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1 **Evolution of the NW Zagros Fold-and-Thrust Belt in Kurdistan Region of Iraq from**  
2 **balanced and restored crustal-scale sections and forward modeling**

3  
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20 **Keywords**

21 Zagros Fold-and-Thrust Belt; Multi-detachment folding; Mechanical stratigraphy; Late

22 Cretaceous obduction; Thin-skinned versus thick-skinned

## 23 **Abstract**

24           We present the first regional balanced and restored sections across the northwestern part  
25 of the Zagros Fold-and-Thrust Belt in Kurdistan Region of Iraq and a 2D kinematic model that  
26 illustrates the evolution of the belt since Late Cretaceous time. The balanced cross-section, based  
27 on surface and sub-surface data, is characterized by multi-detachment folds detached above a  
28 Lower Triassic basal ductile level, with intermediate detachment levels that induced internal  
29 complexities like accommodation thrusting and/or disharmonic folding. Our work suggests that  
30 the two main structural steps in the detachment level in the High Folded Zone may be related to  
31 low-angle thrusts rooted at the brittle/ductile transition. Growth strata of Late Cretaceous and  
32 Paleocene times have been recognized for the first time in the Kurdistan Fold-and-Thrust Belt.  
33 This allows us to constrain timing of deformation and to estimate the evolution of the shortening  
34 and the advance of the deformation front since Late Cretaceous. Deformation of the Zagros belt  
35 is characterized by a combination of thin- and thick-skinned tectonics that reactivated the Late  
36 Cretaceous-Paleogene obduction belt.

## 37 **1. Introduction**

38           The Kurdistan Region of Iraq (KRI) is one of the most petroleum-rich provinces that  
39 could become one of the main producers in the near future (English et al., 2015). All significant  
40 hydrocarbon discoveries in the KRI occur in compressional structures buried in the foreland,  
41 which are mostly produced from Cretaceous and Tertiary reservoirs, while older petroleum  
42 systems are yet to be evaluated in detail (Jassim and Goff, 2006). In recent years, with the end of  
43 the second Iraq War, the KRI has regained a strong interest for petroleum exploration-related  
44 investigation which triggered numerous structural studies. These studies have investigated this  
45 region focusing on (i) the stratigraphy and the geologic evolution of the Iraqi Zagros (e.g., Alavi,

46 2004; Aqrabi et al., 2010; Sissakian, 2013; English et al., 2015), (ii) the tectonic and river  
47 drainage development of the High Folded Zone (e.g., Burberry et al., 2010; Bretis et al., 2011;  
48 Burtscher et al., 2012), (iii) the structure of the belt and its deformation style (e.g., Vera et al.,  
49 2009; Chalabi et al., 2010; Csontos et al., 2012; de Fehner et al., 2012; Hinsch and Bretis,  
50 2015), (iv) the timing of deformation and the geodynamic evolution of the Zagros in KRI (e.g.,  
51 Lawa et al., 2013; Koshnaw et al., 2017), and (v) the fracture patterns and their related  
52 petrophysical properties (e.g., Reif et al., 2012; Awdal et al., 2016). Several structural cross-  
53 sections have been published across KRI, mostly restricted to the upper part of the sedimentary  
54 cover (Bretis et al., 2011; Csontos et al., 2012; Fehner et al., 2012; Awdal et al., 2013; Al-  
55 Kubaisi, 2014; Zebari and Burberry, 2015). Very few of these cross-sections have been  
56 constructed down to the basement to discuss the deep basement structure controlling the uplift of  
57 the High Folded Zone (de Vera et al., 2009; Hayward, 2014; Hinsch and Bretis, 2015). Fold  
58 mechanisms have been interpreted differently and the nature of the basal detachment level is still  
59 discussed. Furthermore, the timing of deformation and large-scale orogenic evolution, although  
60 crucial for hydrocarbons exploration, are still poorly known in this folded region.

61         The main goals of this study are (i) to discuss the role of the mechanical stratigraphy, and  
62 its control on folding style, (ii) to address the significance of basement involvement and its role  
63 on the stepwise morphology of the basal detachment level towards the hinterland, (iii) to  
64 calculate the shortening by comparing the regional balanced and restored cross-sections, and (iv)  
65 to determine the relative ages of tectonic deformation and the evolution of the orogenic system  
66 since the Late Cretaceous. For these purposes, regional balanced and restored cross-sections  
67 were constructed across the central part of the KRI Fold-and-Thrust Belt and the Mesopotamian  
68 basin, based on surface and sub-surface data (seismic lines and well data). In addition, a new

69 detailed geological map is proposed, combining published geological maps with our own work  
70 based on several fieldwork campaigns, and remote sensing mapping using high resolution  
71 satellite images. A 2D kinematic and geometric forward model that traces the evolution of the  
72 KRI Fold-and-Thrust Belt from the latest Cretaceous to present has been performed. Nine new  
73 vitrinite reflectance points, collected in different stratigraphic units, have been used to infer the  
74 amount of burial and erosion in the KRI Fold-and-Thrust Belt. The forward model presented in  
75 this study, integrates all datasets and provides a robust geological history of the KRI Fold-and-  
76 Thrust Belt.

## 77 **2. Geological Setting**

78 The Taurus-Zagros Fold-and-Thrust Belt extends over 2000 km from Turkey to SE Iran  
79 (Fig. 1) and resulted from the closure of the Neo-Tethys Ocean between the Arabian and  
80 Eurasian Plates (e.g., Dewey et al., 1973; Talbot and Alavi, 1996; Stampfli and Borel, 2002).  
81 This orogenic belt has two distinct trends, NW-SE between the Arabian and the Central Iranian  
82 Plates (called the Zagros trend), and E-W between the Arabian and South-Armenian Plates  
83 (called the Taurus trend). The KRI Fold-and-Thrust Belt includes the intersection of the Zagros  
84 and Taurus trends (Fig. 1).

85 The Zagros orogenic belt consists of five NW-trending tectonic domains, from NE to SW (Fig. 1): (i) the Urumieh-  
86 Dokhtar Magmatic Arc formed by the subduction of the Neo-Tethys Ocean, (ii) the metamorphic and magmatic  
87 Sanandaj-Sirjan Zone, (iii) the Thrust Zone (Nappe Zone) in Kurdistan and the Imbricated Zone in Iran (also called  
88 High Zagros Thrust Belt or Crush Zone), (iv) the High Folded Zone (Mountain Foothills) in Kurdistan and the  
89 Simply Folded Belt in Iran, and (v) the Low Folded Zone (Buried Foothills or Foothill Zone) in Kurdistan linking to  
90 the SE with the Mesopotamian foreland basin and its continuation along the Persian Gulf. The Sanandaj-Sirjan Zone  
91 and the Thrust Zone are separated by the Main Zagros Fault (MZF), which is classically interpreted as the Neo-  
92 Tethys suture (Blanc et al., 2003).

93 **Figure 1.**

94

95 The Thrust Zone is a highly deformed domain composed of multiple tectonic slices  
96 including the distal part of the Arabian margin, fragments of Cretaceous ophiolites and remains  
97 of island arcs and accretionary prisms (e.g., Blanc et al., 2003; Vergés et al., 2011b; Ali et al.,  
98 2014). The Thrust Zone was thrust on top of the High Folded Zone (HFZ) above the High  
99 Zagros Fault (HZF; Fig. 1). The HFZ is mainly characterized by a fold and thrust system  
100 involving the sedimentary cover of the Arabian Margin subducting Plate. In Iran, folding  
101 involved the whole sedimentary succession above a weak basal detachment level, which  
102 corresponds to the lower Cambrian-Ediacaran Hormuz salt or lateral equivalent (Blanc et al.,  
103 2003; McQuarrie, 2004; Molinaro et al., 2004; Sherkati and Letouzey, 2004; Sepehr et al., 2006;  
104 Alavi, 2007; Mouthereau et al., 2007; Vergés et al., 2011a). In the KRI, the basal detachment  
105 seems to be located higher in the sedimentary succession as indicated by de Vera et al. (2009),  
106 Csontos et al. (2012), Awdal et al. (2013), Hayward (2014), and Hinsch and Bretis (2015). The  
107 HFZ and the Low Folded Zone (LFZ) are separated by the Mountain Front Flexure or the  
108 Mountain Front Fault (MFF) (Falcon, 1961; Berberian, 1995), a major morphotectonic  
109 discontinuity that uplifted the HFZ by 3-6 km with respect to the LFZ (Sepehr and Cosgrove,  
110 2004; Sherkati et al., 2006; Emami et al., 2010). In map view, the MFF exhibits an irregular  
111 shape defining arcs and embayments along the HFZ, from SE to NW: the Fars arc, the Dezful  
112 embayment, the Lurestan arc (or Pusht-e Kuh arc), and the Kirkuk embayment (Fig. 1).

113 The development of the Zagros Fold-and-Thrust Belt began in the Late Cretaceous with  
114 the obduction of sub-oceanic to oceanic crust above the Arabian continental margin from

115 Campanian to Paleocene times, and culminated in the Neogene with the continental collision  
116 between Arabian and Central Iranian blocks (Alavi, 2004; Homke et al., 2010; Saura et al.,  
117 2015).

118 In the SE part of the KRI and in the Lurestan, three main tectonic slices were emplaced  
119 during the obduction event, from bottom to top (e.g., Wrobel-Daveau et al., 2010; Ali et al.,  
120 2014): the Cretaceous Qulqula/Kermanshah radiolarian chert, the Triassic Avroman/Bisotun  
121 carbonates, and the Late Cretaceous ophiolite complex (Hasanbag, Mawat, Penjween and  
122 Kermanshah ophiolites). In the Central part of the KRI, the Avroman-Bisotun Mesozoic  
123 carbonate platform is missing suggesting that the continental block that was supporting it, did not  
124 extend further to the NE (Fig. 1). The ophiolitic obduction above the Arabian continental crust  
125 was associated with the development of an early foredeep or proto-foreland basins in response to  
126 the flexure of the Arabian lithosphere: the Amiran Basin in the Lurestan Province (e.g., Homke  
127 et al., 2009; Saura et al., 2011), and the Kolosh/Tanjero Basin in the KRI (e.g., Aqrabi et al.,  
128 2010). In KRI, the earliest deformation events related to the obduction of the oceanic remnants  
129 onto the Arabian Margin were only recorded in the hinterland (Lawa et al., 2013; Ali et al.,  
130 2014), but never in the foreland as it is described in Iran (Homke et al., 2009; Piryaei et al., 2010;  
131 Saura et al., 2011; Farahpour and Hessami, 2012).

132

133 **Figure 2.**

134

135           The collision of the Iranian block onto the Arabian margin initiated during the Neogene  
136 and is still active nowadays (e.g., Vernant et al., 2004). In KRI, the Eocene-Oligocene volcano-  
137 sedimentary rocks of the Walash-Naopurdan intra-oceanic island-arc (equivalent of the Gaveh  
138 Rud domain in Iran) were accreted during the Miocene and were transported over the Cretaceous  
139 ophiolite complex and the early foreland basin (Ali et al., 2014). Then, the Sanandaj-Sirjan Zone  
140 composed of Mesozoic metamorphic rocks, including volcanic and intrusive rocks, was  
141 emplaced and led to the development of the major Mesopotamian foreland Basin in response to  
142 the crustal thickening in the hinterland. This foreland basin was later deformed with a general  
143 southwest propagation of deformation (e.g., Wrobel-Daveau et al., 2010; Lawa et al., 2013). The  
144 Zagros belt is classically interpreted as a thin-skinned belt evolving to a thick-skinned tectonic  
145 wedge based on large-scale crustal sections (Vergés et al., 2011b; Mouthereau et al., 2012) and  
146 numerical modeling (Saura et al., 2015). Recent studies established sequences of deformation for  
147 the KRI Fold-and-Thrust Belt (Lawa et al., 2013; Ali et al., 2014; Koshnaw et al., 2017). Lawa et  
148 al. (2013) proposed a sequential deformation towards the foreland coeval to a decrease of the  
149 deformation intensity. Koshnaw et al. (2017) suggested an out-of-sequence thrusting in the  
150 hinterland and along the Mountain Front Flexure by means of low-temperature  
151 thermochronology, stratigraphy and provenance results.

### 152 **3. Central KRI Fold-and-Thrust Belt**

153           The study area is located in the Central part of the KRI Fold-and-Thrust Belt (Fig. 2).  
154 Map in Figure 2 is a new map based on existing 1:250000 scale geological maps of this region.  
155 The HFZ has been entirely reinterpreted with the interpretation of high resolution satellite  
156 images (AVNIR ALOS data) and mapping based upon our field data. Three field campaigns

157 covering mainly the HFZ were realized in 2015 and allowed the acquisition of hundreds of dip  
158 data, the stratigraphic calibration and the sampling for vitrinite reflectance data.

159 The Kirkuk embayment is characterized by NW-SE trending folds, which are sub-parallel  
160 to the High Zagros Fault (HZF) that separates the HFZ from the Thrust Zone (Fig. 2). To the NE  
161 of the HZF, the Cretaceous ophiolite complex, the Qulqula radiolarite nappes, and the Paleogene  
162 Walash-Naopurdan accretionary complex are SW-transported thrust sheets cropping out along  
163 the Iraq-Iran border. The basal thrusts of these allochthonous sheets are low-angle (almost flat)  
164 thrust faults above footwall strata constituted by Paleocene-Miocene Red Beds (Fig. 2).

165 The youngest rocks exposed in the LFZ correspond mostly to Pliocene Bakhtiari  
166 conglomerates and to Quaternary alluvium, while the Fars Formation forms the core of most of  
167 the exposed anticlines (Fig. 2). In the HFZ, the most frequently exposed rocks are Cretaceous  
168 and Paleogene (Fig. 2). Anticlines are mostly capped by the competent limestones of the  
169 Qamchuqa Fm., or by the thick reefal limestones of the Aqra and Bekhme formations, while  
170 synclines are cored by units of Paleocene (Kolosh Fm.) to Miocene age (Fars Fm.). This abrupt  
171 change in the level of exposure illustrates the structural relief generated by the MFF. From the  
172 Makook anticline to the HZF, anticlines are usually pierced revealing in their core Jurassic to  
173 Triassic rocks (e.g. Makook, Handreen, Tanun anticlines), while the younger rocks exposed in  
174 the synclines are of Late Cretaceous age. This second step in the level of exposure, accompanied  
175 by an increase of elevation, suggests the presence of a second structural step below the Makook  
176 anticline which delimits the Inner and the Outer HFZ (Fig. 2).

177 The LFZ is characterized by an irregular distribution of the anticlines, while the HFZ is  
178 an intensely folded area where anticlines are separated by narrow and tight synclines (Fig. 2).

179 The anticlines are mostly NW-SE to NNW-SSE trending, and the axial traces are relatively  
180 straight, even if some anticlines have curvilinear shapes that can be interpreted as related to fold  
181 linkages (e.g., Bretis et al., 2011). In the Outer HFZ, very few thrust faults have been recognized.  
182 Field analysis as well as repetitions seen in the well data (Sapin et al., 2017) indicate that the  
183 amount of displacement along these faults is limited. In the Inner HFZ, thrusting becomes a more  
184 common feature (Fig. 2). Some anticlines (Zozic, Tanun, Makook and Bradost) show thrustured  
185 forelimbs with displacements up to 2-3 km.

186 The observed surface shape of many of the anticlines showing the so-called whaleback  
187 shape can be associated with detached concentric folding (Fig. 3b and 3d). However, it is rather  
188 common to find short wavelength disharmonic folds along the limbs of the main anticlines like  
189 “rabbit ear” or “gravity flap” structures (Fig. 3a and 3c). For example, in the Safeen-Shakrook  
190 area (Fig. 2), fieldwork indicates that the competent Qamchuqa platform thins in this area and is  
191 replaced by the softer Sarmord marly limestones unit that was activated as a restricted  
192 intermediate detachment level (Fig. 3c).

193

194 **Figure 3.**

195

#### 196 **4. Stratigraphy of the Kurdistan and its mechanical behavior**

197 The Proterozoic crystalline basement of the Arabian Plate beneath KRI is covered by a  
198 thick sedimentary pile (10-15 km) deposited from Cambrian to Cenozoic times and disrupted by  
199 several sedimentary gaps (Fig. 4a). Most of the stratigraphy described in this section is based on

200 fieldwork, unpublished commercial well data and published works from Van Bellen et al. (1959)  
201 and Aqrawi et al. (2010).

#### 202 *4.1. The Paleozoic Gondwana intracratonic basin*

203 The Paleozoic sequence is composed of a thick sedimentary pile (up to 7 km) divided by  
204 two main unconformities (Fig. 4a). The Cambro-Ordovician epicontinental deposits, mainly  
205 clastic, are composed by the Sadan quartzite, the Koruk dolomite and the Khabour quartzite-  
206 shale formations, which are unconformably overlain by the Upper Devonian Pirispiki reds beds  
207 (English et al., 2015). The Upper Devonian (Famennian) Kaista Formation is considered as a  
208 transitional sequence from continental to marine sedimentation. This Late Devonian to Early  
209 Carboniferous marine transgression is associated to the deposition of the Upper Devonian-Lower  
210 Tournaisian Ora shales and the Lower Tournaisian-Lower Carboniferous Harur limestones (Fig.  
211 4a). A second major unconformity is recognized between the Harur formation and the Permian  
212 Chia Zairi limestones.

#### 213 *4.2. The Mesozoic Arabian passive margin*

214 In the Early Triassic, a continental passive margin developed along the northeastern and  
215 northern borders of the Arabian Plate related to the opening of the Neo-Tethys Ocean, which is  
216 characterized by the deposition of the Mirga Mir marly limestones and evaporites and the Beduh  
217 shales in the Kurdistan Region of Iraq (Fig. 4a). During the Mesozoic, this region was dominated  
218 by large carbonate platforms associated to the drowning of the Arabian margin during its passive  
219 margin stage. From Middle Triassic to Late Jurassic, the depositional environment alternated  
220 between semi-restricted platform and evaporitic lagoon (Van Bellen et al., 1959; Aqrawi et al.,  
221 2010), with the deposition of the extensive Middle and Upper Triassic carbonate–evaporite

222 sequences of the Geli Khana and Kurra Chine formations followed by the development of a  
223 large-scale intrashelf basin. This Early Jurassic basin, relatively isolated from the open-marine  
224 waters of the Neo-Tethys, was infilled by rich source rocks and evaporites (Fig. 4a): the Baluti,  
225 Sarky, Sehkaniyan, Sargelu, Naokelekan and Barsarin formations (Aqrawi et al., 2010). A total  
226 thickness of up to 3 km characterized the Triassic-Jurassic succession in the northeastern corner  
227 of the Arabian Plate.

228         The restricted northeastern Arabian margin was replaced in Late Tithonian time with the  
229 Balambo-Garau Basin, which was characterized by a more open depositional environment  
230 following an important drowning of the Arabian margin. This basin is characterized by the  
231 deposition of the basinal carbonates of the Balambo Fm., while the most external part of the  
232 basin is characterized by the deposition of the Qulqula radiolarian sediments. The Balambo Fm.  
233 passes laterally into the marly transitional Sarmord Fm. (outershelf carbonate) and the massive  
234 neritic limestones of the Qamchuqa Fm. (shallow marine carbonate) (Fig. 4a). The geometry of  
235 the Balambo-Garau Basin is characterized by a main basin situated in the SE region of KRI and  
236 in the Lurestan Province of Iran, while the Central and Northern part of the KRI is dominated by  
237 the shallow marine carbonate platform of the Qamchuqa Fm. (Aqrawi et al., 2010).

#### 238 *4.3. The latest Cretaceous-Eocene obduction related foredeep to foreland basin*

239         In response to the obduction of ophiolite and radiolarite thrust sheets on the northeastern  
240 margin of the Arabian Plate during the Campanian-Maastrichtian, passive margin conditions  
241 ended and a foredeep basin developed. The transition between the passive margin and the  
242 flexural basin conditions is recorded by the deposition of the Shiranish Fm. (Fig. 4a) that is  
243 composed of blue marls, and thin-bedded marly and globigerina limestones, which evidence the

244 presence of a clastic source. This flexural basin is filled by the Maastrichtian clastic Tanjero Fm.  
245 (Fig. 4a), mainly formed by silty marls, siltstones and sandstones partially composed of detrital  
246 ophiolite and radiolarian material revealing the subaerial erosion of the ophiolite nappe complex.  
247 The effects of this obduction event extended during the Paleocene and Eocene epochs with the  
248 deposition of the clastic deep-water to shelfal Kolosh Formation (Fig. 4a). Northeastwards, the  
249 Kolosh Fm. passes laterally to the Red Beds continental deposits of the same age. The Sinjar  
250 Fm., overlying the Kolosh Fm., is reef-like facies of the Paleocene and Lower Eocene epochs,  
251 which forms a discontinuous wall with several separate reef-banks and islands (Aqrabi et al.,  
252 2010). Above, the predominantly continental Gercüs Fm. consists of red shales, sandy marls and  
253 pebbly sandstones. Middle-Upper Eocene Pilaspi carbonate platforms, consisting of well-bedded  
254 white chalky limestones (Fig. 4a), infilled the early foreland basin related to obduction events  
255 (see related Amiran basin in Iran, Homke et al., 2009; Saura et al., 2011).

#### 256 *4.4. The Miocene collisional foreland basin*

257 In the inner part of the Zagros Fold-and-Thrust Belt, the sedimentation is characterized by  
258 a major hiatus encompassing the entire Oligocene and the Lower Miocene (Fig. 4a), while to the  
259 SW, shallow-water carbonate platforms were deposited: the Oligocene Kirkuk Group and the  
260 Lower Miocene Group. The sedimentation resumed with the onset of the Zagros collision, and a  
261 typical foreland basin formed: the Mesopotamian Basin. During the Middle Miocene the marine  
262 transgression extended South forming shallow basins with carbonate deposits, whereas in closed  
263 lagoon domains, evaporites were deposited. The Middle Miocene Lower Fars Formation is  
264 characterized by thick salt horizons occurring in the southern part of the KRI, while in the central  
265 and northern parts the Lower Fars Fm. is mainly composed of sandstones, mudstones and red  
266 claystones (Fig. 4a). From the Late Miocene, the marine environment changed to continental and

267 the Mesopotamian foreland Basin was filled by a classical lake-fluvial-alluvial sedimentary  
268 succession coarsening upwards from the pebbly sandstones of the Upper Fars Fm. (Late  
269 Miocene), conglomeratic sandstones of the Lower Bakhtiari (Pliocene) and massive  
270 conglomerate of the Upper Bakhtiari (Pleistocene). In total, up to 5 km of Cenozoic sediments  
271 were originally deposited within the Mesopotamian foreland Basin (Fig. 4a), with the greatest  
272 thickness in the southeastern KRI and Iran, and thinning progressively up toward the Mosul High  
273 in NW KRI.

274

275 **Figure 4.**

276

#### 277 *4.5. The Mechanical Stratigraphy*

278 Figure 4 presents new mechanical subdivisions of the stratigraphy, based on fieldwork,  
279 well data and seismic evidence, which consists of several competent structural units (mainly  
280 limestones) that are separated by disharmonic levels consisting of interbedded shales-sandstones  
281 or marls-limestones units, and detachment levels which correspond to shales and/or evaporitic  
282 deposits (Fig. 4a).

283 The Paleozoic sequence is estimated 7 km thick and is considered as a competent  
284 interval, which is mechanically linked with the Proterozoic basement. The Upper Devonian-  
285 Lower Tournaisian Ora shales correspond to the only known potential detachment level in the  
286 Paleozoic succession, but fieldwork and remote sensing investigations performed in the Northern

287 part of the Kurdistan reveal that Ora shales are deformed harmoniously with the rest of the  
288 Paleozoic units, and thus is not considered as the main basal detachment level.

289 The Beduh and Mirga Mir formations are considered to be the basal detachment level in  
290 the Kirkuk Embayment (Fig. 4a). We assumed this because (i) the lithologies of these units  
291 (shales, marly limestones and evaporites) are consistent with an efficient detachment level, (ii) in  
292 the Northern part of the KRI near the Turkish border, field evidence of highly disharmonic  
293 deformation was observed at different scales into the Beduh and Mirga Mir units (Fig. 4d), and  
294 (iii) the anticline wavelengths that ranged between 5 and 8 km are inconsistent with a basal  
295 detachment deeper than the Beduh-Mirga Mir level.

296 The Pre-Campanian Mesozoic sequence in the KRI is approximately 4 km thick and is  
297 considered at first order as one competent unit detached on the Beduh-Mirga Mir basal  
298 detachment level. However, three intermediate detachment levels have been identified from field  
299 evidence and well data: the main anhydrite interval of the Kurra Chine Fm., the Baluti shales and  
300 the Chia Gara shales (Fig. 4a). In the field, these levels are characterized by well-developed  
301 shear zones along the interface with the underlying unit and well-developed cleavage (Fig. 4b).  
302 The most remarkable field evidence highlighting the presence of intermediate detachments is the  
303 occurrence of short wavelength folds or “rabbit ears” on the limb of some anticlines as in the  
304 Shakrook anticline showing short wavelength thrust anticlines capped by the Qamchuqa  
305 limestones and probably detached on the Chia Gara intermediate detachment layer (Fig. 3).  
306 Moreover, it is common to find major bedding dip changes and repeated sections along wells  
307 penetrating the Jurassic and Cretaceous intervals (Sapin et al., 2017).

308 In the pre-Campanian Mesozoic sequence, two main disharmonic intervals were  
309 identified (Fig. 4a): the Barsarin-Naokelekan formations (Fig. 4c), and the Sarmord formation.  
310 Usually, field observations reveal that these intervals are folded harmoniously with the above  
311 and below competent units, but it is common to observe disharmonic folding and minor thrusting  
312 in these formations that allow accommodating shortening in specific zones like the fold hinges,  
313 the deeper part of anticlines, or close to thrust faults.

314 From Campanian to present, the sedimentation is syn-tectonic and associated with the  
315 development of two successive flexural foredeep-foreland basins that induced strong lateral  
316 variations of thickness and facies, and thus variable mechanical behaviors. Within the  
317 stratigraphic sequence related to the latest Cretaceous-Paleogene proto-foreland basin, three  
318 main disharmonic levels exist: the Tanjero, the Kolosh and the Gercus formations (Fig. 4a).  
319 Thickness, nature and distribution of these three formations influence folding style of the  
320 overlying competent Sinjar and Pilaspi limestones as described in the Lurestan (Casciello et al.,  
321 2009). These disharmonic units are responsible for the development of disharmonic folding,  
322 rabbit ears, collapse structures and minor thrusting.

## 323 **5. Balanced and restored sections across the Central Kurdistan Region of Iraq**

324 The construction of the balanced and restored Erbil sections across the central KRI were  
325 carried out in MOVE software (Midland Valley Exploration, Scotland) in using line length  
326 restoration techniques for competent units and area balancing method for decollement layers, and  
327 in combining information from extensive fieldwork, remote sensing analysis, existing geological  
328 maps and subsurface data (Fig. 5). Formation tops from Mirawa-01, Qush-Tappa-01 and Bina-  
329 Bawi-04 wells were used to calibrate seismic reflectors and formations thicknesses, while dip

330 data from Safeen-01, Shakrook-01 and Bina-Bawi-04 wells allow the characterization of the  
331 internal structure of anticlines. The 2D seismic data, that covers the south-western and central  
332 segments of the cross-section, vary from high quality in the LFZ to very poor quality in the HFZ  
333 because of surface conditions (topography, near-surface karstified rocks and steeply dipping  
334 strata) as well as subsurface structural complexities. Most of the time, synclines are relatively  
335 well-imaged, while seismic reflectors observed in the anticlines are often non-continuous and  
336 inconsistent with dip data measured in the wells. The seismic lines were converted to depth using  
337 a first-order velocity law provided by Total. The depth projection of all this data has been  
338 calibrated down to the main Lower Triassic detachment level, whereas below this level the  
339 section is less constrained. Finally, the cross-section proposed in this study is not a unique  
340 solution, but it represents a consistent interpretation accounting for all the available data along  
341 the section trace, in addition to key geological features collected over the entire study area as  
342 fold geometries, stratigraphic positions of intermediate detachment and disharmonic levels, and  
343 the localization of growth strata.

344         The NE-SW trending Erbil cross-section traverses all structural domains of the Central  
345 KRI Fold-and-Thrust Belt: Thrust Zone, Inner HFZ, Outer HFZ and LFZ (Fig. 2). The cross-  
346 section is balanced from the High Zagros Fault to the deformation front and is 206 km long (Fig.  
347 6a). The Moho profile has been extracted from the crustal thickness map published by Jiménez-  
348 Munt et al. (2012), and shows Moho depths around 35 km in the LFZ, around 40 km in the HFZ,  
349 and a maximum of 46 km in the Thrust Zone (Fig. 6a). Crustal thickening is accompanied by two  
350 main structural steps that induced major uplift of the HFZ. These two steps correspond to the  
351 Inner and the Outer HFZ. The proposed interpretation for these morphotectonic features is  
352 crustal-scale thrusting rooted at the brittle/ductile transition and connected with the Beduh-Mirga

353 Mir basal detachment level, as it is classically interpreted in the Iranian Zagros belt (e.g.,  
354 Berberian, 1995; Molinaro et al., 2005). The geometry of these crustal faults will be discussed  
355 later.

356 The Erbil cross-section is composed of eight closely spaced anticlines in the HFZ (Tanun,  
357 Zozic, Handreen, Korak, Makook, Shakrook, Safeen and Bina Bawi anticlines) and 4 anticlines  
358 in the LFZ which are separated by large synclines (Kirkuk, Qarah Chauq, Khanuqah and Makhul  
359 anticlines). The deformation style is characterized by multi-detachment folds, which have  
360 evolved into thrusting tight folds in the Inner HFZ with larger shortening (Tanun, Zozic and  
361 Makook anticlines; Fig. 6a). Fold shape is variable in terms of wavelength, vergence and amount  
362 of thrusting. The pre-Campanian Mesozoic sequence is quite constant in thickness throughout  
363 the section, and lateral facies variations have been integrated into the Early Cretaceous in the  
364 detailed cross-section (Fig. 7). On the contrary, the post-Campanian units, which are composed  
365 of sediments related to the successive foreland basins, display major lateral thickness variations  
366 (Fig. 6a). Analysis of these syntectonic deposits, especially their geometry and the occurrence of  
367 specific sedimentary features (e.g. growth strata, progradation), is crucial for constraining the  
368 flexure, the timing and the dynamics of the system.

369

## 370 **Figure 5.**

371

372 The two-step restored sections extend from the Deformation Front SW of the Makhul  
373 anticline to a pin line corresponding to the High Zagros Fault (Fig. 6). Cross-section restoration

374 was performed to determine the geometry of the foreland basin, the evolution of the flexure, and  
375 to estimate the amount of shortening in the sedimentary cover as well as its migration with time.  
376 Restorations have been constructed at pre-Campanian time (i.e. before the obduction event, Fig.  
377 6c) and at Late Eocene time (i.e. after the obduction event, Fig. 6b).

378 To restore the pre-Campanian section, we used the top of the Qamchuqa Formation as the  
379 horizontal datum for unfolding the sedimentary cover. The comparison of balanced and restored  
380 sections yields a total of 19 km of shortening within the sedimentary cover, corresponding to a  
381 ratio of 8.4 %, of which 16.4 km (ratio of 22.7 %) corresponds to the HFZ (Fig. 6). The foreland  
382 flexure through time has been estimated by flattening the top Tanjero, top Pilaspi, top Fars and  
383 top Quaternary levels and calculating the bending of pre-Tanjero strata (Fig. 6c). In the HFZ, top  
384 Tanjero and the top Pilaspi levels have been reconstructed by joining the maximum Tanjero and  
385 Pilaspi stratigraphic thicknesses preserved in the synclines, while in the LFZ these lines are  
386 continuous and well calibrated by seismic data. The lines corresponding to the top Fars and the  
387 top Quaternary are well calibrated by seismic data and are restricted to the LFZ. It is important to  
388 note that flexure is underestimated because compaction and paleobathymetry are not included.

389 A restored cross-section illustrating the Late Eocene configuration of the basin was  
390 constructed (Fig. 6b) to quantify the amount of shortening initiated during the latest Cretaceous-  
391 Eocene obduction event using the top of the Pilaspi Formation as the horizontal datum. When the  
392 top of the Pilaspi is unfolded, the underlying strata still show folding, and therefore the amount  
393 of shortening can be calculated (Fig. 6c). We determined the thickness of the eroded syn-tectonic  
394 sediments on the crestal domain of anticlines in respecting their constant thinning observed in the  
395 synclines. This is well calibrated in the Outer HFZ (field and seismic calibration), while in the  
396 Inner HFZ the calibration is worst because it is based only on the syn-tectonic geometry of the

397 Latest Cretaceous Tanjero unit. But we believe that this approximation implies a small error on  
398 the Pre Eocene shortening estimation.

399           The restored cross-section at Late Eocene time is 220 km long, and gives a shortening  
400 related to the Late Cretaceous-Eocene obduction event around 5 km within the sedimentary  
401 cover (Fig. 6), 4 km of them being accommodated within the Inner HFZ. Field and seismic data  
402 suggest that the deformation front of the obduction phase was situated between the Safeen and  
403 the Bina Bawi anticlines (see following sections for more details).

404

405 **Figure 6.**

406

407 *5.1. The Thrust Zone*

408           The Thrust Zone is poorly constrained and is mainly based on the work of Ali et al.  
409 (2014) and on scarce field observations. The allochthonous thrust sheets along the Iranian border  
410 are composed of the Cretaceous ophiolite complex, the Qulqula radiolaritic nappes, and the  
411 Paleogene Walash-Naopurdan accretionary complex and are bounded by flat-lying thrust planes  
412 (Fig. 2). Map relationships show that the Paleogene Walash-Naopurdan units are overlain by the  
413 Cretaceous ophiolite complex through out-of-sequence thrusting (Ali et al., 2014; Koshnaw et  
414 al., 2017). Below the Walash-Naopurdan complex, we have represented the Qulqula radiolaritic  
415 nappes (Fig. 7) stacked during the obduction event above the distal part of the Arabian margin as  
416 proposed by Ali et al. (2014). Indeed, this unit is not outcropping along the section but it is  
417 observed a few kilometers on both sides of the section (Fig. 1).

418 *5.2. The Inner High Folded Zone*

419           The contact between the Thrust Zone and the HFZ consists of a highly deformed zone 10-  
420 20 m thick, characterized by a tectonic mélange of carbonates, basalts, ophiolitic breccia,  
421 volcano-sedimentary rocks and metamorphosed cherts. The main splay of the High Zagros Fault  
422 is NE-dipping ( $\sim 45^\circ$ ), while the autochthonous Paleocene-Miocene Red Beds are dipping at 65-  
423 70° toward the NE along its footwall. These Red Beds are composed of pebbly sandstones, red  
424 shales and conglomerates, with several intercalations of limestones corresponding to the  
425 Oligocene Govanda Formation (Van Bellen et al., 1959). The Red Beds directly overlie

426 Maastrichtian Aqra reef limestones with no apparent angular unconformity. The 100-150 m thick  
427 Aqra limestones are dipping 40° to the NE and are conformable on Tanjero deposits in the  
428 syncline NE of the Tanun anticline, while these limestones are directly deposited on Qamchuqa  
429 limestones through an erosive contact on the crest of the anticline (Fig. 7). The Tanjero Fm.  
430 showing thickness exceeding 1000 m in the growth syncline (Ahmed, 2013) thins dramatically  
431 towards the crest of the Tanun anticline, and thus indicating its development during the  
432 Maastrichtian epoch (Fig. 7c).

433           The Tanun and the Zoic anticlines are both characterized by NE-dipping thrust faults  
434 cutting across the SW forelimbs (Fig. 7). These thrusts carry the Jurassic rocks to surface and put  
435 them in contact with the Qamchuqa limestones SW of the Tanun anticline (Fig. 7f), and with the  
436 Tanjero Fm. SW of the Zoic anticline. The relatively short wavelength of these anticlines and  
437 the geometries observed at surface are inconsistent with a deep-rooted thrust, because of  
438 geometrical problems and a lack of space in the deeper part of the anticline. Thus, these thrusts  
439 are proposed to branch into the Baluti intermediate detachment layer, while Triassic imbrications  
440 are used at depth in order to balance these structures (Fig. 7).

441           The Handreen anticline with a length of about 50 km and a wavelength around 12 km is  
442 the largest fold intersected by the Erbil cross-section (Fig. 2). The shape of the Handreen  
443 anticline is sub cylindrical and shows a slight asymmetry with a steeper NE-dipping limb and a  
444 less inclined SW-dipping limb (Fig. 7). A thick isolated patch of reefal carbonates,  
445 corresponding to the Aqra-Bekhme formations, crops out along the crestal domain of the  
446 Handreen anticline grading to the Shiranish and Tanjero formations towards adjacent synclines  
447 (Fig. 7b). These changes in sedimentary facies and thus paleobathymetry indicate an early phase

448 of growth of the Handreen anticline during the latest Cretaceous as determined also in the  
449 Amiran basin in Lurestan (Saura et al., 2012).

450         Towards the SW, the Korak and Makook anticlines are both characterized by outcropping  
451 Jurassic units in their core along the strike of the line of the section (Fig. 2). The Korak anticline  
452 shows a local NE-vergence whereas the Makook anticline is foreland verging (Fig. 7). Fold  
453 asymmetry is believed to be related to thrust faults rooted in the Baluti intermediate detachment.  
454 At depth, a multi-detachment geometry is proposed with fishtail thrusting as observed in the  
455 large Shakrook anticline towards the SW (Fig. 7). This interpretation allows accommodation of  
456 some shortening below the Baluti detachment along the cross-section.

457

458 **Figure 7.**

459

### 460 *5.3. The Outer High Folded Zone*

461         The Outer HFZ is constituted by three large anticlines in which seismic lines and well-  
462 data are available: Shakrook, Safeen and Bina Bawi anticlines from NE to SW (Fig. 5 and Fig.  
463 7).

464         At surface, the Shakrook anticline presents an irregular geometry due to the disharmonic  
465 folding of the Early Cretaceous Qamchuqa unit (Fig. 7). The progressive thickness decrease of  
466 the competent Qamchuqa limestones in favor of the disharmonic Sarmord unit produced the  
467 modification of the mechanical stratigraphy and facilitated the activation of intermediate  
468 detachment levels in this area. This resulted in the development of typical rabbit ears in the limbs

469 of the Shakrook anticline (Fig. 3). The Shakrook-01 well (SHK-01 in Fig. 7) shows constant dip  
470 of about 50° to the NE from top Jurassic to the Triassic Kurra Chine Fm., and a fault zone  
471 duplicating the lowermost part of the Jurassic succession (Fig. 7). This steeply dipping limb is  
472 situated in the central part of the anticline just below the rabbit ear observed at surface and thus  
473 far away from the observed NE limb of the anticline at surface. Our interpretation suggests a NE-  
474 dipping thrust duplicating the Jurassic succession and a complex fishtail thrust system  
475 interconnecting multiple detachment levels superposed in this part of the KRI Mesozoic basin  
476 from the evaporites of the Kurra Chine to the Chia Gara shales (Fig. 7). Fishtail thrust systems  
477 involving several intermediate detachment levels is a common feature in multi-detachment  
478 folding (e.g., Driehaus et al., 2014).

479         The Safeen anticline, with a length of about 50 km and wavelength of about 6 km, is  
480 characterized by an extremely tight hinge at surface coinciding with the position of the lateral  
481 facies change between the competent Qamchuqa carbonates and the weaker Sarmord deeper  
482 marly Formation (Fig. 7a). Dipmeter logs from the Safeen-01 well were used to construct the  
483 geometry of the core of the Safeen anticline at depth (Fig. 7d). From 1000 m TVD/RT to 2100 m  
484 TVD/RT, the well drilled through the Cretaceous Chia Gara Fm. and most of the Jurassic  
485 succession. Along this interval, bedding changes from 25-40° toward NE, to sub-horizontal in  
486 the upper part of the Sehkaniyan Fm., to 70-80° toward SE and finally to overturned in the lower  
487 part of the Sehkaniyan Fm. (Fig. 7d). In the next interval between 2100 m TVD/RT and 2500 m  
488 TVD/RT, two main thrust faults bound an overturned domain of repeated Sehkaniyan Fm. (Fig.  
489 7d). Finally, along the deeper 1800 m, the well drilled through the upper and middle Jurassic  
490 succession, characterized by a dip domain with constant steep beds dipping to the SW. The core  
491 of the Safeen anticline is thus constructed by a steep SW limb cut at high angle by a NE-verging

492 thrust fault probably rooted in the Baluti intermediate detachment level. In the deeper part of the  
493 anticline, fishtails thrusting has been inferred to provide similar amounts of shortening than the  
494 one determined for the units above the Baluti intermediate detachment (Fig. 7). Although the  
495 trace of the Erbil cross-section is located away from the Safeen-01 well drilling position, we  
496 accommodated the described Safeen anticline geometry in the study section. The geometry of the  
497 adjacent syncline to the NE of the Safeen anticline is imaged at depth by seismic lines showing a  
498 relatively constant thickness for the 300-400 m thick Maastrichtian Tanjero deposits but well-  
499 defined growth strata patterns for the 1500 m thick Paleocene-Early Eocene Kolosh Formation  
500 (Fig. 7e). This suggests that folding of the Safeen and the Shakrook anticlines was active until  
501 the Paleocene.

502         The Bina Bawi anticline is the frontalmost fold of the Outer HFZ (Fig. 6). The Bina Bawi  
503 anticline shows a rounded geometry and NE-vergence due to its steeper forelimb dipping  $55^\circ$  to  
504 the NE, whereas the long and low  $25^\circ$ -SW dipping backlimb is combined with the flank of the  
505 large monocline that separates the Outer HFZ from the LFZ in which the Kirkuk anticline is the  
506 first cropping out fold (Fig. 7). The Bina Bawi anticline displays this typical whaleback  
507 geometry when compared to the more complex fold geometries of Safeen and Shakrook because  
508 of the higher competence of the thicker Early Cretaceous Qamchuqa carbonates. Subsurface data  
509 (seismic lines and Bina Bawi-04 well) confirm the projection of the surface geometry of the  
510 anticline at depth (Fig. 7). The roughly constant thickness of the Paleocene-Early Eocene Kolosh  
511 Fm. along the SW limb of the Bina Bawi anticline suggest that folding of this anticline postdated  
512 Kolosh deposition. To the NE, however, the Safeen and Shakrook were clearly active during the  
513 Kolosh deposition as indicated by the mutual growth syncline. The syn-Kolosh growth of the  
514 Bina Bawi anticline is not possible to identify with the existing data set and thus the front of

515 deformation linked to the oceanic obduction was probably located in the Safeen anticline but not  
516 further SW.

#### 517 *5.4. The Low Folded Zone*

518 Thick Neogene and Quaternary syntectonic sedimentary successions corresponding to the  
519 Fars and Bakhtiari formations fill the LFZ. These deposits progressively increase their thickness  
520 towards the NE reaching a maximum preserved thickness of 3500 m in the large syncline  
521 between the Bina Bawi anticline and the Kirkuk anticline (Fig. 6). This sedimentary succession  
522 corresponds to classical molasse sediments that are characterized by upward coarsening and  
523 thickening packages.

524 The underlying syntectonic sediments corresponding to the Late Cretaceous-Eocene  
525 proto-foreland basin are characterized by their progressive thinning towards the SW. The clastic  
526 and deep-water deposits of the Kolosh Fm. pass laterally to the marly facies of the Aaliji Fm. in  
527 the region of Kirkuk, while the clastic sediments of the Tanjero Fm. pass laterally to the marly  
528 carbonates of the Shiranish Fm. to the southwest of the Bina Bawi anticline showing the flexural  
529 propagation of the foreland from latest Cretaceous to Eocene (Fig. 6). This progradation is  
530 observed in the seismic lines by well-imaged oblique reflectors dipping to the SW within the  
531 siliciclastic Kolosh Formation below the Sinjar carbonates (Fig. 7).

532 The Erbil cross-section intersects 4 anticlines in the LFZ that from NE to SW are:  
533 Kirkuk, Qarah Chauq, Khanuqah and Makhul (Fig. 6). The Kirkuk anticline is asymmetric with a  
534 short and steeper forelimb dipping 25-30° to the SW and a long and less inclined backlimb  
535 dipping 10° to the NE. Towards the foreland, the slightly SW-verging Qarah Chauq anticline  
536 shows a higher culmination as a result of its steeper limbs (Fig. 6). Both Kirkuk and Qarah

537 Chauq anticlines are characterized by cores showing fishtail thrust geometry connecting the  
538 Beduh-Mirga Mir basal detachment with higher intermediate detachments as observed in good-  
539 quality seismic lines. This structural style for the core of the anticlines has been used to construct  
540 the structure of the core of some of the anticlines in the HFZ. The Khanuqah and Makhul  
541 anticlines, in the front of the deformed foreland, are only constrained by data from the geological  
542 map and simple detachment folding above the Beduh-Mirga Mir basal detachment is applied  
543 (Fig. 6). In this region of the KRI, the Lower Fars formation is not evaporitic or is too thin to be  
544 an efficient detachment level, while this stratigraphic level strongly controlled the deformation  
545 style in the SE region of KRI (Koshnaw et al., 2017) as well as in Iran (e.g., Sherkati et al.,  
546 2005). To the northeast of the Kirkuk anticline, short wavelength folding is identified in the  
547 Jurassic and Triassic successions, which are completely decoupled from the overlying  
548 sedimentary pile by an intermediate detachment layer probably corresponding to the Jurassic  
549 Alan Formation grading from anhydrite in the HFZ to salt in the Kirkuk Area (Fig. 6).

550         Although Neogene syntectonic patterns have not been observed in the data sets along the  
551 Erbil cross-section, seismic data crossing the Kirkuk and Pulkhana thrust faults situated 80km SE  
552 of the section line (Fig. 2) show typical growth strata geometries (Fig. 8). In the footwall of the  
553 Pulkhana thrust, the Fars deposition seems pre-thrusting whereas the strong reduction of  
554 thickness of the Bakhtiari Formation close to the thrust indicate its syn-sedimentary activity (Fig.  
555 8). To the NE, the seismic line shows older growth strata in the footwall of the Kirkuk thrust and  
556 thus indicating that the (Pliocene?) Kirkuk anticline occurred before the onset of growth in the  
557 Pulkhana anticline (Pleistocene?) (Fig. 9). However, both anticlines were later thrust and  
558 transported to the SW on top of the Kirkuk and Pulkhana emerging thrust faults (Fig. 8).

559

560 **Figure 8.**

561

562 **6. Evolution of the Central Kurdistan Region of Iraq Fold-and-Thrust Belt: Forward**  
563 **modeling**

564 The aim of the kinematic forward model is to validate the presented balanced and  
565 restored cross-sections using the sequence of deformation constrained by syntectonic deposits  
566 and crosscutting relationships. The restored cross-section is used as the initial set up and the  
567 balanced cross-section as the target. In addition, the kinematic forward model includes  
568 sedimentation and flexure in the foreland domain, while 9 new vitrinite reflectance data are used  
569 to determine more accurate amounts of erosion and uplift in the HFZ domain.

570 *6.1. Modeling procedure*

571 Three kinematic algorithms were used in Midland Valley 2DMove software during the  
572 construction of the forward kinematic model: detachment fold, fault-bend fold and vertical shear.  
573 The detachment fold algorithm was used to deform the Mesozoic sedimentary cover above the  
574 Lower Triassic basal detachment level. The fault-bend fold algorithm was used to simulate (i)  
575 the accretion of tectonic slices above the Arabian Margin, (ii) the crustal-scale thrusting, and (iii)  
576 the reactivation of the detachment folds initiated during the obduction tectonic event. The  
577 vertical shear algorithm allowed reproduction of the flexure of the foreland basin using time lines  
578 assuming a sub-horizontal deposition (Fig. 6c).

579 The restored cross-section illustrating the Late Cretaceous configuration of the Arabian  
580 margin is used as a starting point for a 2D kinematic model showing the evolution of the Zagros

581 Fold-and-Thrust Belt along the Erbil cross-section up to present configuration (Fig. 6c). The  
582 successive stages of this evolution are constrained by syntectonic depositional patterns, flexural  
583 estimations and shortening amounts determined for the four selected evolution stages. For each  
584 main stage, we firstly modeled the stacking of tectonic slices above the Arabian Margin and  
585 crustal-scale thrusting (fault-bend-fold method). Secondly, we determined the deformation in the  
586 cover (detachment folding method), and finally we included the flexure (vertical shear method).  
587 Although we only describe 4 main stages (Fig. 9 and Fig. 10), we constructed a total of 33 steps.  
588 The deformation in the marginal domain of the Arabian Plate, the emplacement of the  
589 radiolaritic and ophiolitic slices and the accretion of the Walash-Naopurdan accretionary  
590 complex have also been tentatively modeled to include them in the tectonic history of the Zagros  
591 Belt in KRI. Nevertheless, the reconstruction of the inner part of the Zagros Belt is not as  
592 accurate as the HFZ and the LFZ.

593 The calibration of the amount of erosion throughout the HFZ is based on nine reflectance  
594 vitrinite points obtained from samples collected close to the Erbil cross-section (Fig. 2). The  
595 vitrinite reflectance values range from 0.55 to 1.51% progressively decreasing towards the top of  
596 the succession (Table 1). The erosion has been estimated using the general relation between  
597 depth of burial, vitrinite reflectance and geothermal gradient proposed by Suggate (1998). The  
598 depth of burial has been calculated for two geothermal gradients of 25°/km and 30°/km and the  
599 results are summarized in the Table 1.

600

601 **Table 1.**

602

603 *6.2. Modeling results*

604 The initial model reflects the geometry of the Arabian margin during pre-Campanian time  
605 not showing syntectonic deposits (Fig. 9a). To model the Late Cretaceous obduction, the  
606 marginal domain of the Arabian Plate and the Neo-Tethys oceanic crust are also represented  
607 using crustal thicknesses and paleobathymetry values used in Vergés et al. (2011b) in the  
608 Lurestan Region of Iran (Fig. 9a).

609 Step A, after 11 intermediate steps, reconstructs the geometry of the obduction-related  
610 foreland basin along the Erbil transect after the deposition of the Tanjero and Aqra sedimentary  
611 successions at the Cretaceous-Tertiary boundary (Fig. 9b and Fig. 10a). During the Campanian  
612 and the Maastrichtian, the obduction of ophiolitic rocks above the Arabian Margin resulted in the  
613 development of the Tanjero flexural Basin occupying the present HFZ with a width of about 75  
614 km (Fig. 9b). The Tanjero flysch succession was sourced from the ophiolitic and radiolaritic  
615 thrust sheets as discussed in Homke et al. (2009) and Saura et al. (2011). In the external part of  
616 the basin, the Tanjero flysch passes gradually to the Shiranish marls and limestones when far  
617 from the clastic influence (Fig. 9b).

618 Synchronous folding of the Mesozoic sedimentary cover above the Beduh-Mirga Mir  
619 basal detachment was modeled using detachment folding method (Fig. 9b and Fig. 10a). In this  
620 time step, the shortening is accommodated by 5 anticlines (Tanun, Zozic, Handreen, Korak and  
621 Makook) and is estimated around 4 km. Detachment folding was associated with growth strata  
622 patterns in the synclines and Aqra-Bekhme reefal carbonates growing on the crestal domains of  
623 some anticlines as described in the Lurestan by Saura et al. (2012). The deformation front at this  
624 time was most probably situated south of the Makook anticline (Fig. 9b and Fig. 10a).

625 Step B, after 5 additional steps, illustrates the geometry of the Arabian margin during the  
626 Late Eocene stage after the deposition of the Pilaspi shallow water carbonates, which extend  
627 along the entire Tanjero-Kolosh flexural basin, marking the near end of the obduction processes  
628 (Fig. 9c and Fig. 10b). During the Paleocene and the Eocene, the ophiolitic thrust sheets  
629 advanced towards the foreland resulting in the propagation of the flexure as well as the  
630 deformation as documented in Barrier and Vrielynck (2008) and Saura et al. (2011). The flexural  
631 foredeep filled up by the thick prograding clastic Kolosh Formation grading from shelf to deep-  
632 water facies associated to well-imaged SW-dipping clinofolds corresponding to the Sinjar  
633 Formation (Fig. 7). Coeval shortening to Paleocene-Eocene Kolosh deposition produced regional  
634 uplift of the Inner HFZ above a NE-dipping crustal-scale low-angle thrusting (Fig. 9c and Fig.  
635 10b). We propose that the deposition of Paleocene-Eocene Red Beds in the Inner HFZ is the  
636 sedimentary record of this thick-skinned thrusting. In this step B, the Kolosh foredeep extended  
637 over the present Kirkuk anticline (Aqrabi et al., 2010) showing a width around 100 km. In the  
638 external part of the basin, further to the southeast, the Kolosh Formation passes to the more  
639 carbonated facies of the Aaliji Formation (Fig. 9c). The 1.5 km of shortening accommodated  
640 along the crustal-scale thrust below the Inner HFZ was transferred to the sedimentary cover  
641 along the Beduh-Mirga Mir basal detachment level allowing the development of the Shakrook  
642 and Safeen anticlines as proved by growth strata in the Kolosh Formation (Fig. 7e). Then the  
643 basin was sealed by a shallowing upwards depositional sequence ending with the terrestrial  
644 Gercus Formation and shallow marine carbonates of the Pilaspi Formation. At Late Eocene time,  
645 the deformation front migrated to the front of the Safeen anticline and the amount of shortening  
646 in the sedimentary cover is of about 5 km.

647 Step C, after 7 more intermediate modeling steps, corresponds to the Arabian margin at  
648 the Miocene-Pliocene transition when continental collision between Arabia and Sanandaj-Sirjan  
649 was already active (Fig. 9d and Fig. 10c). The final closure of the Neo-Tethys was accompanied  
650 by the final accretion and emplacement of the Walash-Naopurdan accretionary complex above  
651 both the Arabian Margin and the allochthonous ophiolite complex. The onset of the accretion-  
652 collision phase was initiated during the earliest middle Miocene (~18 Ma) contemporaneously  
653 with the deposition of the Lower Fars Formation (Koshnaw et al., 2017). Deformation related to  
654 this tectonic event was superimposed on the pre-existing obduction belt with the reactivation of  
655 crustal units below the Thrust Zone and the Inner HFZ. Shortening accommodated along the  
656 low-angle crustal-scale thrusts was transferred to the sedimentary cover tightening most of the  
657 pre-existing anticlines and thrusting them (Fig. 9d and Fig. 10c). Shortening in the hinterland  
658 reactivated the previously emplaced ophiolitic thrust sheets producing large out-of-sequence  
659 thrusting that mask the sequence of thrusting as indicated in Ali et al. (2012, 2014). Significant  
660 uplift of the Inner HFZ triggered erosion and deposition of relatively thin Miocene Red Bed  
661 series. The deformation front is situated southwest of the Makook anticline, indicating that the  
662 Safeen and Shakrook anticlines were not yet reactivated (Fig. 9d).

663 Step D, after 9 additional modeling steps, corresponds to the present-day geometry of the  
664 Arabian margin (Fig. 9e and Fig. 10d). From Pliocene to present, the deformation propagated  
665 towards the SW with the reactivation of the basement thrust beneath the Inner HFZ and then the  
666 displacement of a new basement thrust sheet beneath the Outer HFZ producing the growth of the  
667 Mountain Front Flexure. In response to the thick-skinned tectonics, shortening was transferred to  
668 the sedimentary cover and the Safeen and Shakrook anticlines were tightened and thrust, while  
669 new folds grew in the LFZ: Kirkuk, Qarah Chauq, Khanuqah and Makhul anticlines (Fig. 9e).

670 Shortening also developed the NE verging Bina Bawi anticline at the frontal part of the HFZ.  
671 The large amplification of the HFZ above the thick-skinned basement thrust imbrication  
672 triggered the SW migration of the foreland basin with its main sedimentary depocentre between  
673 the Bina Bawi and the Kirkuk anticlines as occurred in the Lurestan during the Fars deposition  
674 (e.g., Vergés and Casciello, 2007). The amount of erosion predicted by this kinematic model in  
675 step D (light colors above topographic line in Fig. 10d) is compared with vitrinite reflectance  
676 data (Fig. 10d). For a high geothermal gradient of 30°/km, estimated erosion is 3 km at the  
677 frontal part whereas it is about 5 km in the Inner HFZ (Fig. 10d). Using a lower geothermal  
678 gradient of 25°/km, erosion increases up to 4 and 6 km, respectively.

679

680 **Figure 9.**

681

682 **Figure 10.**

683

### 684 *6.3. Modeling validity*

685 The final step of the forward modeling (Fig. 9e) shows geometry close to the Erbil  
686 balanced cross-section (Fig. 6). Detailed geometries of some structures are sometimes  
687 significantly different, but this comes from the difficulties to reproduce complex structures with  
688 simple algorithms. For example, it is complicated to model with the Move software multi-  
689 detachment folds, or deep structures involving the ductile lower crust below the Thrust Zone.

690           Some geometric parameters of these two models can be quantitatively compared. The  
691 geometric and kinematic models show similar widths of the HFZ (71 km), and of the  
692 Tanjero/Kolosh proto-foreland Basin (112 and 119 km respectively), while the width of the  
693 Thrust Zone is overestimated in the kinematic model (66 km versus 32 km). The maximum depth  
694 of the proto-foreland basin is 2.3 km in the geometric model and 3.4 km in the kinematic model.  
695 This strong difference can be explained because compaction and paleobathymetry have not been  
696 taken into account for flexure estimation (see section 6.1). On the other hand, the maximum  
697 depth of the Mesopotamian Basin is very similar in both models (3.4 km and 3.2 km). The  
698 geometric and kinematic models also present similar maximum crustal thicknesses below the  
699 Thrust Zone (46 km and 44 km respectively).

700           In addition, the final step of the kinematic model is relatively consistent with vitrinite  
701 reflectance data (Fig. 10d). In the Outer HFZ, the model fits perfectly with vitrinite reflectance  
702 data for a geothermal gradient of 25-30°/km. On the other hand, in the Inner part of the HFZ, the  
703 model underestimated the amount of erosion of around 1 km (Fig. 10d), but this could be  
704 explained by an increase of the geothermal gradient toward the hinterland or an underestimation  
705 of the growth-strata thicknesses in our structural model.

706           Finally, the kinematic model proposed in this study respects the sedimentary history of  
707 the flexural basins, their geometry, the timing of the deformation and the amount of shortening  
708 estimated from the crustal balanced and restored sections described previously. This confirms the  
709 geometrical viability of the balanced section.

## 710 **7. Discussion**

### 711 *7.1. Cover folding style*

712           The Zagros Fold-and-Thrust Belt displays strong differences of structural style from the  
713 Kirkuk embayment to the Fars arc, which are closely related to the changes in the mechanical  
714 behavior of the sedimentary pile (e.g., Bahroudi and Koyi, 2003; Sepehr and Cosgrove, 2004;  
715 Sherkati et al., 2006; Casciello et al., 2009; among others). Whereas the lower Cambrian-  
716 Ediacaran Hormuz salt is widely accepted as the basal detachment level in the Fars arc in Iran,  
717 no consensus exists in the Lurestan arc and Dezful embayment as well as in the Kirkuk  
718 embayment. In the Lurestan arc, the presence of the Hormuz salt is not proven but some authors  
719 suggested that geometry and distribution of large folds indicate detachment folds above a weak  
720 level located near or at the base of the cover (e.g., Vergés et al., 2011a). In KRI, some authors  
721 proposed the occurrence of a main detachment possibly in the Ordovician and Silurian shales (de  
722 Vera et al., 2009), the Carboniferous Ora shales (Hayward, 2014), or other undetermined levels  
723 in the Paleozoic succession (Csontos et al., 2012; Hayward, 2014; Hinsch and Bretis, 2015),  
724 while others used the lower Triassic units (Awdal et al. 2013; Hayward, 2014). The lower  
725 Triassic Beduh-Mirga Mir layer most probably constitutes the main detachment level in the KRI  
726 belt fitting the surface and subsurface structural data and cross-section construction presented in  
727 this study. Fold wavelengths in the Fars and the KRI regions show distinct distributions with  
728 median values of 15.8 km (Mouthereau et al., 2007) and 7.4 km (this study), respectively (Fig.  
729 11). This simple geometric analysis confirms that the basal detachment is shallower in the KRI  
730 Belt than in the Fars region.

731           Fold mechanism in the KRI Fold-and-Thrust Belt has been variably interpreted as fault-  
732 related folding (de Vera et al., 2009; Awdal et al., 2013), detachment folding (Frehner et al.,  
733 2012; Hayward, 2014), fault-bend folding (Hinsch and Bretis, 2015), fold related to normal fault  
734 positive inversion (Csontos et al., 2012; Al-Kubaisi, 2014), or a combination of these

735 mechanisms (Wrobel-Daveau, 2011; Hayward, 2014; Zebari and Burberry, 2015). According to  
736 the mechanical stratigraphy and the Erbil regional balanced cross-section constructed in this  
737 study, we propose that the KRI Fold-and-Thrust Belt is mainly composed by multi-detachment  
738 folds detached. Indeed, the style of folding in the KRI Fold-and-Thrust Belt is characterized by  
739 regularly spaced anticlines of similar amplitude and the lack of significant thrusts at surface  
740 except near the High Zagros Fault (e.g., Tanun and Zozic anticlines) and where basement  
741 faulting has been recognized (e.g., Makook anticline). The anticlines are commonly symmetrical  
742 and show a fairly simple geometry, which is typical of box-folds. These characteristics indicate  
743 that most anticlines are detachment folds rather than fault propagation or fault bend folds.

744

745 **Figure 11.**

746

747 Surface and sub-surface data indicate that the two most efficient intermediate detachment  
748 levels are the uppermost Triassic Baluti shales and the Lower Cretaceous Chia Gara shales  
749 (Sapin et al., 2017). Increasing fold tightening modified earlier detachment folds to faulted-  
750 detachment folds, like Makook, Zozic and Tanun anticlines (Fig. 7). The intermediate  
751 detachment levels in the core of the anticlines are responsible for the increase of the structural  
752 complexity, which is not always easy to solve by seismic interpretation, especially if anticline  
753 limbs are steeper, augmenting the difficulty for exploring oil and gas creating the following  
754 complications: (i) lateral shift of the anticline crests with depth, (ii) tight internal anticline with  
755 narrower crestal domain, and (iii) fishtails and/or duplexes.

756

757 *7.2. Basement structural style*

758           The Mountain Front Flexure (MFF in Fig. 1) is a key structural step separating the  
759           uplifted anticlines of the HFZ from the less-deformed and still buried LFZ (e.g., Berberian, 1995;  
760           Saura et al., 2015). In KRI, from the MFF, the basal detachment level raises across two structural  
761           and topographic steps (Fig. 12). The Outer structural step is located at the front of the HFZ  
762           corresponding to the MFF. The structural relief increases about 3.5 km between the foreland and  
763           the outer HFZ whereas the topography increases about 800 m in 20 km across dip (the  
764           intermediate step on the Fig. 12a). From the Bina Bawi anticline to the Shakrook anticline, the  
765           structural relief is fairly constant along 30 km as determined by the position of the hinges of the  
766           synclines. The inner structural step is situated below the Makook anticline corresponding to the  
767           boundary between the Inner and the Outer HFZ. The structural relief increase is 2 km with a  
768           parallel topographic rise of about 600 m in less than 5 km of horizontal distance (Fig. 12a).  
769           Finally, from the Makook anticline to the High Zagros Fault, the structural relief is sub-  
770           horizontal along 25 km.

771           Several mechanisms have been proposed to explain this major uplift and to reconcile at  
772           best the present geometry of the structural steps and the amount of shortening calculated for the  
773           folded sedimentary cover: (i) duplex in the Paleozoic cover (Hayward, 2014; Hinsch and Bretis,  
774           2015), (ii) crustal-scale blind newly-formed thrusts (de Vera et al., 2009), and (iii) blind thrusts  
775           that possibly inverted earlier normal faults (Csontos et al., 2012).

776           Duplex structures of Paleozoic age in the core of the anticlines could explain the rise in  
777           regional elevation across the MFF by thin-skinned structural thickening. However, this model

778 causes a strong imbalance of shortening in the section between the lower Paleozoic unit and the  
779 upper folded sedimentary cover. Hinsch and Bretis (2015) justified this inconsistency by  
780 deformation transfer outside of the balanced section through shallower detachment levels, but the  
781 amount of deformation that has to be transferred toward the LFZ is estimated by Hinsch and  
782 Bretis (2015) around 16 km while the amount of shortening calculated in this study for the LFZ  
783 does not exceed 3km. In addition, this duplex model can't explain the characteristic width of the  
784 structural steps which suggests rather thick-skinned deformation, as proved by deep seismicity  
785 below the HFZ (Berberian, 1995; Maggi et al., 2000; Utkucu, 2017; Tavani et al., 2018).

786 In order to reproduce the present geometry of these structural steps (uplift and width), we  
787 performed some 2D kinematic forward models (2DMove ©) of the deep structures. The main  
788 factor controlling the morphology of the uplifted domains is the overall geometry of the thrust at  
789 depth (geometry, dip and depth of flattening of the thrust plane): low-angle thrust will generate  
790 wide structural step and low uplift, while inverted high-angle normal faults will generate narrow  
791 structural step and high uplift. The best geometrical fit to reproduce these two wide structural  
792 steps below the Outer and the Inner HFZ consists of two crustal low-angle (15-30°) blind thrusts  
793 rooted at the brittle/ductile transition (25-28 km) and connected with the Beduh-Mirga Mir basal  
794 detachment level using foreland sequence of thrust emplacement as was already modelled in the  
795 Lurestan region by Saura et al. (2015) (Fig. 12). Each basement blind thrust has a displacement  
796 of about 10 km. The first thrust below the Inner structural step is modelled with a complex  
797 frontal geometry characterized by two thrust splays showing 6 and 4 km of displacement. The  
798 blind thrust below the Outer structural step shows a hanging wall characterized by a low angle  
799 monocline dipping towards the foreland where a thick syntectonic sedimentary succession of the  
800 Fars Group is exposed (Fig. 12). The 13th November 2017 earthquake of Mw 7.3 rupturing near

801 the Iran-Iraq border at a depth of about 20 km above a fault plane dipping  $16^{\circ}$  to the NE (Utkucu,  
802 2017; Tavani et al., 2018), perfectly fits with the geometry of the basement thrust system  
803 proposed in this study (see location of seismic event in map Fig. 1 and in the cross-section in Fig.  
804 12).

805 Finally, we believe that low-angle crustal blind thrusting is the principal mechanism  
806 behind the structural steps in the HFZ. However, this does not rule out the possibility of partially  
807 inverted and short cutting normal faults below the structural steps, but it is not our preferred  
808 scenario because (i) inversion of high-angle normal faults would generate narrower structural  
809 steps, and (ii) Permo-Triassic graben have never been evidenced in the KRI, on the field or on  
810 seismic.

811

812 **Figure 12.**

813

### 814 *7.3. The early evolution of the Zagros Belt during Late Cretaceous period*

815 In response to the obduction of the ophiolite on the northeastern margin of the Arabian  
816 Plate during the Campanian and Maastrichtian stages, flexural basins developed all along the  
817 Zagros belt from SE Turkey to Oman. The Tanjero-Kolosh foreland Basin corresponds to the  
818 lateral continuity of the well-known Amiran Basin in the Lurestan Province (e.g., Homke et al.,  
819 2009; Saura et al., 2011). The infill of this early foreland basin consists of a thick mixed  
820 siliciclastic-carbonate sedimentary succession composed by several formations in the KRI that  
821 are equivalent to the Lurestan ones: Tanjero and Kolosh Fm. (Amiran Fm.); Aqra, Bekhme and

822 Sinjar Fm. (Taleh Zang Fm.); Gercüs Fm. (Kashkan Fm.); and Pilaspi Fm. (Asmari-Shahbazan  
823 Fm.). The reconstruction of the architecture and evolution of the Amiran Basin mainly based on  
824 chronostratigraphic data, revealed a diachronous infilling related to the progressive propagation  
825 of the foreland basin to the SW (Homke et al., 2009; Saura et al., 2011). This evolution is very  
826 similar to the kinematic model proposed in this study for the Tanjero-Kolosh foreland Basin.  
827 Indeed, we observed the same southwestward propagation of the basin flexure from the  
828 Campanian-Maastrichtian clastic Tanjero Fm. to the Paleocene-Eocene Kolosh-Gercus  
829 succession. The widths of the Tanjero-Kolosh and Amiran proto-foreland basins are also very  
830 close, with values around 120-125 km in the Kirkuk embayment (this study) and 135 km in the  
831 Lurestan arc (Homke et al., 2009; Saura et al., 2011). The proto-foreland basin changed along the  
832 strike with sedimentary thicknesses exceeding 2.3 km in the Central Kurdistan (this study) and  
833 decreasing southeastward with values around 1.5 km in the Lurestan (Homke et al., 2009; Saura  
834 et al., 2011). To the Northwest, the sedimentary thicknesses rapidly decrease and the  
835 sedimentation is characterized by the deposition of thick reef limestones of the Bekhme and Aqra  
836 Formations revealing that flexure is insignificant in the Northern part of KRI and is probably  
837 shifted northward in Turkey.

838         Several studies in the Lurestan domain show that folding initiated during the obduction  
839 stage and coeval development of the flexural basin (Homke et al., 2009; Piryaei et al., 2010;  
840 Saura et al. 2011; Farahpour and Hessami, 2012). Based on syntectonic sediments, Farahpour  
841 and Hessami (2012) demonstrate that a growth pattern involving Cretaceous units was recorded  
842 over the entire Zagros belt in Iran, with onset of folding since the Late Aptian in some areas. In  
843 the Amiran Basin, Saura et al. (2011) observed the earliest evidence for fold growth in the  
844 Amiran Fm. indicating at least a Maastrichtian age for the initiation of folding. In this study, we

845 presented the first field and seismic evidences of early folding in KRI during the development of  
846 the Tanjero-Kolosh foreland basin. In addition, the presence of thick isolated Aqra-Bekhme  
847 patch reefs on top of several anticlines indicates a fold-growth control on carbonate distribution  
848 as proposed by Saura et al. (2012). These authors used stratigraphic numerical modeling  
849 approach and show that shallow bathymetries on top of growing folds enhance carbonate  
850 production and these authors proposed that build-ups on top of anticlines record its growth and  
851 can be used as a dating method.

852         The onset of the main Zagros deformation event related to the collision between the  
853 Arabian and Iranian blocks is early Miocene and is characterized by the accretion of the  
854 Sanandaj-Sirjan Zone above the Arabian margin and the development of the Mesopotamian  
855 foreland basin. Deformation related to this tectonic phase is characterized by a combination of  
856 thin- and thick-skinned tectonics (e.g., Molinaro et al., 2005; Mouthereau et al., 2007; Vergés et  
857 al., 2011b; Saura et al., 2015) that reactivated the Late Cretaceous-Paleogene obduction belt.  
858 Folding propagated toward the foreland (e.g., Wrobel-Daveau et al., 2010; Lawa et al., 2013) in  
859 response to the in-sequence involvement of crustal units beneath the HFZ. Displacement along  
860 basement crustal-scale thrusts was transferred to the sedimentary cover reactivating and  
861 tightening most of the pre-existing anticlines and developing new ones. As a consequence, the  
862 kinematic model proposed in this study where each step of crustal thrusting (i.e. thick-skinned) is  
863 followed by folding and minor thrusting of a part of the sedimentary cover (thin-skinned), allows  
864 to have a satisfactory balancing of the amount of shortening between thick- and thin-skinned  
865 deformation.

## 866 **8. Conclusions**

867 A new geological map of the Kurdistan Region of Iraq (KRI) is presented using the  
868 integration of fieldwork, remote sensing, and compilation of previous maps to improve the  
869 tectono-stratigraphic framework of the study region. The map integrates the lateral facies  
870 changes for the Lower Cretaceous Balambo basin and for the Late Cretaceous-Paleogene  
871 Tanjero-Kolosh foreland basin. These lateral changes of facies influenced the variations of the  
872 mechanical behavior of the depositional units and the changes in folding style.

873 We present a revisited mechanical stratigraphy of the Central KRI characterized by the  
874 Early Triassic Beduh-Mirga Mir formations as the basal detachment level, while the underlying  
875 Paleozoic rocks are considered mechanically linked with the crystalline basement. The Late  
876 Triassic Kurra Chine anhydritic level, the latest Triassic Baluti Fm., and the earliest Cretaceous  
877 Chia Gara Fm. are the main intermediate detachment levels in the up to 4.5 km thick Mesozoic  
878 sedimentary succession. This makes a significant change with respect to Lurestan in Iran where  
879 the basal detachment is located within the basement-cover interface.

880 Balanced and restored 200 km long cross-sections through Central KRI Fold-and-Thrust  
881 Belt, from the Sanandaj-Sirjan to the undeformed Mesopotamian foreland, characterized  
882 detachment folding style above the Lower Triassic ductile layer combined by an internal multi-  
883 detachment system that induced complex disharmonic folding at different scales. The  
884 topographic and structural steps situated below the HFZ are triggered by a low-angle set of  
885 basement faults rooted at around 25 km of depth as indicated by recent large Mw 7.3 magnitude  
886 earthquake.

887 The comparison between the balanced and restored cross-sections yielded 19 km of total  
888 shortening in the sedimentary cover from the High Zagros Fault to the undeformed

889 Mesopotamian foreland basin: 5 km of those were synchronous of the Late Cretaceous-Early  
890 Eocene obduction stage and 14 km were attributed to the Early Miocene continental collision  
891 phase.

892 Late Cretaceous and Paleocene growth strata were widely determined along the trace of  
893 the Erbil cross-section constraining the time of folding from Late Cretaceous to Pliocene and to  
894 estimate the evolution of the shortening and the advance of the deformation front.

895 Forward modeling results performed in this study kinematically validate the Erbil  
896 regional balanced cross-section proposed in this study using a sequence of deformation  
897 constrained by syn-tectonic sediments and cross-cutting relationships. Deformation of the Zagros  
898 belt is characterized by a combination of thin- and thick-skinned tectonics that reactivated the  
899 Late Cretaceous-Paleogene obduction belt. In addition, this forward model was constrained by 9  
900 new vitrinite reflectance samples in order to determine maximum burial thicknesses that reach 4-  
901 6 km in the HFZ.

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## 1136 **Figures captions**

1137 **Figure 1.** Synthetic map showing the main tectonic units of Iran deformed between Arabia and  
1138 Eurasia (modified from Vergés et al., 2011b). The map of the NW domain of the Thrust Zone is  
1139 compiled from Oberhänsli et al. (2010), Wrobel-Daveau et al. (2010), Ali et al. (2014) and  
1140 Moghadam and Stern (2015). Main tectonic features of the Arabian Plate come from Frizon de  
1141 Lamotte et al. (2011). ZDF – Zagros Deformation Front; MFF - Mountain Front Flexure; HZF -  
1142 High Zagros Fault; MZF - Main Zagros Fault. The focal mechanism of the 13th November 2017  
1143 earthquake of Mw 7.3 is represented near the Iran-Iraq border (Utkucu, 2017; Tavani et al.,  
1144 2018).

1145 **Figure 2.** New geological map of the Central KRI Fold-and-Thrust Belt based on field data,  
1146 remote sensing and compilation of existing geological maps (Geological Map of Iraq, 1:250000).  
1147 Red lines indicate the trace of the Erbil regional balanced cross-section. Positions of wells used  
1148 for cross-section construction are represented as green circles. Red circles correspond to samples  
1149 for reflectance vitrinite analysis. BB-04: Bina-Bawi-04; MIR-01: Mirawa-01; QT-01: Quah-  
1150 Tappa-01; SAF-01: Safeen-01; SHK-01: Shakrook-01. MFF - Mountain Front Flexure; HZF -  
1151 High Zagros Fault.

1152 **Figure 3.** Examples of folding style in the Central KRI Fold-and-Thrust Belt. (a) Google Earth  
1153 © view of the Shakrook anticline characterized by disharmonic folding and minor thrusting

1154 along its limbs (rabbit ear). This multi-scale geometry of folding is highlighted by serial  
1155 topographic profiles. (b) Google Earth © view of the Hareer anticline, which is an example of  
1156 concentric fold exposed at the Aqra-Bekhme limestones level. This whaleback anticline  
1157 geometry is highlighted by serial topographic profiles. (c) Rabbit ear structure on the northern  
1158 limb of the Shakrook anticline. (d) Field view of the Hareer box fold characterized by short and  
1159 steep dip domains along the flanks of the anticline.

1160 **Figure 4.** (a) Stratigraphic profile of the Central KRI Fold-and-Thrust Belt combined with  
1161 mechanical stratigraphy showing detachments, and disharmonic and competent levels. Pictures  
1162 from the field illustrate the mechanical behavior of (b) the Chia Gara intermediate detachment  
1163 level, (c) the Upper Jurassic disharmonic level, and (d) the Lower Triassic Beduh-Mirga Mir  
1164 basal detachment.

1165 **Figure 5.** Data distribution along the Erbil cross-section. The structure of the LFZ and the Outer  
1166 HFZ is constrained by seismic profiles, well data and surface data, while the Inner HFZ and the  
1167 Thrust Zone are exclusively based on surface data.

1168 **Figure 6.** Balanced and restored cross-sections through the Central KRI Fold-and-Thrust Belt.  
1169 (a) The structure of the Thrust Zone is modified from Ali et al. (2014), and the base of the crust  
1170 has been adapted from Jiménez-Munt et al. (2012). The focal mechanism of the 13th November  
1171 2017 earthquake of Mw 7.3 is projected along the section (Utkucu, 2017; Tavani et al., 2018)  
1172 and perfectly fits with the geometry of the basement thrust system proposed in this study. (b)  
1173 Restored cross-section after the obduction event at Late Eocene time. The top Pilaspi is used as  
1174 the horizontal datum. (c) Restored cross-section before the obduction event at pre-Campanian  
1175 time. The top Qamchuqa is used as the horizontal datum. Black lines correspond to the tops of

1176 the Late Cretaceous-Quaternary units used to estimate the flexure. The comparison with the  
1177 balanced section yields a minimum of 19 km of total shortening and a minimum of 5 km of  
1178 shortening for the obduction event.

1179 **Figure 7.** Zoom of the HFZ from the Erbil regional balanced section across the Central KRI  
1180 Belt. Lateral sedimentary facies variations in the Cretaceous and Tertiary are integrated based on  
1181 fieldwork, well data and remote sensing mapping. (a) Very tight hinge of the Safeen anticline  
1182 located between the competent Qamchuqa platform and the slope carbonates of the disharmonic  
1183 Sarmord formation. (b) Thick isolated patch of reefal carbonates of Aqra-Bekhme Fm. on the  
1184 crest of the Handreen anticline, passing laterally to the marls and limestones of the Shiranish  
1185 Formation towards the adjacent synclines. (c) Tanjero growth strata filling the syncline to the  
1186 SW of the Tanun anticline indicating that folding was active during Maastrichtian time. (d)  
1187 Structural interpretation along the Safeen-01 well showing the tight geometry of the Safeen  
1188 anticline, with its very steep forelimb developing thrusts detached along the Baluti level  
1189 becoming SW-verging thrust ramps cutting the entire post-Baluti stratigraphy at high angles. (e)  
1190 Growth syncline at the Kolosh Fm. level, between the Safeen and the Shakrook anticlines,  
1191 showing that the onset of folding is of Paleocene age. (f) Perched syncline in the footwall of the  
1192 main thrust cutting through the SW limb of the Tanun anticline.

1193 **Figure 8.** The folding and thrusting in the LFZ propagated to the southwest as indicated by the  
1194 growth strata geometries in the Bakhtiari deposits becoming younger from the Kirkuk to  
1195 Pulkhana thrusts.

1196 **Figure 9.** Crustal-scale evolution of the KRI Fold-and-thrust belt in 4 main steps. (a) Pre-  
1197 Campanian initial stage showing the reconstructed geometry of the Arabian margin. (b) Step A at

1198 Campanian-Maastrichtian ages displaying the development of the Tanjero flexural basin during  
1199 Neo-Tethys oceanic obduction event. (c) Step B at Paleocene-Eocene ages reproducing the  
1200 foreland wards propagation of the deformation and concomitant sedimentary depocentre. (d)  
1201 Step C at Miocene age during the Fars deposition showing the continental collision dominated by  
1202 thick-skinned tectonic. (e) Step D during the Bakhtiari and younger deposition reproducing  
1203 thrusting beneath the Mountain Front Flexure and the thin-skinned propagation of the  
1204 deformation in the LFZ.

1205 **Figure 10.** Detailed evolution of the KRI Fold-and-Thrust belt in 4 main steps combined with  
1206 erosion estimates (dotted lines) based on vitrinite reflectance data and two potential geothermal  
1207 gradients of 30°C and 25°C. Same legend as in Figure 9.

1208 **Figure 11.** Distribution of fold wavelengths in the Fars (Mouthereau et al., 2007) and in the KRI  
1209 Fold-and-Thrust Belt (this study).

1210 **Figure 12.** (a) Geometry of the basal detachment below the HFZ. The width and the amount of  
1211 uplift of the two main structural steps are indicated. (b) Forward kinematic model based on the  
1212 fault-bend fold algorithm (2DMove ©) showing the in-sequence thick-skinned deformation that  
1213 reproduces the geometry of the basal detachment level. (c) Cross-section using thin-skinned  
1214 cover structure from surficial studies and thick-skinned basement structure based on forward  
1215 modeling results. The focal mechanism of the 13th November 2017 earthquake of Mw 7.3 is  
1216 projected along the section (Utkucu, 2017; Tavani et al., 2018) and perfectly fits with the  
1217 geometry of the basement thrust system proposed in this study.

1218

1219 **Tables**

1220

Sample	Age	Formation	Elevation (m)	Type	Standard Deviation	Number of measurements	Eq Vro% Bitumen	Ro %	Burial (km) 25°/km	Burial (km) 30°/km
01	Maastrichtian	Tanjero	946	Vitrinite	0.08	36	-	0.58	3.66	2.88
02	Early Eocene	Kolosh	1059	Vitrinite	0.05	40	-	0.59	3.74	2.94
03	Maastrichtian	Tanjero	991	Vitrinite	0.06	30	-	0.65	4.41	3.54
04	Malm	Sargelu	948	Anisotropic Bitumen	0.10	9	1.18	1.2	5.94	4.92
05	Kimmeridgian	Barsarin	796	Bitumen	0.11	50	1.09	1.1	5.82	4.83
06	Malm	Sargelu	641	Anisotropic Bitumen	0.12	50	1.51	1.51	6.24	5.18
07	Lias	Sarki	718	Vitrinite	0.15	40	-	1.41	6.13	5.10
08	Berriasian	Chia Gara	761	Vitrinite	0.03	4	-	1.25	5.99	4.96
09	Paleogene	Red Beds	834	Vitrinite	0.08	18	-	0.55	3.28	2.58

1221

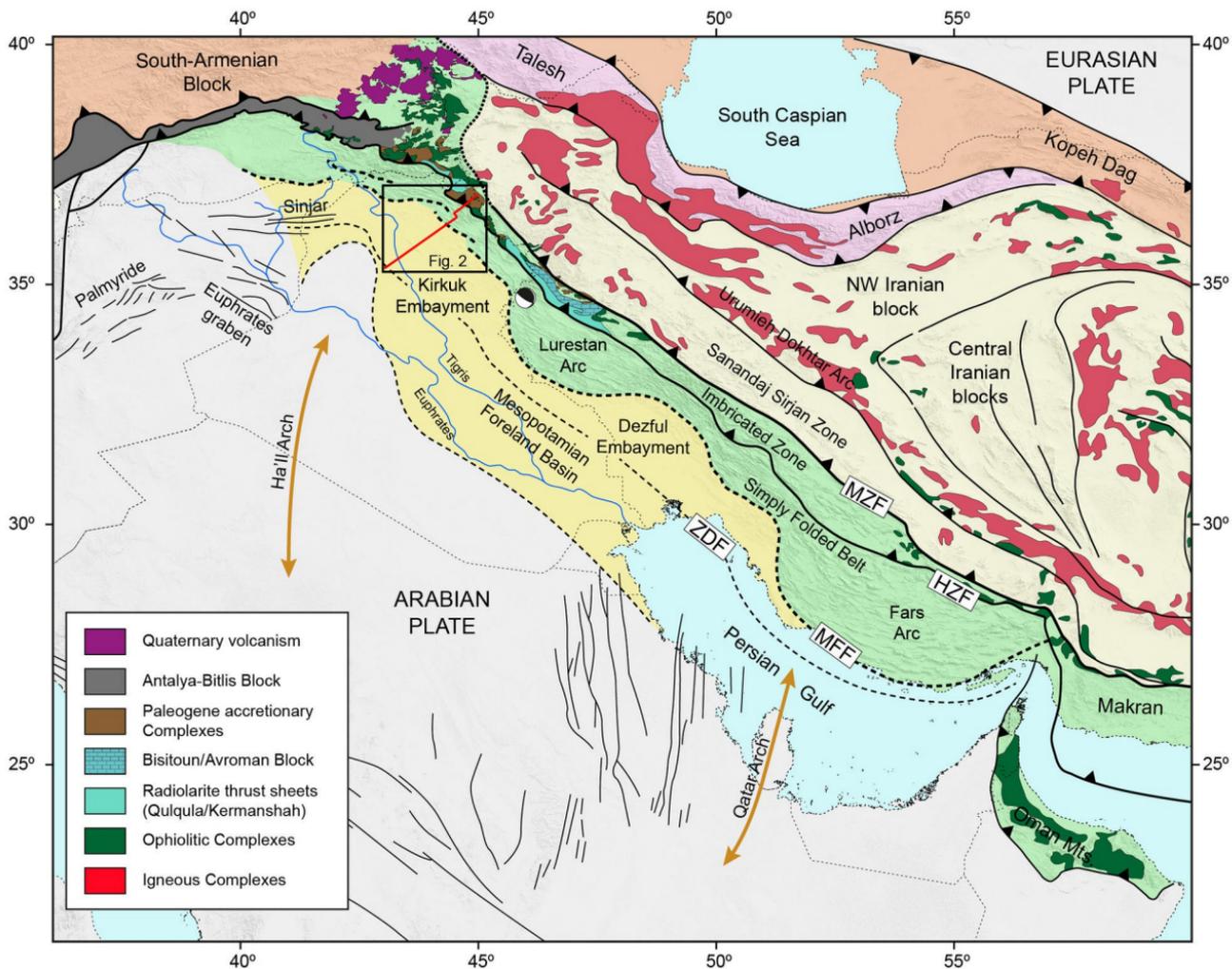
1222 **Table 1.** Samples collected from the HFZ and related organic matter maturity. Burial values

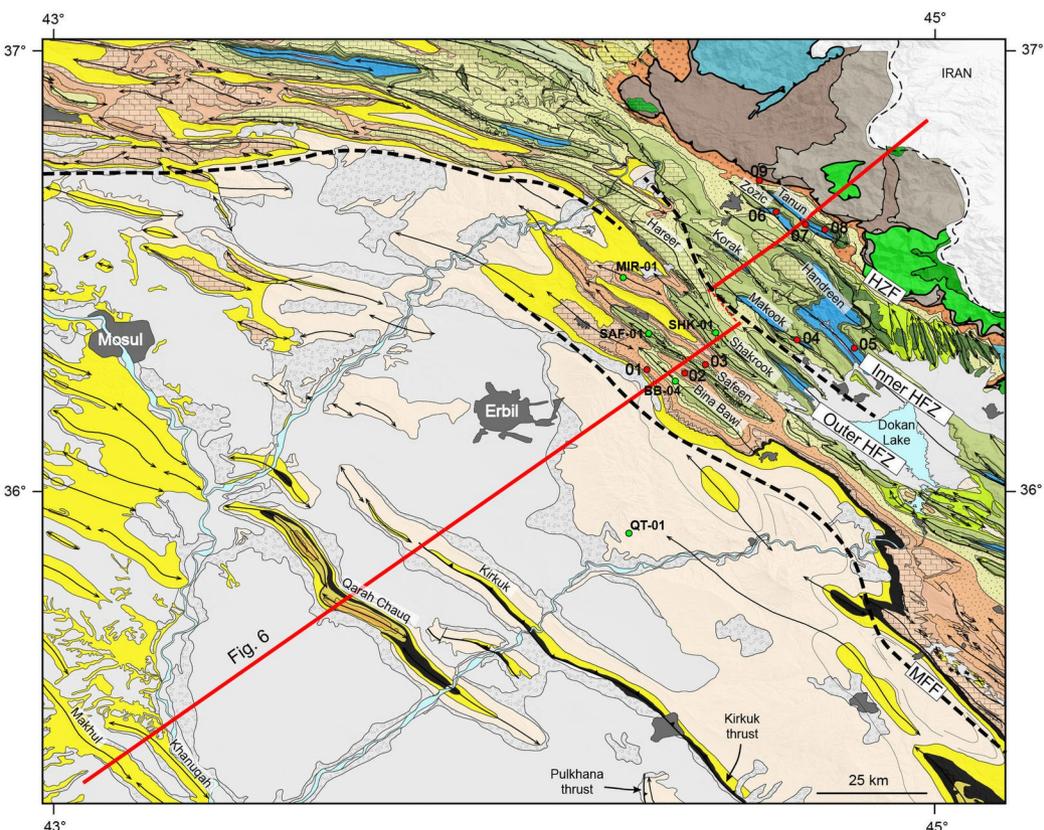
1223 have been estimated using the general relation between depth of burial, vitrinite reflectance and

1224 geothermal gradient proposed by Suggate (1998).

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1226





## Sedimentary rocks of the Arabian Margin

### Collision Foreland Basin (Neogene-Present)

- Alluvial plain
- Quaternary terraces and slopes
- Bakhtiari Fm.
- Fars Fm.
- Lowers Fars evaporitic
- Lower Miocene Group
- Govanda limestones
- Kirkuk Group

### Proto-Foreland Basin (Late Cretaceous-Eocene)

- Pilaspi Fm.
- Gercus, Sinjar, Khurmala Fms.
- Kolosh Fm.
- Red Beds (Paleocene-Miocene)
- Aqra, Bekhme Fms.
- Tanjero Fm.
- Shiranish Fm.
- Kometan Fm.

### Mesozoic Passive Margin

- Balambo Fm.
- Qamchuqa, Sarmord Fms.
- Chia Gara Fm.
- Jurassic
- Triassic

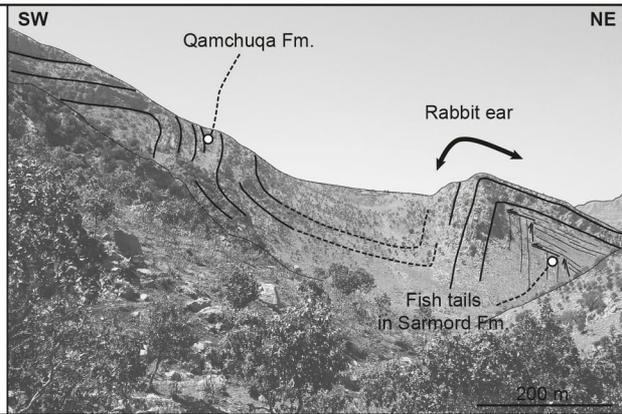
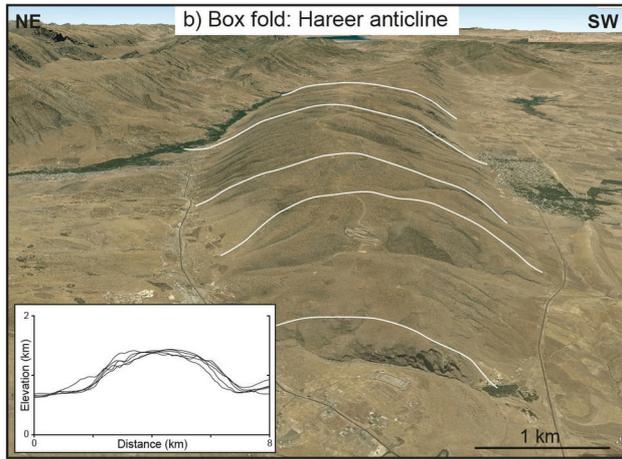
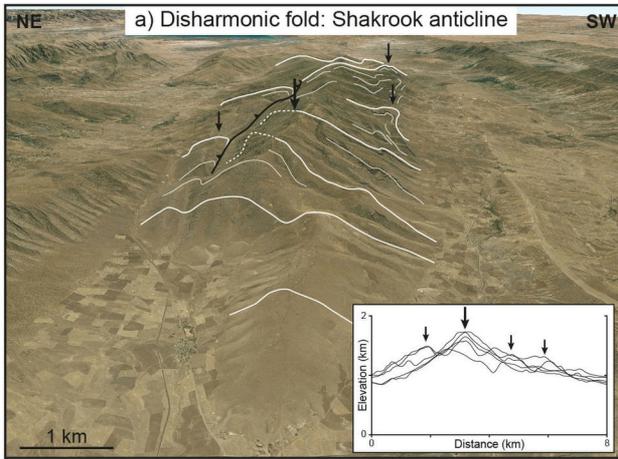
## Thrust Zone

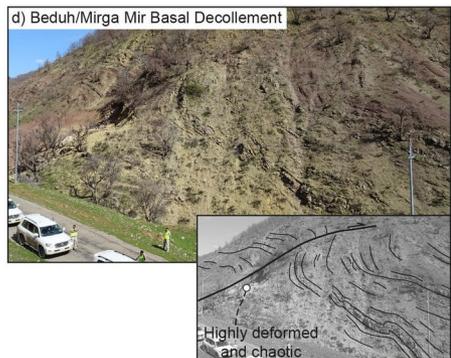
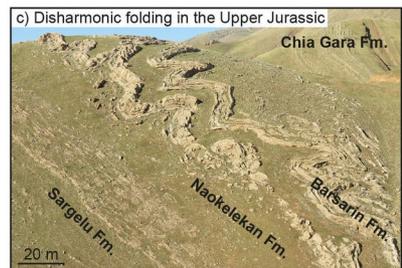
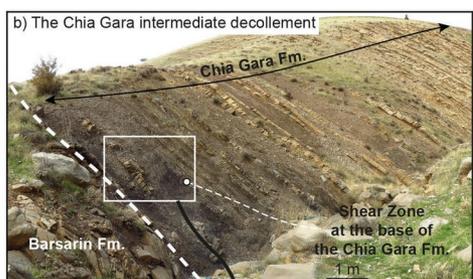
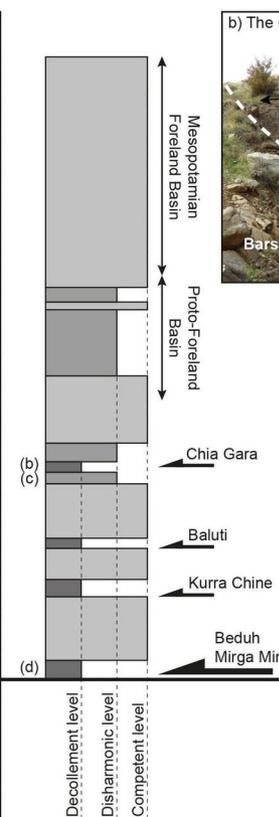
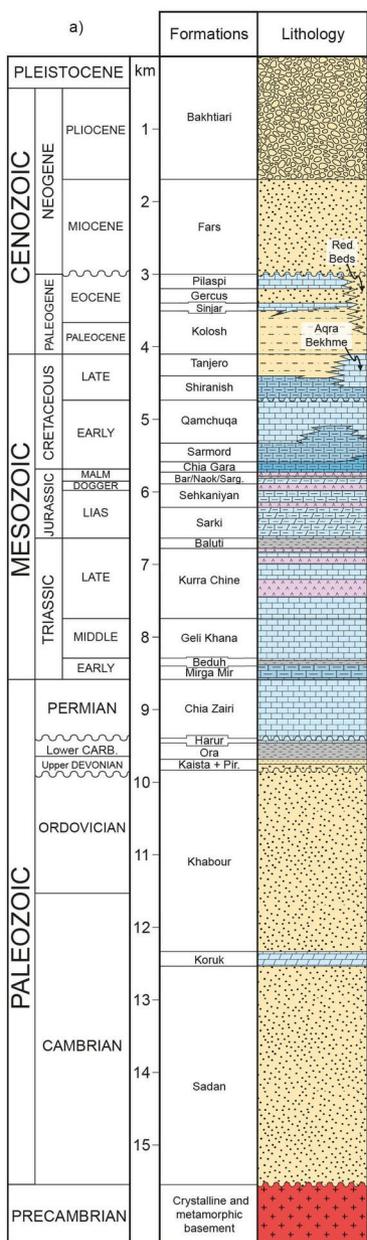
### Walash Naopurdan complex (Paleocene-Oligocene)

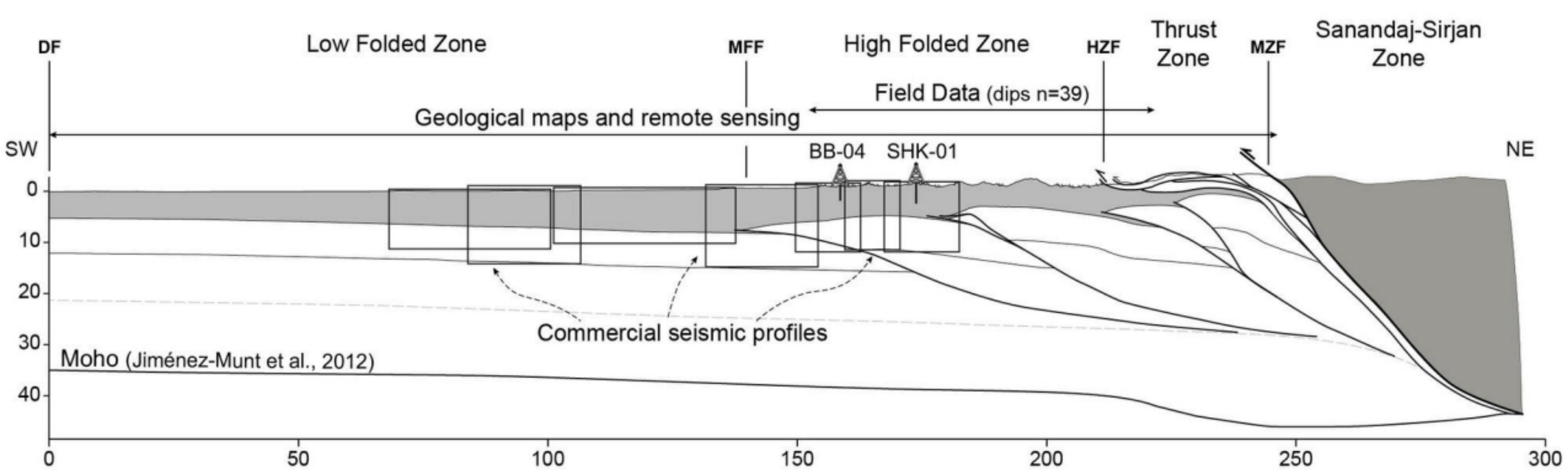
- Oligocene Naopurdan shaly group
- Paleocene-Eocene Walash volcanic group

### Ophiolitic complex (Late Cretaceous)

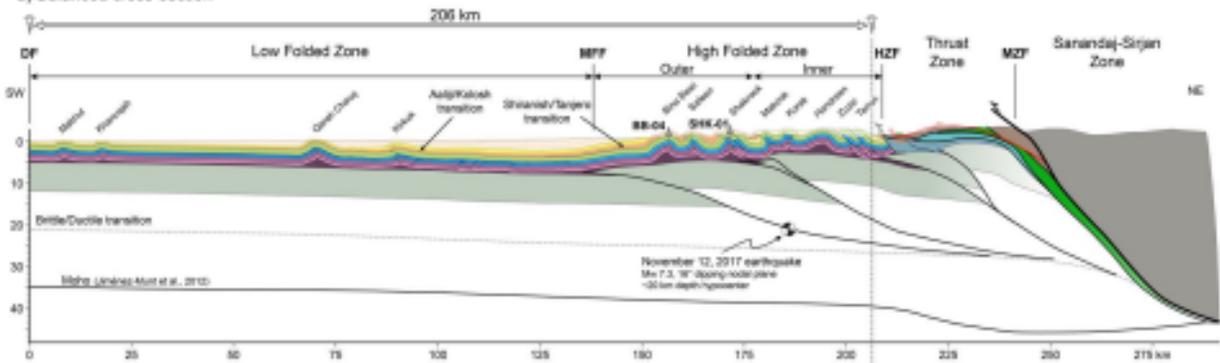
- Ophiolites
- Volcanosedimentary complex
- Piran limestones
- Qulqula radiolarites



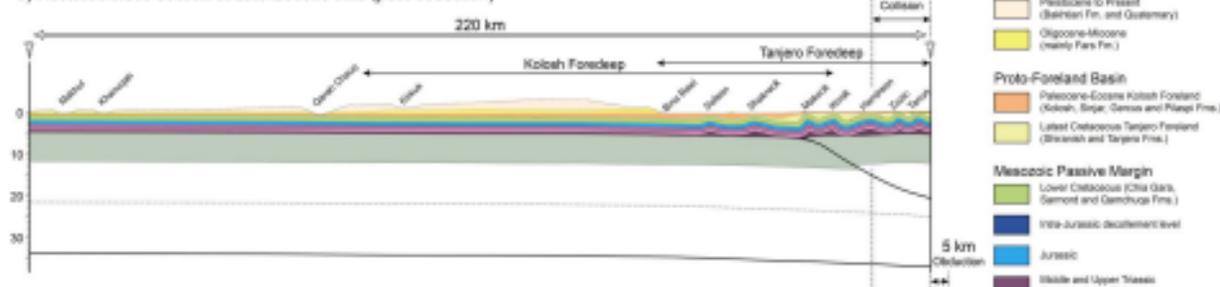




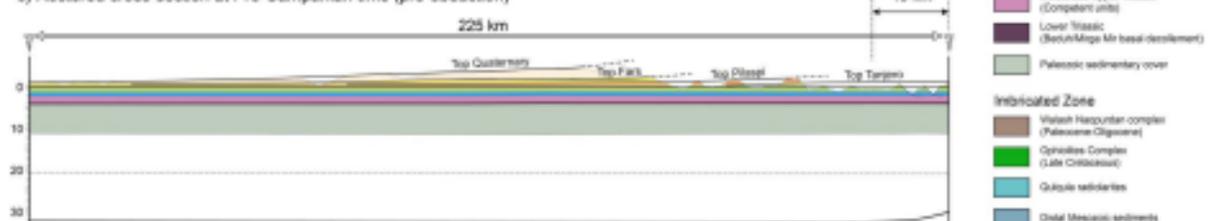
a) Balanced cross-section



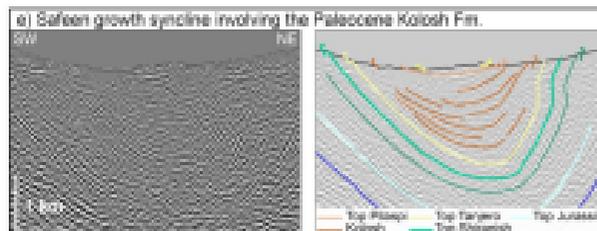
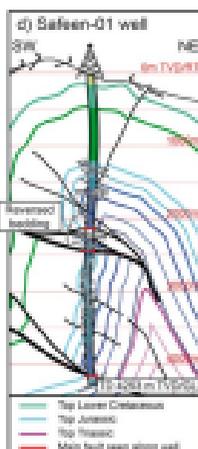
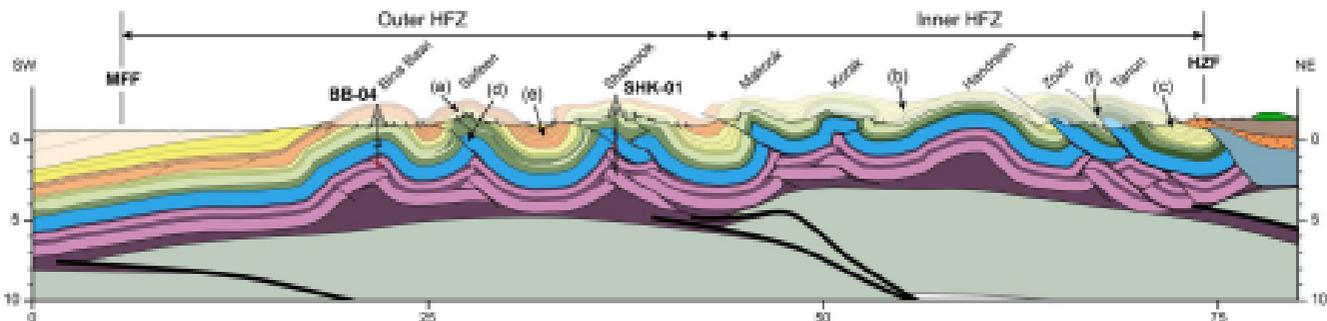
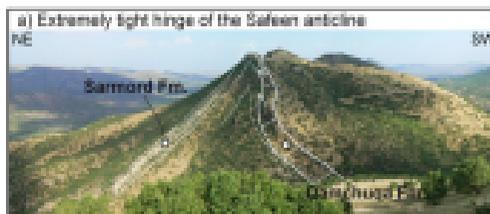
b) Restored cross-section at Late Eocene time (post-obduction)

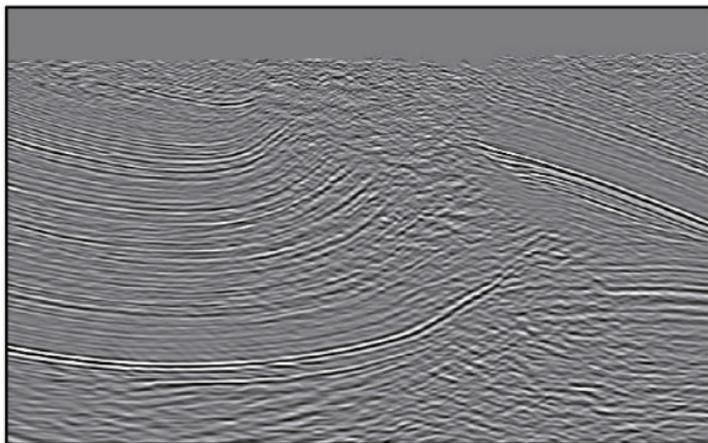


c) Restored cross-section at Pre-Campanian time (pre-obduction)

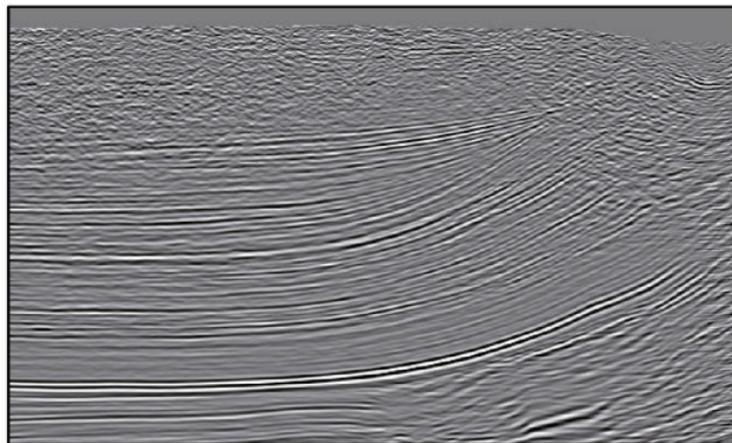


- Collision Foreland Basin**
- Paleocene to Present (Beltein Fm. and Galesman)
  - Oligocene-Miocene (mainly Fars Fm.)
- Proto-Foreland Basin**
- Paleocene-Eocene Kolbah Foreland (Kolbah, Beger, Garmou and Pasaq Fms.)
  - Latest Cretaceous Tanjero Foreland (Shirvanik and Tanjero Fms.)
- Mesozoic Passive Margin**
- Lower Cretaceous (Chir Gark, Garmou and Garmouq Fms.)
  - Intra-Jurassic decollement level
  - Jurassic
  - Middle and Upper Triassic (Compilert unit)
  - Middle and Upper Triassic (Compilert unit)
  - Lower Triassic (Beruti/Muga Air basal decollement)
  - Paleozoic sedimentary cover
- Introducted Zone**
- Vitahik Haccupner complex (Paleocene-Oligocene)
  - Ophiolite Complex (Late Cretaceous)
  - Gakula sediments
  - Older Mesozoic sediments

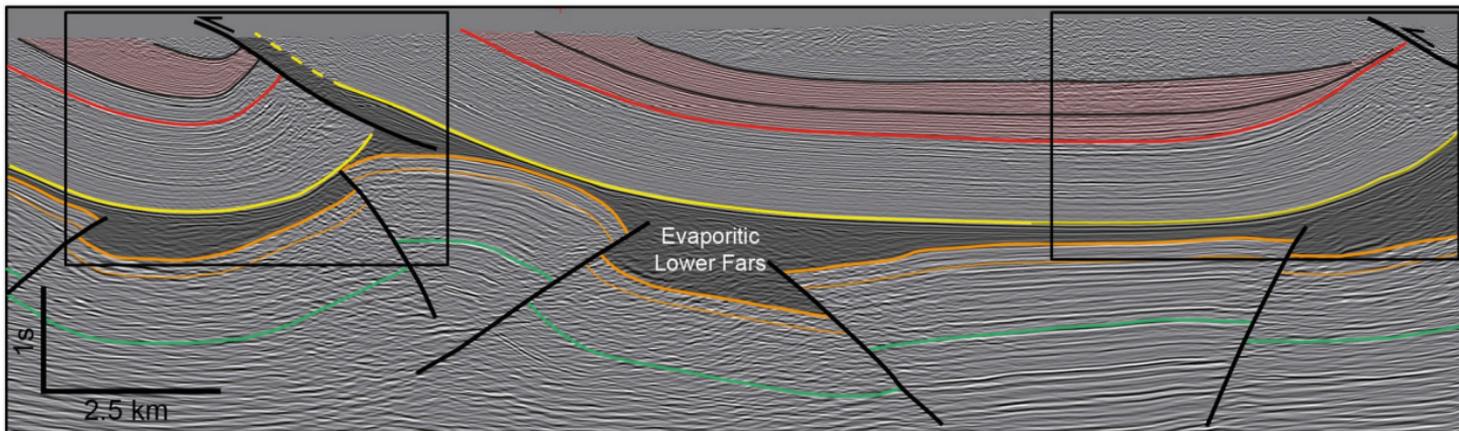




Pulkhana thrust



Kirkuk thrust



— Intra Bakhtiari

— Top Upper Fars

— Top Lower Fars

— Top Pilaspi

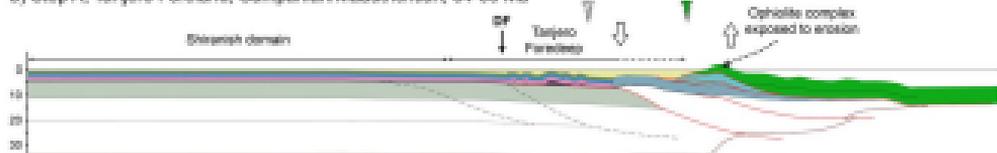
— Top Qamchuqa

▭ Syn-folding units

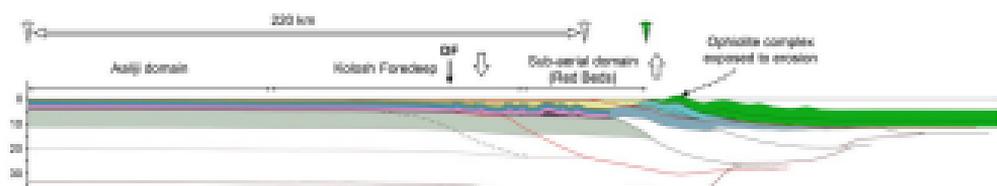
a) Initial stage, Before obduction, Pre-Campanian, 84 Ma



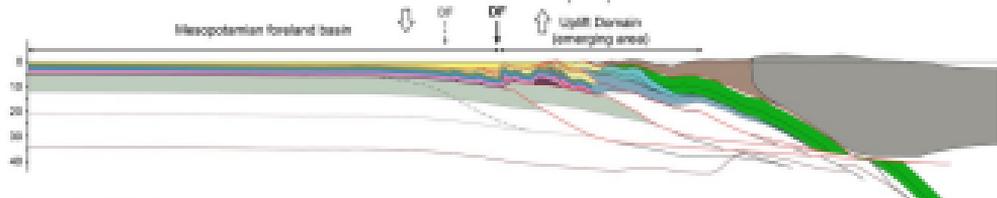
b) Step A, Tarjero Foreland, Campanian/Maastrichtian, 84-66 Ma



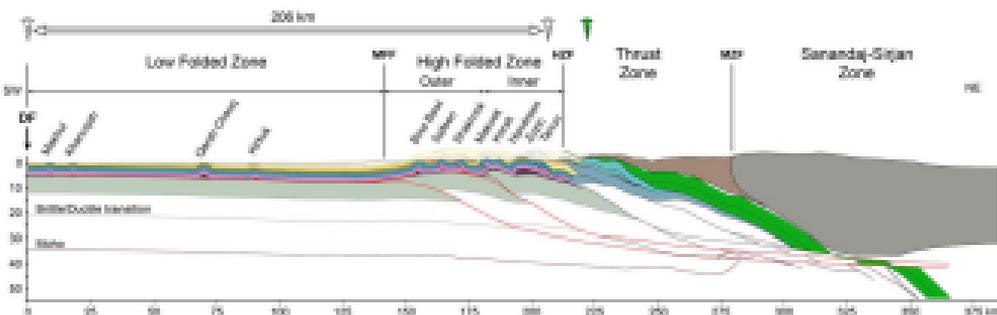
c) Step B, Kolosh Foreland, Paleocene-Eocene, 66-34 Ma



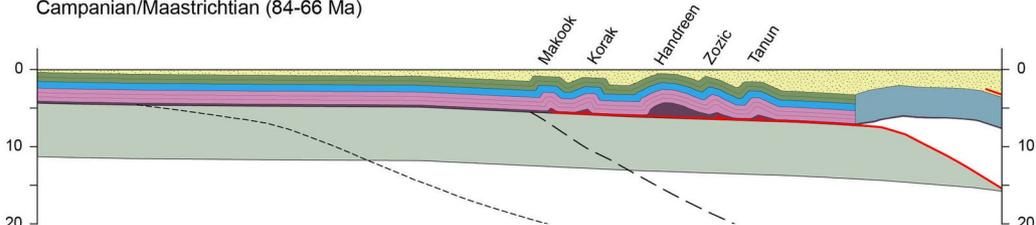
d) Step C, Mesopotamian Foreland, Miocene, 20-10 Ma



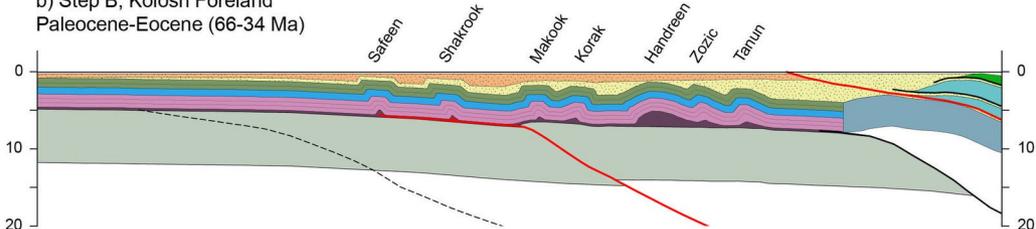
e) Step D, 10 Ma-Present



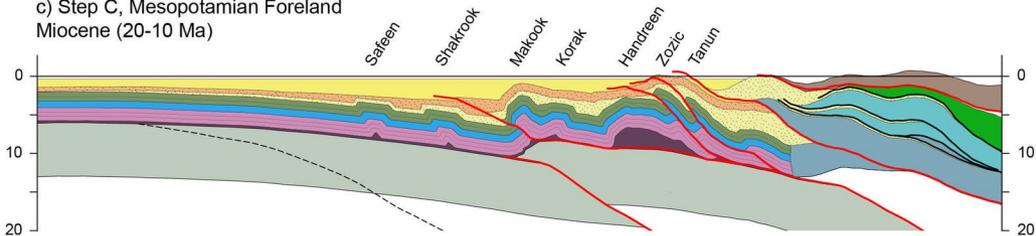
a) Step A, Tanjero Foreland  
Campanian/Maastrichtian (84-66 Ma)



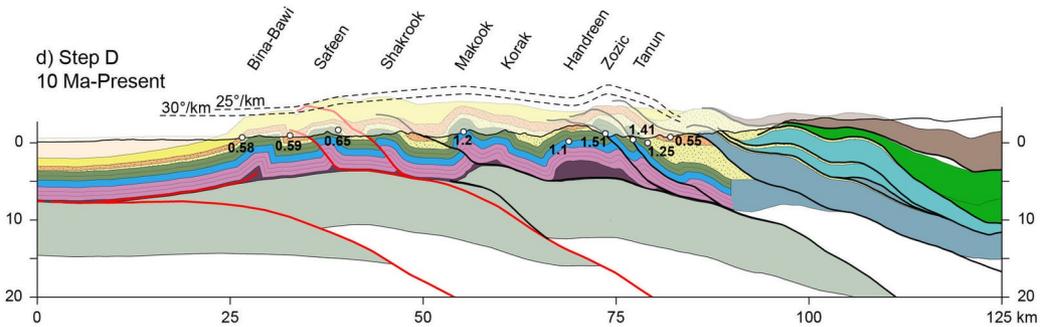
b) Step B, Kolosh Foreland  
Paleocene-Eocene (66-34 Ma)



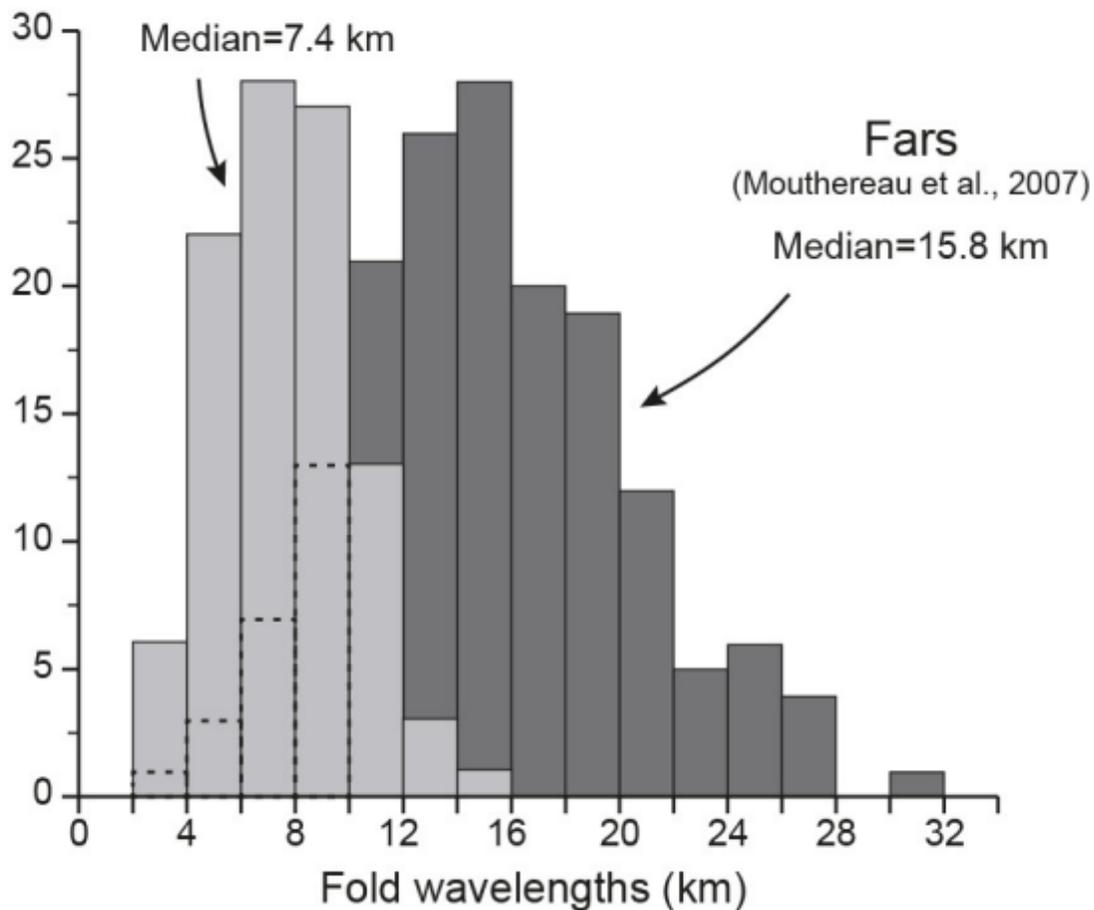
c) Step C, Mesopotamian Foreland  
Miocene (20-10 Ma)



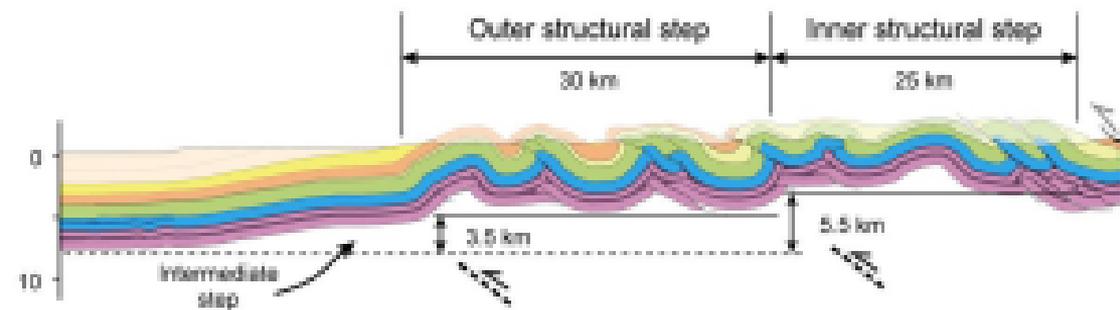
d) Step D  
10 Ma-Present



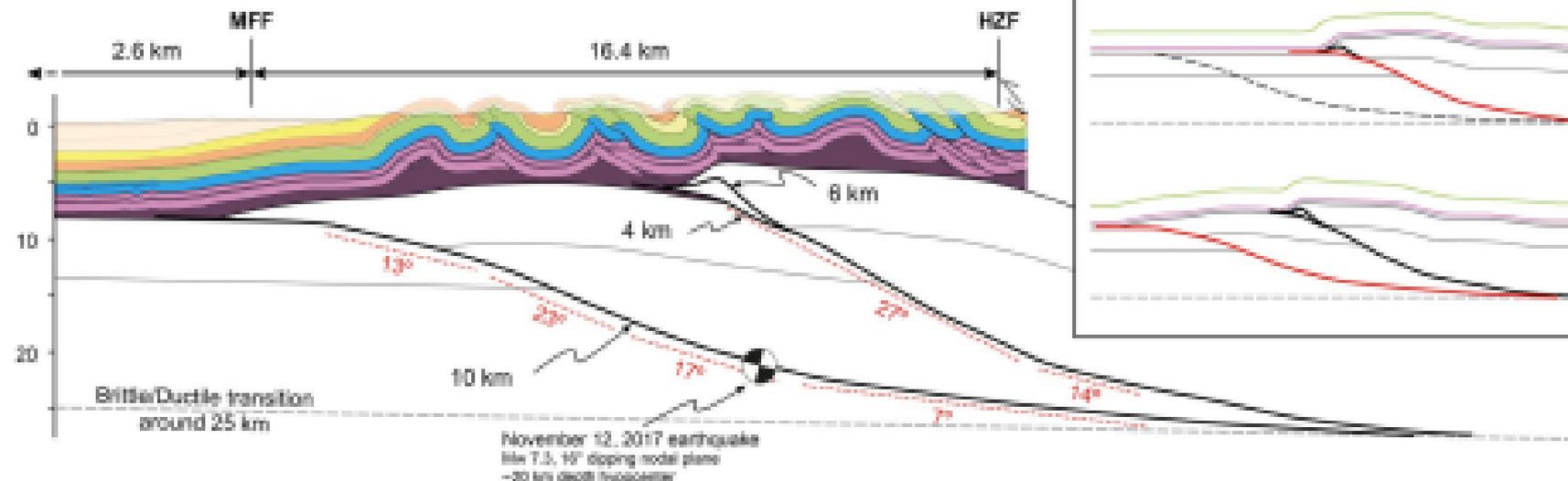
**Kurdistan**  
(this study)



(a) Basement steps geometry



(c) Comparison with the kinematic modeling



(b) Kinematic modeling

