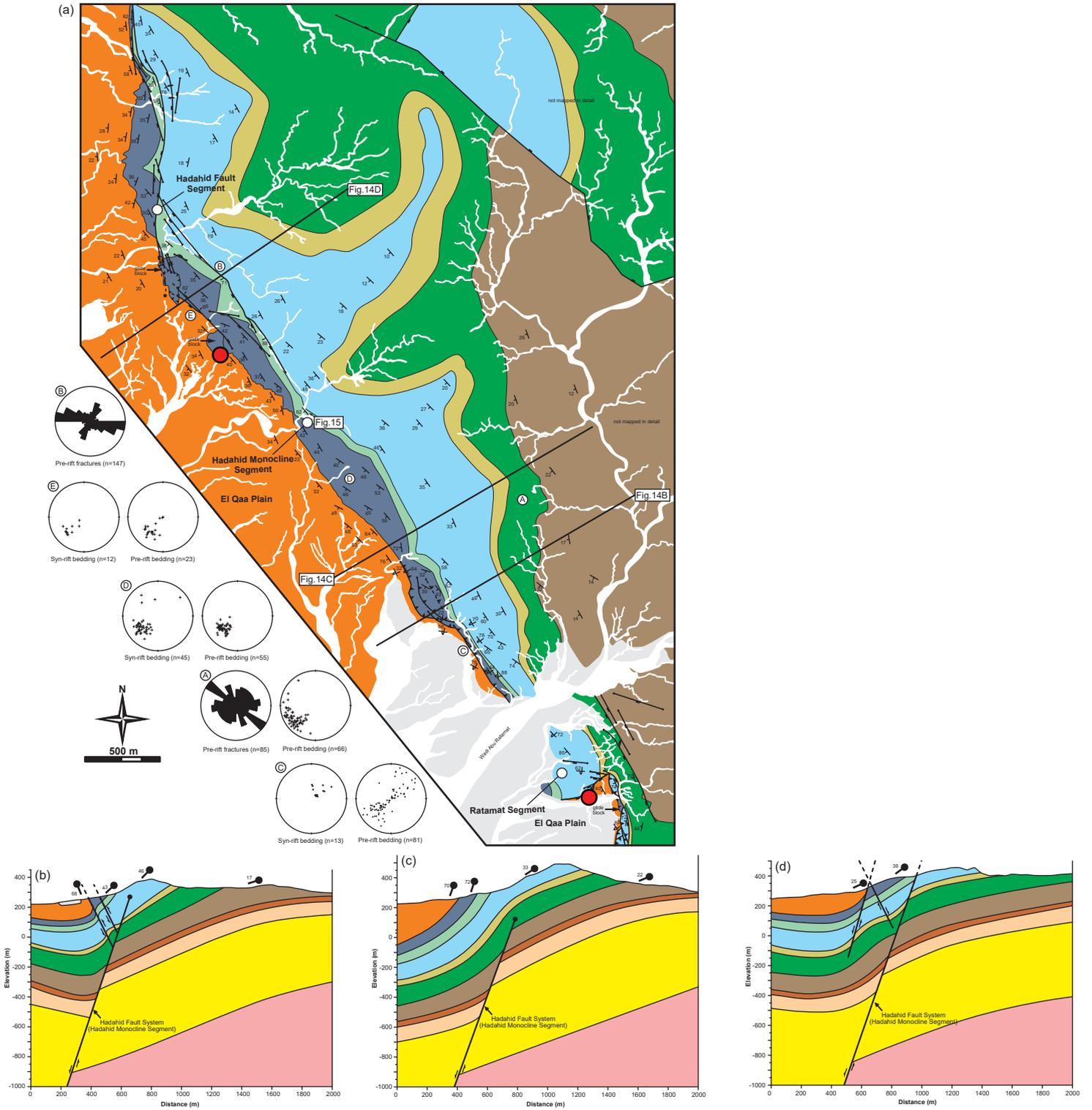


Fig.15

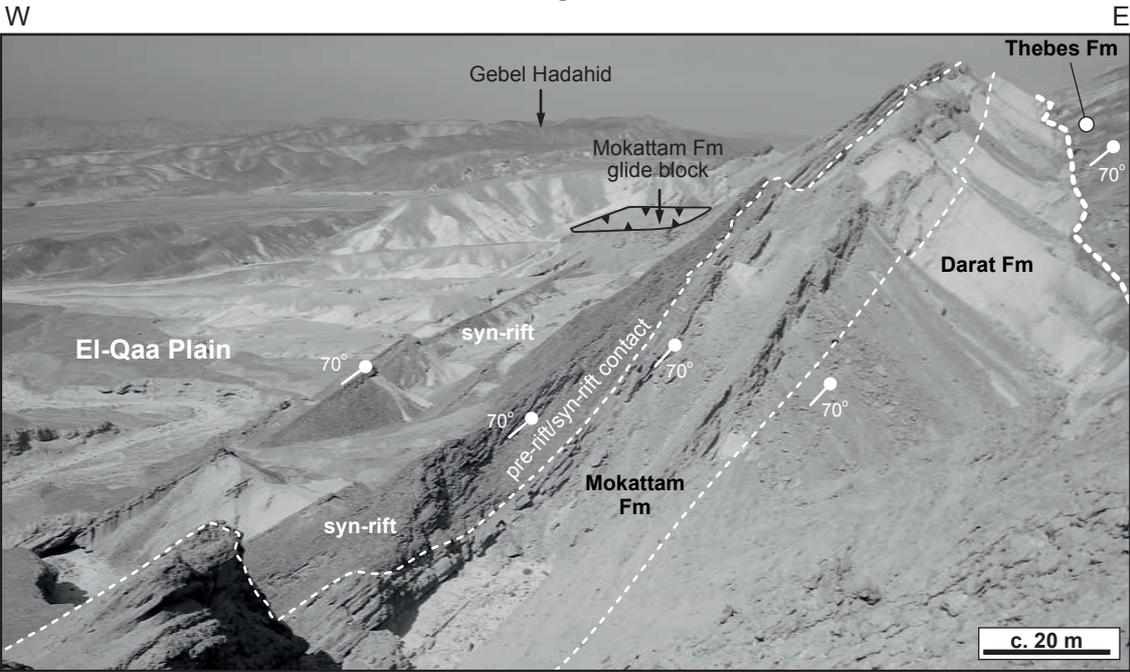


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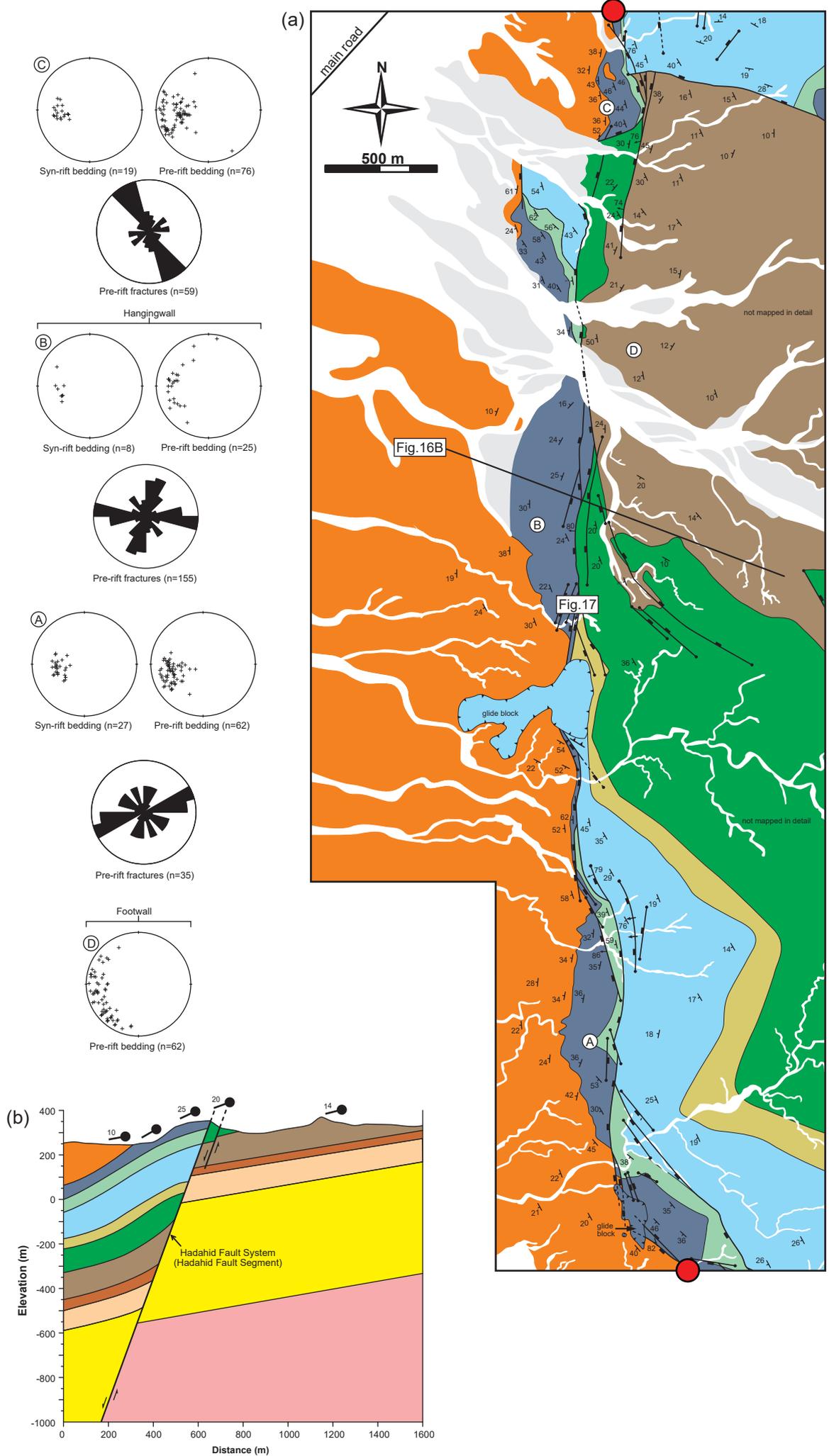


Fig. 17

S

N

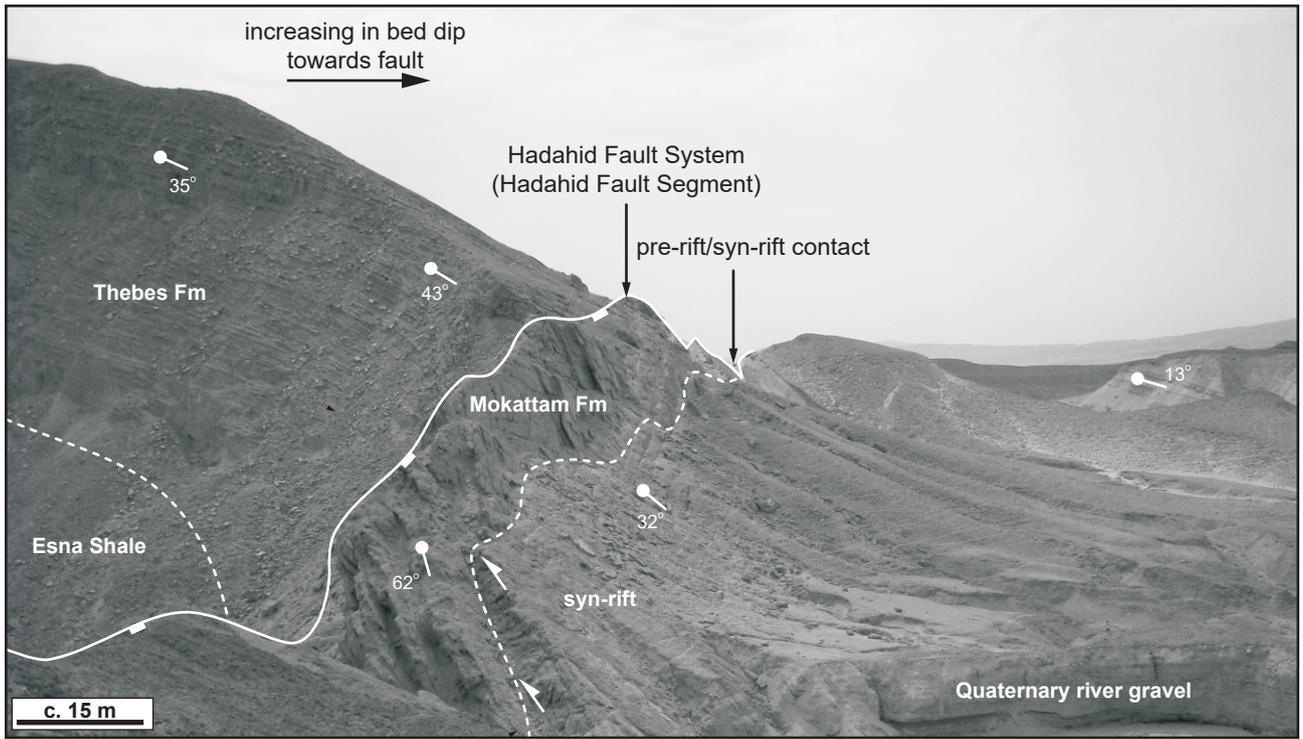


Fig.18

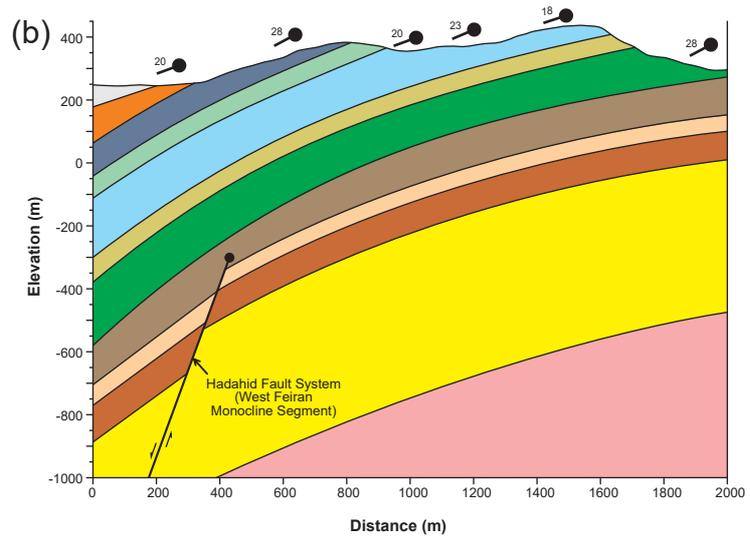
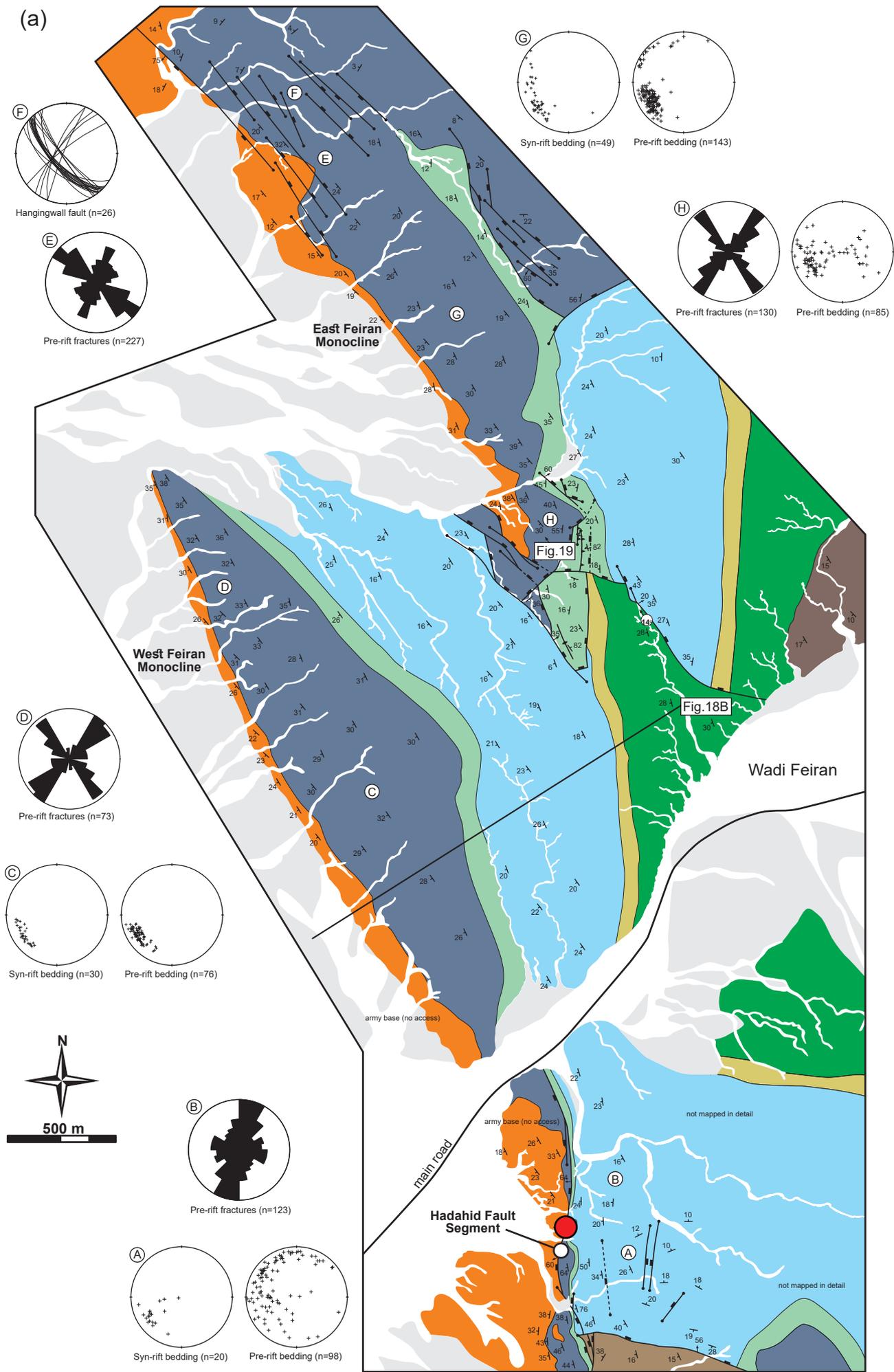


Fig.19

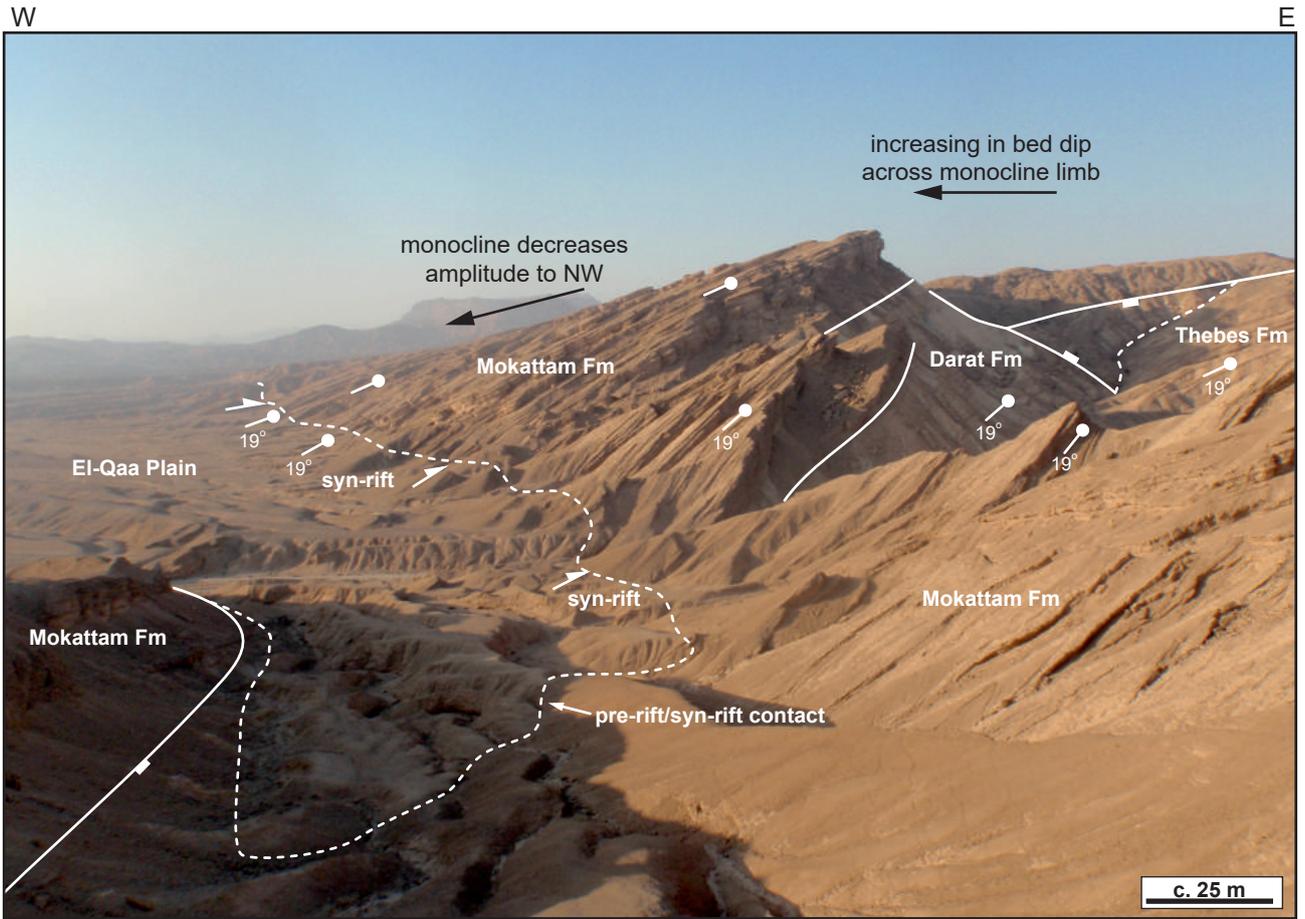


Fig. 20

