

# Tectonophysics

## Hanging-wall deformation at the active Sierra Palomera extensional fault (Jiloca basin, Spain) from structural, morphotectonic, geophysical and trench study --Manuscript Draft--

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<b>Abstract:</b>	<p>The NNW-SSE trending Sierra Palomera fault is characterized as an active, nearly pure extensional fault with mean transport direction towards N230°E, consistent with the ENE-WSW extension trajectories of the recent to present-day regional stress field. Its macrostructure is described from surface geology and magnetometric and electromagnetic surveys, which have allowed identifying two subsidiary, nearly parallel normal faults (antithetic and synthetic, respectively). The structural contour map of an extensive planation surface, dated to 3.8 Ma, provides a maximum fault throw s.s. of 330 m for the main fault (480 m including bending), and a net slip rate of 0.09 mm/a (0.13 mm/a including bending). Trench study focussed on the subsidiary antithetic fault shows evidence of its activity during Middle-Late Pleistocene times, offsetting ca. 2.5 m the slope of a well-preserved alluvial fan. Detailed analysis and retrodeformation of the antithetic fault and other minor ruptures in the trench has allowed defining seven deformation events. The lack of a consistent age model for the involved sedimentary sequence makes them almost meaningless in terms of paleoseismic history. However, geometry and sequential development of meso-scale faults (intermediate between seismic-scale and analogue models) allows unravelling the extensional deformation history within the hanging-wall block of the Sierra Palomera fault. Progressive rupture patterns reveal shifting from dominantly synthetic to dominantly antithetic faulting, suggesting both kinematical control linked to rollover growth, and dynamical control by the regional stress field.</p>

## Abstract

The NNW-SSE trending Sierra Palomera fault is characterized as an active, nearly pure extensional fault with mean transport direction towards N230°E, consistent with the ENE-WSW extension trajectories of the recent to present-day regional stress field. Its macrostructure is described from surface geology and magnetometric and electromagnetic surveys, which have allowed identifying two subsidiary, nearly parallel normal faults (antithetic and synthetic, respectively). The structural contour map of an extensive planation surface, dated to 3.8 Ma, provides a maximum fault throw *s.s.* of 330 m for the main fault (480 m including bending), and a net slip rate of 0.09 mm/a (0.13 mm/a including bending). Trench study focussed on the subsidiary antithetic fault shows evidence of its activity during Middle-Late Pleistocene times, offsetting 2.6 m the slope of a well-preserved alluvial fan. Detailed analysis and retrodeformation of the antithetic fault and other minor ruptures in the trench has allowed defining seven deformation events. The lack of a consistent age model for the involved sedimentary sequence makes them almost meaningless in terms of paleoseismic history. However, geometry and sequential development of meso-scale faults allows unravelling the extensional deformation mechanisms within the hanging-wall block of the Sierra Palomera fault, suggesting both kinematic control linked to rollover growth, and dynamic control by the regional stress field.

**Keywords:** Active fault, antithetic fault, rollover, magnetometry, Pleistocene, Iberian Chain.

## HIGHLIGHTS

- The Sierra Palomera fault bounds the central sector of the active Jiloca Graben
- This fault offsets ca. 480 m a mid-Pliocene (3.5 Ma) planation surface
- A large antithetic fault in the hanging-wall block accommodates simple shear associated to roll-over
- The antithetic fault was active during Late Pleistocene time, at the rate of XXX
- Hanging-wall subsidiary faulting is controlled by both roll-over kinematics and the regional extensional stress field

1 ***Hanging-wall deformation at the active Sierra Palomera extensional fault***  
2 ***(Jiloca basin, Spain) from structural, morphotectonic, geophysical and trench***  
3 ***study***

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18  
19 **Abstract**

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21 extensional fault with mean transport direction towards N230°E, consistent with the ENE-  
22 WSW extension trajectories of the recent to present-day regional stress field. Its  
23 macrostructure is described from surface geology and magnetometric and electromagnetic  
24 surveys, which have allowed identifying two subsidiary, nearly parallel normal faults  
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26 surface, dated to 3.8 Ma, provides a maximum fault throw *s.s.* of 330 m for the main fault  
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29 Middle-Late Pleistocene times, offsetting 2.6 m the slope of a well-preserved alluvial fan.  
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## 38 1. Introduction

39 Our understanding of geometry and kinematics of extensional fault systems has been  
40 significantly improved thanks to analytical and scaled analogue models, particularly  
41 concerning deformation of the hanging-wall block of listric faults. Such models provide  
42 interesting inferences about controls that the shape of the main fault surface exerts on the  
43 development of hanging-wall folds and fractures. Fault surfaces with irregular geometry  
44 induce antithetic simple shear along a deformation band that nucleates at shallowing fault  
45 bends, while synthetic shear is induced at steepening fault bends (McClay and Scott, 1991;  
46 Xiao and Suppe, 1992; Withjack *et al.*, 1995; Delogkos *et al.*, 2020). Depending on the  
47 mechanical properties of materials, such overall simple shear results in either fault-related  
48 folding (rollover and drag folds, respectively) or faulting (antithetic and synthetic,  
49 respectively). Analogue models provide insights into both differential behaviours, *e.g.*, by  
50 comparing experimental materials as clay and sand (*e.g.*, Withjack *et al.*, 1995). Nevertheless,  
51 as discussed by Xiao and Suppe (1992), models give limited information about the actual  
52 small-scale mechanisms that accommodate deformation. Therefore, contribution of data  
53 directly supplied by field examples is necessary for full understanding of kinematics of  
54 extensional systems.

55 Methodology of trench analysis, extensively used and standardized for  
56 paleoseismological studies (*e.g.*, McCalpin, 1996), offers new insights for detailed analysis of  
57 progressive extensional deformation. Each identified paleoseismic event can be considered as  
58 an incremental or ‘infinitesimal’ deformation episode, and hence the reconstructed  
59 paleoseismic sequence provides a realistic view of extension kinematics (although ineludibly  
60 constrained to a given space and time window).

61 The Sierra Palomera fault is one of the most conspicuous recent, hypothetically active  
62 extensional faults in the central Iberian Chain (Spain). Nevertheless, in contrast with other  
63 neighbouring faults (Concud, Teruel, Valdecebro, Calamocha, Munébrega faults), in which  
64 numerous trench studies have been carried out in the last two decades (Gutiérrez *et al.*, 2009;

65 Lafuente, 2011; Lafuente *et al.*, 2011a, 2014; Martín-Bello *et al.*, 2014; Simón *et al.*, 2016,  
66 2017, 2019), no paleoseismological analysis has been developed in the Sierra Palomera fault  
67 owing to lack of appropriate sites for digging a trench at the main fault zone.

68 **The Sierra Palomera fault belongs to the Jiloca graben, the youngest Neogene-Quaternary**  
69 basin of the central-eastern Iberian Chain (eastern Spain; Fig. 1) linked to rifting of the  
70 Valencia Trough (Vegas *et al.*, 1979). In overall, it is a half-graben that exhibits a NNW-SSE  
71 trend resulting from en-échelon, right-lateral arrangement of NW-SE striking normal faults at  
72 its eastern, active border. This basin has developed since Late Pliocene time, under a nearly  
73 biaxial or multidirectional extension regime ( $\sigma_2 \approx \sigma_3$ ) with maximum extension trajectories  
74 ( $\sigma_3$ ) oriented ENE-WSW (Simón, 1983, 1989; Arlegui *et al.*, 2005; Liesa *et al.*, 2019).

75

76 **[PREFERENTIALLY, FIG.1 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

77

78 The northern and southern sectors of the Jiloca basin are bounded by the Calamocha and  
79 Conclud faults, respectively (Fig. 1c). Both faults cut and offset the uppermost, early Pliocene  
80 lacustrine deposits of the neighbouring Calatayud and Teruel basins, respectively. Based on  
81 clearly recognized stratigraphic markers, the corresponding maximum throws are calculated at  
82 about 210 m for the Calamocha fault (Martín-Bello *et al.*, 2014), and 260 m for the Conclud  
83 fault (Ezquerro *et al.*, 2020).

84 In the central segment of the basin (Fig. 2), the displacement at the Sierra Palomera fault  
85 cannot be calculated in the same way since no recent stratigraphic marker is available. The  
86 tectonic nature of the boundary itself, and particularly the discrimination between the role of  
87 erosive lowering and vertical tectonics in the creation of the mountain scarp has been the  
88 object of controversy indeed. After Cortés and Casas (2000), its topography is essentially a  
89 result of erosive incision in response to orogenic uplift. Gracia *et al.* (2003) reinterpret the  
90 Jiloca depression as a polje, developed during Late Pliocene-Quaternary times on an incipient  
91 half graben. Rubio and Simón (2007) and Rubio *et al.* (2007) analyse these arguments and  
92 provide new sedimentary, geomorphological and hydrogeological evidence on the tectonic  
93 origin of the Jiloca depression, from both surface and subsoil data. These authors conclude  
94 that: (i) the basin is a tectonic graben limited by Plio-Quaternary faults; (ii) the Sierra  
95 Palomera fault has a maximum throw approaching 350-400 m; and (iii) although the basin is  
96 noticeably underfilled, its sedimentary infill shows thickness and facies distribution consistent  
97 with such basin model.

98

99 **[PREFERENTIALLY, FIG.2 SHOULD BE INSERTED HERE, AS A 1.5-COLUMN FIGURE]**

100

101       Concerning the signs of Quaternary activity, these are again conspicuous in the northern  
102 and southern sectors of the graben. The Conclud fault has been object of intense  
103 paleoseismological research at both natural outcrops and trenches, which have allowed  
104 reconstructing a wide paleoseismic succession of eleven events since ca. 74 ka BP to the  
105 present day, with average recurrence period of 7.1-8.0 ka, total net accumulated slip of about  
106 20 m, and average slip rate of 0.29 mm/a (Lafuente, 2011; Lafuente *et al.*, 2011a,b, 2014;  
107 Simón *et al.*, 2016). Quaternary activity of the Calamocha fault is revealed by the mechanical  
108 contact between Neogene units of the Calatayud basin and Late Pleistocene alluvial deposits  
109 that infill the northernmost Jiloca basin. Three distinct fault branches are well exposed at the  
110 slopes of the A-23 highway and an industrial area in the neighbourhoods of Calamocha town  
111 (Martín-Bello *et al.*, 2014).

112       On the contrary, no exposure of the Sierra Palomera fault cutting Quaternary deposits has  
113 been described. It is mainly due to the fact that the Quaternary fluvial incision is virtually  
114 absent. Endorheic conditions in this sector have remained until historical times, with  
115 development of a palustrine area at the basin centre (ancient Cañizar lake; Rubio and Simón,  
116 2007). Observation of Quaternary surficial ruptures has not been possible, thus their evidence  
117 is only indirect.

118       The purpose of the present work is contributing to fill this gap, with three specific  
119 objectives: (i) improving our overall knowledge on the structure and evolution of the Jiloca  
120 basin; (ii) reporting evidence on the activity of the Sierra Palomera fault during the  
121 Quaternary, and (iii) characterizing the style of extensional deformation within its hanging-  
122 wall block. Especial attention will be paid to structural features that indicate recent activity of  
123 the Sierra Palomera fault and other structures associated to it, showing how geophysical  
124 exploration provides complementary subsoil information with that respect. We will go deeper  
125 into the morphotectonics of the area, analysing the effects of fault activity on the relief. In the  
126 absence of stratigraphic markers, extensive Late Neogene planation surfaces existing in the  
127 region will be especially useful as geomorphological markers of deformation. Finally, we will  
128 address a detailed analysis of ruptures within a portion of the hanging-wall block of the Sierra  
129 Palomera fault by using trenching techniques.

130

## 131 **2. Geological setting**

132 The Iberian Chain is a NW-SE trending, 450 km long intraplate mountain range located  
133 in the eastern Iberian Peninsula (Fig. 1a). This chain developed in Paleogene to Early  
134 Miocene times due to the convergence between the Africa and Eurasia plates, under which an  
135 heterogeneous ensemble of fold-and-thrust belts, depicting a roughly double-vergence  
136 structure, was built by positive inversion of the extensional Mesozoic Iberian basin (Álvaro *et al.*  
137 *et al.*, 1979; Guimerà and Álvaro, 1990; Capote *et al.*, 2002; Liesa *et al.*, 2018). After a  
138 transition period during the Early Miocene, in which the longitudinal Calatayud basin  
139 developed under a transpressional regime (Colomer and Santanach, 1988; Simón *et al.*, 2021),  
140 a new extensional stage associated to rifting of the Valencia Trough took place. Extensional  
141 deformation propagated onshore towards the central part of the Iberian Chain (Álvaro *et al.*  
142 1979, Vegas *et al.*, 1979), inducing both reactivation of the main inherited Mesozoic faults  
143 and formation of new normal faults, and generating a number of diversely oriented  
144 intracontinental grabens and half-grabens (Simón, 1982, 1989; Gutiérrez *et al.*, 2008, 2012;  
145 Ezquerro, 2017; Liesa *et al.*, 2019).

146 Relationships of extensional macrostructures with geomorphic features and stress  
147 evolution in the Iberian Chain allow defining two main extensional phases. During the first  
148 phase (Late Miocene to Early Pliocene in age), the 90-km-long, NNE-SSW trending Teruel  
149 half-graben basin developed, filled with terrestrial sediments up to 500 m thick (Simón, 1982,  
150 1983; Moissenet, 1983; Anadón and Moissenet, 1996; Ezquerro, 2017; Ezquerro *et al.*, 2020).  
151 Throughout this period, the Teruel basin propagated northwards, acquiring a N-S trend at its  
152 northern sector (El Pobo fault zone; Fig. 1b; Ezquerro *et al.*, 2019, 2020), while other N-S  
153 trending half-grabens were settled in its footwall block (western and eastern El Pobo basins;  
154 Simón-Porcar *et al.*, 2019). The second extensional phase started in the Late Pliocene and  
155 shows a more widespread deformation. In the central Iberian Chain, a large number of  
156 compressional and extensional structures were reactivated, producing new NNW-SSE  
157 trending grabens and half-grabens that are inset or cross-cut the pre-existent Teruel and  
158 Calatayud basins (Simón, 1983, 1989; Gutiérrez *et al.*, 2008, 2020; Liesa *et al.*, 2019). They  
159 include (Fig. 1): (i) the 80-km-long Jiloca graben, which results from en-échelon, right  
160 releasing arrangement of the NW-SE striking Conclud, Sierra Palomera and Calamocha faults  
161 (Simón, 1983; Rubio and Simón, 2007; Simón *et al.*, 2012, 2017; Peiro *et al.*, 2019, 2020);  
162 (ii) the 30-km-long Daroca half-graben (Colomer, 1987; Gracia, 1992; Gutiérrez *et al.*, 2008,  
163 2020; Casas *et al.*, 2018); (iii) the 88-km-long Río Grío-Pancrudo Fault Zone, made of two  
164 main faults, Río Grío-Lanzuela and Cucalón-Pancrudo (Peiro and Simón, 2021). In the first  
165 extensional phase, the direction of maximum extension ( $\sigma_3$ ) was E-W to ESE-WNW (under a



166 triaxial extensional regime), whereas ‘multidirectional’ extension with ENE-WSW  $\sigma_3$   
167 trajectories characterizes the second phase (Simón, 1982, 1983, 1989; Cortés, 1999; Capote *et*  
168 *al.*, 2002; Arlegui *et al.*, 2005, 2006; Liesa, 2011; Ezquerro, 2017; Liesa *et al.*, 2019).  
169 Regional uplift during the Late Pliocene-Quaternary resulted in: (i) constraining  
170 sedimentation to underfilled residual basins, with a modest sedimentary infill (normally less  
171 than 100 m thick), and (ii) driving most of the area to exorheic conditions.

172 Geometric construction of normal fault profiles of the Teruel fault system locates the sole  
173 detachment at a depth of 14-17 km b.s.l. (Ezquerro *et al.*, 2020), *i.e.*, in an intermediate  
174 location within the ~30-km-thick crust of the central Iberian Chain, although it diminishes up  
175 to ~14 km in the central part of the Valencia Trough (*e.g.* Roca and Guimerà, 1992). Ezquerro  
176 *et al.* (2020) estimate an average E-W stretching factor  $\beta=1.1$  since the formation of the  
177 Teruel basin (11.2 Ma ago), accommodated by major faults that have vertical slip between a  
178 few hundred metres and 1 km. The total vertical slip rate (considering fault throw and  
179 associated bending) shows a similar value (0.09 mm/a) for distinct transects across the Teruel  
180 half graben, but a clear increase between both extensional phases (from 0.05-0.07 mm/a to  
181 0.12-0.16 mm/a) has been reported (Ezquerro *et al.*, 2020). Slip rate increase has been  
182 attributed to: (i) onshore, westwards propagation of extensional deformation from the inner  
183 parts of the Valencia Trough, enhanced by crustal doming that would have affected the  
184 eastern Iberian Chain; (ii) change of the regional stress field, which evolved to  
185 multidirectional extension driven by a crustal doming mechanism; (iii) progressive fault  
186 linkage since the beginning of the Late Miocene, which is documented from tectono-  
187 stratigraphic information.

188 Mountains surrounding the Teruel and Jiloca basins show extensive erosion surfaces  
189 modelling Mesozoic-Palaeogene rocks and bevelling compressional structures. Two large  
190 planation surfaces, whose remnants appear at different heights either on the upthrown blocks  
191 or in the basin floors, have been traditionally defined (Gutiérrez and Peña, 1976; Peña *et al.*,  
192 1984; Sánchez-Fabre *et al.*, 2019): (i) *Intra-Miocene Erosion Surface (IES, middle Miocene)*,  
193 generally recognized in the upper part of the main reliefs, and (ii) *Fundamental Erosion*  
194 *Surface (FES, middle Pliocene)*, easily recognizable as a vast planation level at lower heights.  
195 They approximately correspond to the *Iberian Chain Surface* and the *Lower Pliocene Surface*  
196 by Pailhé (1984), and the S1 and S2 by Gutiérrez and Gracia (1997), respectively. Recent  
197 detailed studies (Simón-Porcar *et al.*, 2019; Ezquerro *et al.*, 2020) have demonstrated that the  
198 *FES* splits into three different surfaces: an Upper Sublevel, the *FES s.s.* (the most widely  
199 developed), and a Lower Sublevel. In this work, these surfaces will be called as *FES1*, *FES2*

200 and *FES3*, respectively. Based on mammal sites as well as on magnetostratigraphic  
201 constraints, the *Intra-Miocene Erosion Surface* has been dated close to the Aragonian-  
202 Vallesian limit (~11.2 Ma; Alcalá *et al.*, 2000; Ezquerro, 2017), *FES1* and *FES2* to the Late  
203 Ruscinian (both merging around ~3.8 Ma), and *FES3* to the Early Villafranchian (~3,5 Ma)  
204 (Ezquerro *et al.*, 2020).

205 Qualitative and quantitative geomorphological features of the mountain fronts and the  
206 associated piedmonts of the eastern margin of the Jiloca graben are those typical of active  
207 normal faults. At the Conclud fault, Lafuente *et al.* (2011b) described conspicuous triangular  
208 facets and short, non-incised alluvial fans, and provided a significantly low value of the  
209 mountain-front sinuosity index defined by Bull and McFadden (1977) ( $S_{mf} = 1.24$ ). At the  
210 Sierra Palomera fault, García-Lacosta (2013) described trapezoidal facets and V-shaped  
211 gullies, and provided a similar value for the sinuosity index ( $S_{mf} = 1.27$ ).

212 Historic and instrumental seismicity of the central-eastern Iberian Chain is low to  
213 moderate. In the Teruel region, the epicentres are concentrated at the Jiloca graben margins,  
214 the central-southern sector of the Teruel basin, and the Albarracín and Javalambre massifs.  
215 Apart from the Albarracín massif, epicentres can be reasonably associated to Neogene-  
216 Quaternary known faults. Measured magnitudes ( $M_b$ ) usually range from 1.5 to 3.5, with  
217 maximum  $M_b = 4.4$  in the Teruel Graben and  $M_b = 3.8$  in the Albarracín massif (data from  
218 seismic database of Instituto Geográfico Nacional, IGN:  
219 <https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>).

220

### 221 **3 Methodology**



222 The structural study is based on recognizing and mapping the main structures on aerial  
223 photographs at 1: 18,000 and 1: 33,000 scale, and satellite imagery, complemented with field  
224 surveys involving outcrop-scale observations. Data of orientation of rupture surfaces and  
225 slickenlines have been collected in a number of sites within the Sierra Palomera fault damage  
226 zone, as well as within the trench described below. Stereoplots (equal-area, lower hemisphere)  
227 of those data sets have been elaborated using Stereonet 8 software (Allmendinger *et al.*, 2012;  
228 Cardozo and Allmendinger, 2013).

229 To characterize the geometry of recent vertical deformation, the three erosional planation  
230 surfaces (*FES1*, *FES2* and *FES3*) described above were used as markers. This required  
231 mapping of erosion surfaces and morphotectonic analysis based on aerial photographs (scales  
232 1: 18,000 and 1: 33,000) and orthorectified photographs (1: 5000), as well as on digital

233 elevation models (DEM, pixel = 5 m) and the resulting hillshade images. A structural contour  
234 map of *FES2* was elaborated by interpolating the altitude of their remnants, which permits  
235 measuring vertical displacement across the main fault and hence calculating slip rate. Changes  
236 of vertical displacement along the fault zone were **inferred** from 1-km-spaced transects  
237 orthogonal to the fault trace and analysed on a **throw vs. distance (T-D) graph**.

238 **Once constrained the age of a planation surface (see Section 2), the main challenge to be**  
239 **addressed when using it as a marker is ensuring its degree of flatness, being aware of the**  
240 **degree of error involved in height treatment.** Continental planation surfaces can show gentle  
241 (short- to middle-wavelength) unevenness, or locally connect with residual, non-flattened  
242 reliefs through pediment slopes. Amplitude of their unevenness advises to use adequate  
243 spacing for **contours in order to represent its present-day geometry with the suitable precision.**  
244 Both the local difference in height between *FES2* and *FES3* and the local unevenness within  
245 each one usually lies within the range of 10-40 m. Therefore, we assume that: (i) **vertical fault**  
246 **throws** calculated from them implicitly include a maximum error bar of  $\pm 40$  m, and (ii) a 50-  
247 m-spaced contour map can be considered as reasonable for assessing recent movements (as  
248 previously proposed by Ezquerro *et al.*, 2020). Such level of uncertainty in the calculated fault  
249 throws results in errors for slip rates around 0.01 mm/a.

250 **Subsurface information was acquired by means of geophysical exploration. Two different**  
251 **techniques were utilised, which had rendered interesting results in other neighbouring sectors**  
252 **(e.g., Pueyo *et al.*, 2016): magnetometry and electromagnetic (EM) multifrequency survey.** A  
253 twofold approach was taken: first, a regional analysis by means of ten transects approximately  
254 orthogonal to the Sierra Palomera mountain front; second, a detailed analysis of a sector  
255 where the highest geophysical anomalies were identified and also where geomorphological  
256 evidences hinted at the presence of a previously unknown antithetic fault. For the  
257 magnetometry survey, a GSM-19 equipment with built-in GPS was used to measure both  
258 Earth magnetic field intensity and vertical magnetic gradient (sensors separation of 0.5 m).  
259 Diurnal correction was performed from a second, stationary, magnetometer (PMG-01) that  
260 permitted to exclude natural earth magnetic field changes during the survey and to compare  
261 the results performed during different days. Then, the regional general trend was identified  
262 and **subtracted** to highlight anomalies in the form of residual values. The EM multifrequency  
263 survey was performed by a GEM-02 device for a range of frequencies between 65 and 0.5  
264 kHz.

265 Subsoil information has been complemented with **borehole data** extensively compiled by  
266 Rubio (2004), whose synthetic results were presented by Rubio and Simón (2007). Such

267 subsoil information, together with surface geology, was used for constructing geological cross  
268 sections that have allowed characterizing the general geometry of macrostructure.

269 A trench study has been carried out following the classical methodology (see, *e.g.*,  
270 McCalpin, 1996): excavating and shoring; cleansing and gridding the most suitable wall;  
271 identifying and marking sedimentary boundaries and deformation structures; drawing a  
272 detailed log and taking photographs of each grid cell; analysing the relationship between units  
273 and faults to identify individual events; and sampling materials for dating. Sedimentary units  
274 were defined on the basis of lithology, bed geometry, texture, colour and sedimentary  
275 structures. Dating of trench samples was achieved by the Luminescence Dating Laboratory of  
276 University of Georgia, USA using the Optically Stimulated Luminescence (OSL) technique.  
277 Unfortunately, five of them were saturated samples that only provided minimum ages, which  
278 drastically decreased the consistency of the age model. Additional, preliminary OSL dating of  
279 shallow alluvial fan sediments had been achieved by Laboratorio de Datación y Radioquímica  
280 de la Universidad Autónoma de Madrid.

281 Please add some text about how displacement along faults are measured/calculated, at which  
interval are measured for which fault activity event and how/if measured values are backstripped.

#### 282 4. Structure and morphotectonics of the Sierra Palomera area

283 The NNW-SSE trending Sierra Palomera extensional fault makes the eastern boundary of  
284 the Jiloca graben at its central sector (Figs. 1b, 2). In the footwall block, Jurassic marine  
285 carbonates are unconformably covered by Paleogene continental clastic materials (Figs. 2, 3).  
286 In the western, hanging-wall block, *i.e.*, the central sector of the Jiloca basin, the sedimentary  
287 infill is made of: (i) Late Pliocene (Villafranchian) to Pleistocene alluvial and episodic  
288 palustrine deposits, all of them exposed at the land surface; (ii) an underlying carbonate unit,  
289 only observed in boreholes, that could represent an early lacustrine stage of Late Miocene-  
290 Early Pliocene age (Rubio and Simón, 2007). Isopach maps elaborated from borehole  
291 information show how the maximum thickness of the total infill approaches ~~one hundred~~  
292 metres, and its geometry is partially controlled by NW-SE to NNW-SSE striking normal  
293 faults (Rubio and Simón, 2007).

294

295

296 [PREFERENTIALLY, FIG.3 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]

297

298 The Jiloca basin runs slightly oblique to previous Paleogene, NW-SE trending folds (Fig.  
299 1b). Their hinges can be tentatively interpolated beneath the Neogene-Quaternary infilling

300 from geology of the basin margins, borehole data and hydrogeological criteria (Rubio and  
301 Simón, 2007; Rubio *et al.*, 2007). In particular, the Sierra Palomera extensional fault follows  
302 the eastern limb, nearly vertical, of an eastwards verging anticline (Fig. 3), suggesting that it  
303 could result from negative inversion of a previous reverse fault linked to that fold. Its core is  
304 represented by the Lower and Middle Triassic rocks that crop out in the neighbourhoods of  
305 Singra village, making two gentle reliefs not completely buried by the basin filling. Its  
306 periclinal closure is partially preserved close to the southern tip of Sierra Palomera fault (Fig.  
307 2).

308 The Sierra Palomera fault trace is ca. 26 km long and trends N152°E in average. The  
309 main fault surface only crops out in a few, very small exposures (1 to 4 m<sup>2</sup> in area). A number  
310 of rupture surfaces observed within the damage zone show orientations consistent with the  
311 map trend: they strike between NW-SE and N-S, and dip between 54° and 87° W (mean  
312 orientation: N155°E, 70° W; Fig. 4). Slickenlines show pitch ranging from 75°N to 70°S,  
313 therefore indicating almost pure normal movement, with mean transport direction towards  
314 N230°E.

315

316 **[PREFERENTIALLY, FIG.4 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

317

318 The Sierra Palomera fault is expressed in the landscape by a conspicuous, 20-km-long  
319 fault mountain front (Fig. 5a,b), which attains heights of 200 to 300 m above its toe, 450 to  
320 550 with respect to the bottom of the Jiloca basin. It is quite rectilinear, with a significantly  
321 low value of the sinuosity index ( $S_{mf} = 1.27$ ; García-Lacosta, 2013). A number of gullies  
322 (most of them exhibiting V-shaped transverse profiles) run across the fault scarp and delimit  
323 some well-preserved trapezoidal facets (Fig. 5c). Gullies feed short, high-slope alluvial fans  
324 (Fig. 5d) that are barely incised, only partially connected to the axial fluvial system, and  
325 exhibit signs of present-day functionality (*e.g.*, gravel aggradation affecting bush vegetation).

326

327 **[PREFERENTIALLY, FIG.5 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

328

329 The envelope of relief at the footwall block is largely represented by the *FES2* planation  
330 surface, which cuts Triassic, Jurassic and Paleogene units, and attains a maximum height of  
331 1430 m close to the edge (Fig. 6). The summit of Sierra Palomera (1533 m a.s.l.) and its  
332 surrounding area constitutes a residual relief that stands out from the *FES2* erosion level,  
333 while remains of an upper erosion sublevel (*FES1*) extend at the eastern foothills. A lower

334 sublevel (*FES3*, usually lying 10-40 m below *FES2*) is also present: (i) eastwards of Sierra  
335 Palomera, over large areas of the northern Teruel basin; (ii) northwards and southwards, at the  
336 relay zones with the Calamocha and Concud faults, respectively; and (iii) along a narrow band  
337 westwards of the Sierra Palomera divide.

338

339 **[PREFERENTIALLY, FIG.6 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

340

341 Within the sedimentary infill of the Teruel basin, these planation surfaces can be  
342 physically correlated with different coeval sedimentary horizons (lacustrine-palustrine  
343 carbonates) that were precisely characterized and dated by Ezquerro (2017) based on both  
344 paleontological and magnetostratigraphic data. As stated above, the age of *FES1* and *FES2* is  
345 constrained at about 3.8 Ma (Late Ruscinian, mammal zone MN15), while *FES3* is dated to  
346 3.5 Ma (Early Villafranchian, MN16) (Ezquerro *et al.*, 2020).

347 The height of *FES2* and *FES3* surfaces within the Jiloca depression can only be inferred  
348 indirectly. Both have been mapped at the eastern margin of the Jiloca depression, W of Santa  
349 Eulalia town, where they descend to ca. 1100 and 1050 m, respectively (Fig. 6). Then they are  
350 supposed to be covered by the Plio-Pleistocene infill, while gentle residual reliefs at the  
351 Singra-Villafranca del Campo area (made of Triassic and Jurassic rocks belonging to the core  
352 of the Sierra Palomera anticline) stand out above the depression bottom. Having in mind the  
353 morpho-sedimentary setting at the nearby Teruel basin, the subsoil data provided by Rubio  
354 and Simón (2007) for the central Jiloca basin can be used for constraining heights of those  
355 planation surfaces. In this way, the boundary between Plio-Pleistocene alluvial deposits and  
356 the underlying carbonate unit, lying at about 950 m a.s.l. in the Santa Eulalia area, could be  
357 correlated with either *FES2* or *FES3*. This piece of data will allow reasonably approaching the  
358 total tectonic offset at the Sierra Palomera fault zone since 3.8-3.5 Ma.

359 Within the Sierra Palomera block, *FES2* and its correlative Late Ruscinian carbonates of  
360 the Teruel basin systematically lose height towards east. Both are in continuity with each  
361 other and show a quite homogeneous slope of about 1.5-2% along a distance of 20 km, in  
362 which the altitude of this morpho-sedimentary marker diminishes from 1400-1430 m (central  
363 sector of Sierra Palomera) to 1090-1120 m (Alfambra area) (Fig. 6). This morphotectonic  
364 setting defines a conspicuously tilted block whose edge has undergone a tectonic uplift of  
365 about 300 m relative to the bottom of the Teruel depression, as can be visualized from  
366 structural contours in Figure 6.

367 The latter value closely approaches the topographic amplitude of the Sierra Palomera  
368 scarp itself, and also the maximum fault throw inferred from offset of the *FES2* marker. Such  
369 fault throw, and its variation along the Sierra Palomera fault, have been analysed on a series  
370 of 1-km-spaced transects across the fault trace on the contour map of Figure 6, assuming that  
371 *FES2* within the Jiloca basin coincides with the base of the Plio-Pleistocene infill. The result  
372 is shown in the throw vs. distance (T-D) graph of Figure 7, where two distinct curves depict  
373 values of (i) fault throw *s.s.*, and (ii) total tectonic offset of *FES2* between the Sierra Palomera  
374 summits and the Jiloca depression bottom (including the bending component). The T-D  
375 curves show an overall bell-shape, while exhibiting slight bimodality in detail. The maximum  
376 values, 330 m and 480 m, respectively, are found at the central sector. Considering the age of  
377 the *FES2* morpho-sedimentary marker (3.8 Ma), and assuming an average dip of 70° for the  
378 fault plane and a pure normal movement, a maximum net slip rate of 0.09 mm/a can be  
379 inferred (0.13 mm/a for the total rate between Sierra Palomera and the Jiloca bottom).

380

381 **[PREFERENTIALLY, FIG.7 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

382

383 Although the initial appearance of the Sierra Palomera fault is that of a single major  
384 rupture that accommodates the entire vertical throw, there are indications of a parallel,  
385 synthetic fault (Las Vallejadas fault) located west of the main escarpment at its southern  
386 sector (Fig. 2). Both delimit an intermediate step within the mountain front, in which *FES2*  
387 lies at an altitude of 1140-1220 m, furthermore offset (ca. 10 m) by a minor antithetic rupture  
388 (La Peñuela fault). Recent activation of both subsidiary faults is revealed by local deformation  
389 of Villafranchian alluvial deposits: (i) back tilting (up to 25°E), due to rollover kinematics,  
390 observed at the foot of the morphological escarpment of Las Vallejadas fault; (ii)  
391 accommodation monocline (dip up to 22°E) in the case of La Peñuela fault (Fig. 8; see  
392 location in Fig. 2).

393

394 **[PREFERENTIALLY, FIG.8 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

395

396

## 397 **5. Geophysical exploration of the overall Sierra Palomera piedmont**

398 Data of magnetic intensity field and vertical magnetic gradient were extensively collected  
399 along ten transects, roughly orthogonal to the Sierra Palomera fault trace and ranging from 2.0  
400 to 5.2 km in length (Fig. 9a). Spacing between successive measurement points was about 0.8

401 m. The two northernmost transects (profiles 01 and 02) and the southernmost one (profile 10)  
402 show a narrow distribution of residuals due to their lesser contrast with respect to the general,  
403 regional trend (Fig. 9b). The central transects (03 to 09) have spikes and lows that depart  
404 considerably from the general trend, and therefore, when data of the ten transects are  
405 considered as a whole, they define the range of the distribution (more specifically, profile 03  
406 has the lowest and the highest values of residual magnetic intensity). Nonetheless, transects  
407 01, 02 and 10 show a similar (albeit reduced in magnitude) outline to the rest.

408  
409 **[PREFERENTIALLY, FIG.9 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

410  
411 The magnetic and EM profiles follow a common pattern of variation of residuals,  
412 portraying three domains that broadly parallel the Sierra Palomera fault (Fig. 9b):

413 a) Closest to the fault, domain A is an area where residual values of magnetic intensity  
414 are close to zero and barely change, except for a subtle decrease to the west.

415 b) Westwards, a sharp change of attitude marks the onset of domain B, a zone of  
416 anomalies expressed as variations of residuals up to 20-30 nT over decametric distances. Such  
417 anomalies reflect the presence of small magnetic dipoles, a slightly higher mean value of  
418 Earth magnetic field, while still homogeneous values for apparent conductivity.

419 c) Finally, domain C is separated from domain B by a sharp decrease in magnetic  
420 intensity (it goes down about 100 nT) with lower relative values of Earth magnetic field,  
421 presence of a lower density of magnetic dipoles (including those of higher wavelength), and  
422 higher apparent conductivity and magnetic susceptibility.

423 In map view, Figure 9a shows the location of transects, on which the residual values of  
424 field intensity (nT) are plotted as a colour palette. The spatial correlation of the described  
425 domains on successive transects is depicted. While the boundary between A and B domains is  
426 largely evident, the northern profiles show a more direct correlation than the southern ones,  
427 where the contact progresses through a magnetic dipole.

428 The reported geophysical results (Earth magnetic field, apparent conductivity, and  
429 susceptibility) suggest the presence of a body of relatively higher susceptibility underlying  
430 domain A, which gets shallower under domain B, and gets again deeper under domain C.  
431 Boundaries between those domains are sharp and clear. This setting can be interpreted as an  
432 uplifted block (made of Paleozoic and Triassic materials belonging to the core of the Sierra  
433 Palomera anticline) bounded by faults nearly parallel to the Sierra Palomera fault trace.

434



435 **6. Detailed study at La Sima alluvial fan: linear topographic anomaly and its**  
436 **geomagnetic expression**

437 In the absence of any visible surficial rupture across Quaternary sediments of the Sierra  
438 Palomera piedmont, the need to excavate and survey a trench arose. After careful field survey  
439 in search of a suitable location for such trench, no locality could be selected on the Sierra  
440 Palomera fault trace itself, owing to non-favourable topographic, lithologic and access  
441 conditions. Our search was then focused on the surface of two of the recent alluvial fans  
442 sourced at the mountain front, at La Cecilia and La Sima areas (see location in Figs. 2 and  
443 5d). Both exhibit well-preserved alluvial fan morphology at its proximal sectors, with  
444 evidence of present-day aggradation at the apex. Shallow sand and silty sedimentary horizons  
445 in those alluvial fans have provided ages of  $28.9 \pm 2.0$  ka BP (La Cecilia) and  $19.2 \pm 1.1$  ka  
446 BP (La Sima) (see Table 1; location in Fig. 2).

447 In the middle sector of La Sima alluvial fan, a sharp NNW-SSE trending lineament is  
448 clearly visible on aerial photographs and DEM images, beyond which the fan surface is more  
449 deeply incised by the local drainage network (Fig. 10a). That lineament involves a  
450 morphological anomaly, a break in the fan slope, which becomes null or even negative up to  
451 take locally the appearance of a gentle, degraded uphill-facing scarplet (Fig. 10c). In view of  
452 these features, it came to mind the hypothesis of an antithetic fault that would have raised the  
453 middle sector of the fan with respect to the proximal one by about 2.6 m. The described  
454 lineament coincides with the boundary between domains A and B defined from geophysical  
455 results (Fig. 9b). Moreover, it is virtually prolonged towards SSE ~~up to~~ connect with the  
456 antithetic La Peñuela fault (Fig. 2).

457

458 **[PREFERENTIALLY, FIG.10 SHOULD BE INSERTED HERE AS A 1.5-COLUMN FIGURE]**

459

460 In order to test the hypothesis of an antithetic fault cutting the La Sima alluvial fan, the  
461 subsoil in the neighbourhoods of the morphological lineament was intensively explored by  
462 means of a magnetic and electromagnetic survey. Seeing at the geophysical domains  
463 described in Section 5, the lineament coincides with the A/B boundary, which is clearly  
464 expressed in the detailed map of residual magnetic anomalies shown in Figure 10b. The area  
465 east of the sharp linear, NNW-SSE trending limit clearly visible on this map shows low  
466 residual values with wide (hectometre-scale) wavelength variations. To the west, an increase  
467 of more than 30 nT is observed, as well as a decrease of more than 50 mS/m in the total

468 conductivity; moreover, the texture of the residual map changes noticeably, showing sharper  
469 magnetic dipoles of decametric wavelength.

470 The amplitude and morphology of the linear anomaly is not consistent with the  
471 susceptibility values of surficial sediments, and suggest the contrast, at shallow levels,  
472 between a high-susceptibility rock body to the west (domain B, as defined in section 5) and  
473 the domain A to the east. In addition, Figure 10b shows other NW-SE trending linear  
474 anomalies in domain B, which involve a lower contrast of magnetic field values. Both the  
475 main anomaly and the secondary ones show high gradient and sharpness of the observed  
476 dipoles, suggesting near-surface, high dipping discontinuities or rock boundaries compatible  
477 with recent faults.

478

## 479 7. Trench study at La Sima alluvial fan

480 Once verified that geophysical and topographic analysis of La Sima lineament reinforced  
481 our preliminary hypothesis about the northwards prolongation of the antithetic La Peñuela  
482 fault, we selected an easily accessible site for trench study. A 40 m long, 1.4 m wide trench  
483 was dug along a N067°E direction, roughly orthogonal to the linear anomaly. A segment of 19  
484 m on its southern wall, with depth ranging from 3.0 to 3.5 m, was logged and analysed in  
485 detail (Fig. 11a).

486

487 [PREFERENTIALLY, FIG.11 SHOULD BE INSERTED HERE IN VERTICAL IF POSSIBLE]

488

### 489 7.1. Sedimentary units

490 The materials exposed at La Sima trench essentially correspond to relatively well-bedded  
491 Pleistocene alluvial sediments (Fig. 11a). Sedimentary features indicate alternating energetic  
492 flows, sometimes flash floods, recorded by gravel channel and bar deposits, and waning  
493 discharges that settled fines over the gravel deposits. All the succession includes clear signs of  
494 calcrete development and periods of time with negligible sedimentation. Bioturbation signs  
495 and carbonate precipitation are related to pedogenesis, and suggest wetting and drying  
496 episodes of the sedimentary surface. The sedimentary succession has been subdivided into  
497 twelve lithological units (Fig. 11a):

498 - Unit 1 (up to 50 cm in thickness): Massive reddish mudstone with isolated, mm- to cm-  
499 sized angular limestone clasts (more abundant at the base), with bioturbation traces and  
500 smooth carbonate nodules.

501 - Unit 2 (25 to 55 cm): Orange massive sandy mudstone with floating angular-subangular  
502 grey limestone granules and pebbles, and some irregular cm-thick gravel bed. Grey  
503 mudstones laminae towards the top.

504 - Unit 3 (55 to 75 cm): Tabular laminated, indurated and brecciated, carbonate crust with  
505 some cm-thick interbedded silts with carbonate clasts. Carbonate fragments are smaller in the  
506 upper part; laminated fragments are less abundant towards W.

507 - Unit 4 (20 to 35 cm): Reddish massive silty sand and mudstone in a tabular level with  
508 vertical root traces filled by fine sands. Some carbonate nodules, plant remains and scattered  
509 grey, angular limestone and caliche clasts up to 10 cm in size can be recognized.

510 - Unit 5 (15 to >50 cm): Clast-supported gravel with silty to sandy matrix in a tabular,  
511 locally channelized sedimentary body with crude horizontal stratification. Gravel is made of  
512 angular-subrounded limestone clasts (up to 8 cm) and smaller caliche clasts.

513 - Unit 6 (25-55 cm): Orange to brownish massive silt and mudstone with greyish  
514 limestone angular clasts and floating whitish caliche rounded nodules (up to 2 cm). Clast  
515 content increases locally. Root traces, plant remains and organic matter patches can be  
516 recognized in the western sector.

517 - Unit 7 (30 to >150 cm): Heterogeneous unit mainly made of grain-supported gravel,  
518 locally cemented, with angular-subrounded limestone clasts (up to 15 cm in size) and caliche  
519 nodules. It includes red mudstone discontinuous intercalations, up to 20 cm in thickness, with  
520 floating cm-sized angular clasts (labelled as 7a in Fig. 11a). The overall geometry of the unit  
521 is tabular in the footwall block and channelized in the hanging-wall block. A level of calcrete  
522 gravel, >50 cm in thickness, appears at the top of this unit within the footwall block.

523 - Unit 8 (10-60 cm): Reddish silt with floating limestone angular granules and pebbles  
524 (up to 8 cm) with evidence of bioturbation.

525 - Unit 9 (45-120 cm): Grey gravel in a channeled body with limestone angular clasts (up  
526 to 12-14 cm in size) and caliche rounded clasts. Crude finning upwards cycles can be  
527 recognized. Pedogenic features increase towards the top, where brecciated limestones locally  
528 appear. It would be helpful if original, uninterpreted trench is also shown.

529 - Unit 10 (55 to 70 cm): Reddish massive silts with floating subangular limestone clasts  
530 (up to 7 cm), whitish carbonate nodules and an interbedded discontinuous clast-supported  
531 gravel level (10b) with subangular clasts up to 10 cm in size.

532 - Unit 11: Wedge-shaped body of orange and whitish massive, highly cemented silt, with  
533 carbonate floating subangular limestone clasts (up to 10 cm) and caliche clasts arranged with  
534 the A-axis subvertical.

535 - Unit 12 (20 to 50 cm): Surface regolith made of silt with angular to subangular clasts,  
536 reworked by agricultural labours.

## 537 7.2. OSL dating

538 Dating of a total of seven samples of alluvial sediments within the trench (see Fig. 11a for  
539 location) has allowed approaching their age distribution, although, unfortunately, the results  
540 show a high level of uncertainty (see Table 1). Other three collected samples did not contain  
541 enough sand grains for providing a representative dose distribution and therefore OSL dates  
542 were not reliable in this case. These samples are not located in Fig. 11a.

543 Samples S2, S3, S4, S6 and S7 have presented signal saturation, *i.e.*, their natural  
544 luminescence signal lies beyond the saturation of the OSL response with dose, making it  
545 impossible to provide adequate results. According to laboratory results, their ages should be  
546 older than 193 to 378 ka, although such figures should not be taken *sensu stricto*. Only one of  
547 the alluvial sedimentary units is directly dated: S1 provides an age  $97.4 \pm 10.2$  ka for the top of  
548 unit 9. Unit 11 (sample S5), which will be next interpreted as a fissure infill, is dated to  
549  $49.2 \pm 5.4$  ka. As a result, the chronology of unit 10, overlapping unit 9 and being cut by the  
550 fissure, can be broadly constrained between both numerical ages.

551 Without the support of further anchors, building an age model for the overall alluvial  
552 succession exposed in the trench is not feasible. In any case, the ensemble of OSL dating  
553 results and geomorphological observations in the study area suggest that: (i) most of that  
554 alluvial succession belongs to the Middle Pleistocene; (ii) a rapid decrease of sedimentation  
555 rate occurs by the Middle-Late Pleistocene transition; and (iii) sedimentation persisting in  
556 proximal and middle sectors of the alluvial fans during Late Pleistocene to present-day times  
557 only represents a small contribution to the surficial aggradation and landscape modelling.

## 558 7.3. Deformation structures

559 In a first approach, the trench log shows a main extensional fault zone at the central  
560 sector, dipping eastward and hence antithetic with respect to the Sierra Palomera fault (Fig.

561 11a), and full consistent with the uphill-facing scarplet described in section 6. The footwall  
562 block of that fault zone shows a gentle monocline, while other normal (both synthetic and  
563 antithetic) faults, cutting most of the sedimentary succession, are distributed along the entire  
564 section. The orientations of all these structures are overall consistent, as depicted in  
565 stereoplots of Fig. 11b,c,d,e.

566 The central fault zone is made of three significant structural elements: (i) Main rupture,  
567 expressed by  $\theta_1$  and  $\theta_2$  fault surfaces. (ii) Splay faults  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ , associated to the tip  
568 of the main rupture and propagated through unit 7. Both the main, westwards dipping rupture  
569 surfaces and the nearly vertical splay faults consistently strike NNW-SSE (Fig. 11b). Such  
570 structural arrangement suggests that, at certain stage of its development, the main rupture  $\theta_1$ -  
571  $\theta_2$  was covered by unit 7, and then reactivated in the form of splay faults related to refraction  
572 at the extensional tip (horse-tail structure, in the sense of Granier, 1985). (iii) Open fissure  
573 bounded by surfaces  $\theta_3$  and  $\eta$ , and filled with unit 11. The interpretation is based on its wedge  
574 shape, the massive internal structure of the infill, and the occurrence of clasts with nearly  
575 vertical A-axes. According to this interpretation, surfaces  $\theta_3$  (smooth) and  $\eta$  (more irregular)  
576 would have represented both walls of a single, also NNW-SSE striking fault, then disengaged  
577 from each other when the fissure opened up and, in the case of  $\eta$ , partially crumbled before  
578 infilling took place.

579 The footwall block is deformed by the monocline and cut by a number of NNW-SSE  
580 striking normal faults (Fig. 11c), all of them synthetic with the Sierra Palomera fault and  
581 exhibiting dip separations in the range of 10 to 20 cm (Fig. 11a). Faults  $\rho$ ,  $\pi_1$  and  $\pi_2$  cut the  
582 horizontal limb of the monocline, and have apparently kept their original, high dip. The rest of  
583 faults ( $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) appear at the hinge and the abrupt limb of the monocline. They  
584 show a progressive decrease in dip towards the east as the bedding dip increases, and some  
585 individual faults ( $\mu$ ,  $\lambda_1$ ,  $\lambda_2$ ) exhibit conspicuously arched traces, so that the angle between  
586 faults and bedding remains broadly constant (mostly within the range of 55-65°). Such  
587 geometrical setting strongly suggests that they were folded by the monocline. Concerning the  
588 relationships between faults and sedimentary units,  $\rho$  and  $\pi_1$  uniformly offset (15-20 cm) the  
589 base of units 2 to 6, while they suddenly vanish and does not affect the base of unit 7. Also  
590 fault  $\sigma$  shows similar relationships, although in this case it does not propagated through the  
591 lower units, probably detached within low-viscosity materials of unit 4. As a consequence,  $\rho$ ,  
592  $\pi_1$  and  $\sigma$  produce a noticeable thickening of unit 6 in their respective hanging-wall blocks.  
593 Faults  $\pi_2$ ,  $\tau$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) also offset rather uniformly the sedimentary boundaries, and at

594 least two of them ( $\pi_2$  and  $\mu$ ) propagated across unit 7.

595 The hanging-wall block shows two ensembles of intersecting faults that cut younger units  
596 (Fig. 11a). Individual faults show distinct offsets for different sedimentary markers, which  
597 indicates diachronic development. The  $\varepsilon_0$ - $\varepsilon_1$  couple offsets more than 1.4 m the base of unit 7,  
598 while it produces a rather uniform dip separation of 8-10 cm in the bases of units 8, 9 and 10.  
599 We should therefore interpret that  $\varepsilon_0$ - $\varepsilon_1$  underwent most of its present-date displacement ( $>1.3$   
600 m) before sedimentation of unit 8, and was then reactivated after the lower part (at least) of  
601 unit 10 was deposited. Splaying from  $\varepsilon_1$ , fault  $\varepsilon_2$  cuts units 7 and 8, and is covered by unit 9,  
602 while  $\varepsilon_3$  cuts the base of unit 9, thus making the three faults a footwall rupture sequence. The  
603 antithetic  $\varepsilon_4$  propagated up to the lower unit 10. At the easternmost trench sector we find a  
604 similar pattern in the NNW-SSE striking faults  $\alpha$  and  $\beta$ . Fault  $\beta$  offsets more than 0.7 m the  
605 base of unit 7, while (together with its splay faults  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ ) produces a smaller separation  
606 (0.4 m) in the bases of units 8 and 9. We interpret that  $\beta$  underwent displacement  $\approx 0.3$  m  
607 before sedimentation of unit 8, and was then reactivated after deposition of unit 9. Fault  $\alpha$   
608 propagated through unit 7, previous to sedimentation of unit 8, and did not undergo further  
609 reactivation.

610 We should emphasize the strict consistence of orientations of the described structures. All  
611 faults systematically strike NNW-SSE (Fig. 11e), and so does the limb of the monocline (Fig.  
612 11c). There is no doubt that the latter is (i) genetically linked to faults, and (ii) responsible for  
613 the decrease in dip of faults  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Bedding and fault surfaces are rotated around a  
614 common, well-defined horizontal axis ca. N160°E (Fig. 11c). Strikes of minor fractures  
615 measured along the trench are also clustered around NNW-SSE, although a small number  
616 among them are oriented NNE-SSW (in blue in Fig. 11d). A brief discussion about the  
617 dynamic framework (stress fields) in which such fault and fracture pattern developed will be  
618 made in Section 7.6.

#### 619 **7.4. Evolutionary model: deformation events**

620 According to the former structural description, in particular to the relationships between  
621 structures themselves and with the sedimentary units, we propose the evolutionary model  
622 explained below, tested by means of careful retrodeformation analysis (Fig. 12). The  
623 evolution has been conventionally divided into a succession of “deformation events”,  
624 following the common practice in paleoseismological reconstruction. Several post-event  
625 sedimentary stages have been also included for better understanding.

626

627 [PREFERENTIALLY, FIG.12 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]

628

629 A number of identifiable faults were either formed, propagated or reactivated during each  
630 deformation event (Fig. 12 and Table 2). Dip separation directly measured on the trench log is  
631 taken as the first approach to the net slip on each fault, since: (i) bedding is roughly  
632 horizontal, (ii) the trench, oriented N067°E, is nearly orthogonal to the prevailing strike of  
633 faults, and (iii) the only kinematical indicator observed during trench survey (slickenlines  
634 with pitch 82°S on fault  $\mu$ ), as well as those collected at the Sierra Palomera fault zone itself  
635 (see Fig. 4b), suggest nearly pure normal movement for the overall extensional fault system.  
636 A precision of 5 cm has been adopted for net slip measurements; those that are synthetic to  
637 the Sierra Palomera fault (downthrown block to the west) are compiled as positive in Table 2,  
638 while those antithetic are compiled as negative.

639 Below we summarize the main features of each of the seven deformation events (T to Z)  
640 distinguished in the La Sima trench (Fig. 12):

641 - **Event T:** Slip on faults  $\rho$ ,  $\pi_1$ ,  $\tau$  and  $\sigma$  after deposition of unit 6 and previous to unit 7.

642 Accumulated net slip: +45 cm.

643 - **Event U:** Slip on faults  $\pi_2$ ,  $\tau$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$ ,  $\lambda_2$  and  $\varepsilon_1$ , subsequent or coeval with deposition of  
644 the lower part of unit 7. Accumulated net slip: +110 cm.

645 - **Event V:** Slip on fault  $\theta_2$ , subsequent to deposition of lower unit 7, then covered by  
646 upper unit 7. Development of the monocline begins; according to our progressive deformation  
647 model depicted in Fig. 12, in which the main rupture had always propagated through units 1  
648 to 6, this monocline should be interpreted as a drag fold. Net slip: -5 cm.

649 - **Event W:** Reactivation of the main, central fault through the rupture surfaces  $\theta_1$ - $\theta_2$ ,  
650 which propagates across upper unit 7 splitting into  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ . Progress of the  
651 monocline produces rotation of faults  $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Slip on faults  $\varepsilon_0$ - $\varepsilon_1$ ,  $\alpha$  and  $\beta$ , all of  
652 them subsequent to top of unit 7 and previous to unit 8. Accumulated net slip: +100 -105 = -5  
653 cm.

654 - **Event X:** Propagation of the main fault zones,  $\theta$  and  $\varepsilon$ , through new rupture surfaces:  
655  $\theta_2$ - $\theta_3$  and  $\varepsilon_2$ , respectively. Both are younger than unit 8 and older than unit 9. Accumulated  
656 net slip: +05 -95 = -90 cm.

657 - **Event Y:** Activation of fault  $\varepsilon_3$ , and propagation of  $\beta$  splitting into  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ . Both  
658 processes are subsequent to deposition of unit 9 and probably previous to unit 10, therefore  
659 close to (or slightly younger than) the numerical age provided by sample S1 ( $97.4 \pm 10.2$  ka).  
660 Accumulated net slip:  $-40$  cm.

661 - **Event Z:** Formation of fault  $\varepsilon_4$  and propagation of  $\varepsilon_1$  cutting the lower part of unit 10.  
662 Slip on  $\theta_2$  that **massively activates** the  $\theta_3$  surface with extensional component, giving rise to an  
663 open fissure (from fault  $\eta$ ) that tears apart units 7 to 10 and is subsequently filled with unit 11.  
664 This event should be dated just prior to the numerical age provided by sample S5 ( $49.2 \pm 5.4$   
665 ka). Accumulated net slip:  $+10 - 135 = -125$  cm.

666

## 667 **8. Overall interpretation and discussion**

### 668 **8.1. Geometry and kinematics of macrostructures**

669 **We have seen** how geophysical results reported in Section 5, defining three adjacent,  
670 NNW-SSE trending elongated domains (A, B, C) suggest the existence of an uplifted block  
671 bounded by faults nearly parallel to the Sierra Palomera fault trace. At the southern sector of  
672 the study area, local coincidence of the A/B and B/C domain boundaries with La Peñuela and  
673 Las Vallejadas faults, respectively, strongly supports such interpretation. The antithetic  
674 rupture exposed in La Sima trench unequivocally represents that map-scale antithetic La  
675 Peñuela fault and corroborates the extensional character of such structure. In this way, the  
676 results of subsoil exploration by geophysical methods and trench survey allow refining the  
677 structural model of the central Jiloca graben, *i.e.*, deformation style of the hanging-wall block  
678 of the Sierra Palomera fault. These new inferred faults separating domains A, B and C have  
679 been incorporated to the geological map of Fig. 2.

680 The Sierra Palomera fault probably resulted from negative inversion, during the Late  
681 Pliocene-Quaternary extensional phase, of a previous contractive structure developed under  
682 the Paleogene-Early Miocene compression. Such origin is suggested by its spatial coincidence  
683 with the eastern, nearly vertical limb of an eastwards verging anticline. Evidence of the same  
684 inversion setting has been described for the other master faults bounding the Jiloca graben,  
685 namely the Conclud fault (Lafuente *et al.*, 2011a) and the Calamocha fault (Liesa *et al.*, 2021).

686 The attitude of the main fault surface is N155°E, 70° W in average, while most ruptures  
687 visible along and close to it are systematically parallel to it. The fault shows pure normal  
688 movement, with mean transport direction towards N230°E. These features are similar to those



689 of the Concud and Calamocha faults, the other structures that make the eastern boundary of  
690 the Jiloca graben. In particular, the average transport direction of those faults is N220°E  
691 (Lafuente *et al.*, 2014) and W to SW (Martín-Bello *et al.*, 2014), respectively, thus jointly  
692 making a geometrically and kinematically consistent major extensional fault system.

693 Two wide right relay zones separate the Sierra Palomera fault from the Calamocha and  
694 Concud faults. The dominant trend of recent, extensional faults and fractures distributed  
695 within both relay zones is similar to that of the main fault or slightly deviates to approach the  
696 N-S direction. Close to the southern tip, such fractures mainly affect Upper Miocene and  
697 Villafranchian sediments, while close to the northern tip they cut Jurassic carbonates giving  
698 rise to narrow N-S trending grabens filled with Pleistocene alluvial sediments (Capote *et al.*,  
699 1981). These relay zones dominated by along-strike fractures were described in detail and  
700 interpreted by Peiro *et al.* (2019, 2020) with the help of analogue modelling. Fracturing in this  
701 new type of fault relay is controlled by both the structural inherited grain and the remote  
702 stress field, and efficiently contribute to slip transfer and dynamical interaction between  
703 adjacent faults. It strongly contrasts with the classical models reported in the literature (*e.g.*,  
704 Peacock and Sanderson, 1994; Young *et al.*, 2001; Fossen and Rotevatn, 2016), in which  
705 transverse connecting faults controlled by the own relay kinematics prevail. According to  
706 Peiro *et al.* (2020), the overall fault system at the eastern boundary of the Jiloca basin is at an  
707 intermediate stage between complete independence and coalescence, and will probably evolve  
708 to an along-strike propagation of the master faults through the distributed longitudinal fracture  
709 ensembles. The slightly bimodal throw vs. distance (T-D) curve depicted in Fig. 7 suggests  
710 that the Sierra Palomera fault itself resulted from coalescence of two distinct fault segments,  
711 although their overall bell-shape indicates full linkage between them. Moreover, the  
712 persistence of an important bending component beyond both tips of the fault trace reveals that  
713 the total length of the Sierra Palomera fault is larger than that exposed at the surface, thus  
714 being propagated towards NNW and SSE as a blind fault.

715 Geophysical and morphotectonic data have allowed characterizing the overall structure of  
716 the hanging-wall block beyond the apparently flat appearance of the Sierra Palomera  
717 pediment. We have explained (sections 5 and 6) how magnetic field linear anomalies parallel  
718 to the Sierra Palomera fault trace suggest a distribution of subsoil lithological domains  
719 consistent with a gentle horst-and-graben setting.

720 The most conspicuous linear anomaly coincides with a morphological lineament (a gentle  
721 uphill-facing scarplet) across the middle sector of La Sima alluvial fan (section 6), and with  
722 the uphill-facing fault scarp east of Las Vallejadas fault. The hypothesis that all of these

723 elements represent an antithetic fault has been corroborated by the exposure of that antithetic  
724 rupture in La Sima trench. In summary, the available information reveals a more complex  
725 structure in the Sierra Palomera hanging-wall block than the one assumed so far, including: (i)  
726 a synthetic fault, located at about 1.5 km basinwards, which at its southern sector emerges at  
727 surface (Las Vallejadas fault); (ii) a recent antithetic fault, at a distance of 0.7-1.0 km, which  
728 would have displaced the surface of the La Sima alluvial fan and would extend southwards up  
729 to La Peñuela fault.

730 In order to depict the refined structural model of the Sierra Palomera hanging-wall block,  
731 both faults have been incorporated to the geological map of Figure 2, as well as to a new  
732 version of the cross section (Fig. 13a). Furthermore, the latter depicts a reinterpretation of the  
733 geometry of the master fault. It is known that the shape of the main fault surface strongly  
734 controls the style of accommodation folding and subsidiary faulting in the hanging-wall block  
735 of extensional faults. Rollover folds and antithetic faults develop above concave-upward fault  
736 bends, whereas drag folds and synthetic faults form above convex-upward fault bends, their  
737 propagation being facilitated by high curvature of such fault bends (McClay and Scott, 1991;  
738 Xiao and Suppe, 1992; Withjack *et al.*, 1995; Delogkos *et al.*, 2020). In our case, the  
739 occurrence of the antithetic and the synthetic inferred subsidiary faults strongly suggests the  
740 presence, at a depth of less than 1 km, of a relative flat in the main fault surface (*i.e.*, a double,  
741 convex-concave bend), probably located at the Middle-Upper Triassic lutite and evaporite  
742 units (Middle Muschelkalk and Keuper facies).

743

744 [PREFERENTIALLY, FIG.13 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]

745

## 746 **8.2. Planation surfaces as structural markers: inferred offsets and slip rates**

747 In contrast to the other master faults bounding the Jiloca graben, namely the Calamocha  
748 and Conclud faults, no dated stratigraphic marker is available at the Sierra Palomera fault in  
749 order to precisely calculate its total offset and slip rate. In such context, the use of planation  
750 surfaces (in our case, the mid-Pliocene *FES2* and *FES3* surfaces; Fig 13b) is necessary for  
751 characterizing the macrostructure and measuring fault throws. As explained in Section 4, fault  
752 throw *s.s.* and total tectonic offset of *FES2* at the Sierra Palomera graben margin attain  
753 maximum values of 330 m and 480 m, respectively, resulting in slip rates of 0.09 and 0.13  
754 mm/a.

755 We should draw attention to the fact that our main geomorphological marker, *FES2*, is

756 poorly represented within the Jiloca bottom, *i.e.*, the hanging-all block of the Sierra Palomera  
757 fault, which makes difficult to calculate the actual throw. We interpret that the boundary  
758 between Plio-Pleistocene alluvial deposits and the underlying carbonate unit probably  
759 represents the first approach to the position of *FES2* (Fig. 13b), although it also could be  
760 correlated with *FES3*. According to the results provided by Ezquerro *et al.* (2020), such  
761 uncertainty introduces a potential error of either 10-40 m in the height of the marker  
762 (equivalent to the thickness of Villafranchian palustrine carbonates  $\approx$  M8 megasequence of  
763 Ezquerro, 2017), or 0.3 Ma in its age. If the top of the buried carbonate unit would be Early  
764 Villafranchian in age (3.5 Ma, therefore correlative of *FES3*): (i) the fault throw *s.s.* and the  
765 total tectonic offset calculated in section 4 (330 m and 480 m, respectively) should be applied  
766 to a 3.5 Ma time span, therefore resulting in slightly higher slip rates (0.10 *vs.* 0.09 mm/a,  
767 0.15 *vs.* 0.13 mm/a, respectively); (ii) *FES2* would lie 10-40 m lower within the downthrown  
768 block, and hence the fault throw *s.s.* and the maximum total tectonic offset could increase up  
769 to 370 m and 520 m, respectively, giving rise to slip rates of 0.10 and 0.15 mm/a for the last  
770 3.8 Ma. In any case, such height uncertainty is of the same order as the unevenness of the  
771 planation surfaces themselves, and results in a very small error in slip rate (0.01-0.02 mm/a).

772 The consistency of this interpretation is further reinforced if a broader morphotectonic  
773 perspective is adopted, considering the whole setting of footwall and hanging-wall blocks of  
774 the Sierra Palomera fault and neighbouring structures. We have explained how the morpho-  
775 sedimentary *FES2* marker defines a tilted Sierra Palomera-Alfambra block whose edge is  
776 tectonically uplifted ca. 300 m relative to the bottom of the Teruel basin. A similar  
777 morphostructural outline can be drawn for the Sierra de Albarracín-Jiloca block, in which  
778 *FES2* shows a progressive eastwards decrease in altitude, from 1400-1500 m to <1100 m.  
779 Therefore, the inference that the fault separating such tilted blocks has a throw in the range of  
780 300-400 m seems well-founded. On the other hand, the notion of recent vertical displacement  
781 on the Sierra Palomera fault being larger than those on Calamocha and Conclud faults (210  
782 and 260 m, respectively; Martín-Bello *et al.*, 2014; Ezquerro *et al.*, 2020) fits a common  
783 structural feature of segmented extensional fault zones, in which maximum throws are found  
784 in central segments (self-similar pattern as that of individual faults; Cowie and Roberts,  
785 2001). Gracia *et al.* (2003) aimed to minimize the role of tectonic subsidence in benefit of  
786 erosional lowering in the development of the central Jiloca depression, and hence to  
787 underestimate the throw of the Sierra Palomera fault (see further discussion by Rubio and  
788 Simón, 2007; Rubio *et al.*, 2007; Gracia *et al.*, 2008). Nevertheless, such controversy is  
789 currently out of place.

790 It is also pertinent to compare the displacement and slip rates on the Sierra Palomera fault  
791 with those in the neighbouring Teruel graben. During the last 3.8 Ma (Late Pliocene-  
792 Quaternary extensional phase), fault zones making the eastern margin of the Teruel basin  
793 underwent total vertical displacement (including bending component) in the range of 440 to  
794 620 m, and hence long-term vertical slip rates of 0.12 to 0.16 mm/a (Ezquerro *et al.*, 2020).  
795 Assuming an average dip of 70° for the fault plane and a pure normal movement, the resulting  
796 total net slip rates for this period are 0.13 to 0.17 mm/a, similar to that calculated for the  
797 Sierra Palomera fault (0.15 mm/a) and higher than those for the Conclud (0.07-0.08 mm/a;  
798 Lafuente *et al.*, 2011a), Calamocha (0.06-0.09 mm/a; Martín-Bello *et al.*, 2014), and Teruel  
799 (0.075 mm/a; Simón *et al.*, 2017) faults.

### 800 **8.3. Geomorphic indices of the mountain front: assessing fault activity**

801 Geomorphic indices constitute an auxiliary tool for assessing fault activity, as enhanced  
802 by, *e.g.*, Bull and McFadden (1977), McCalpin (1996), Silva *et al.* (2003), or Burbank and  
803 Anderson (2012). With this respect, it is interesting to compare the values proposed for the  
804 Sierra Palomera mountain front with those of other faults in the same geodynamic framework.

805 At Sierra Palomera, García-Lacosta (2013) calculated values of two significant  
806 geomorphic indices defined by Bull and McFadden (1977), *i.e.*, mountain-front sinuosity ( $S_{mf}$ )  
807 ), and valley width/height ratio ( $V_f$ ). The value of  $S_{mf}$  is 1.27. The average width/height ratio  
808 calculated for 10 gullies crossing the fault is  $V_f = 0.22$  (measured 250 m upstream from the  
809 fault trace). These values, together with other mentioned qualitative attributes of the mountain  
810 front (trapezoidal facets, V-shaped gullies, small alluvial fans not connected to the regional  
811 fluvial system), indicate ‘rapid’ fault slip according to the classification by McCalpin (1996),  
812 and ‘active’ (according to Silva *et al.*, 2003) (Fig. 14). The range of slip rates that those  
813 authors estimate for such categories in their respective classifications (0.08 to 0.5 mm/a)  
814 encloses the value calculated for our fault from offset of the *FES2* marker (0.09-0.13 mm/a).

815

816 **[PREFERENTIALLY, FIG.14 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

817

818 The sinuosity index  $S_{mf}$  at the Sierra Palomera mountain front is very similar to that at the  
819 Conclud fault ( $S_{mf} = 1.24$ ; Lafuente *et al.*, 2011b), and to those calculated by Perea (2006) for  
820 twenty fault-generated mountain fronts at the Maestrat grabens, eastern Iberian Chain ( $S_{mf} =$   
821 1.04-1.60; mean = 1.27). They also resemble those obtained at well-known active faults of the

822 Betic Chains (SE Spain), such as the Carboneras, Lorca-Alhama or Baza faults, in which  $S_{mf}$   
823 usually ranges from 1.05 to 1.4 (Silva *et al.*, 2003; García-Tortosa *et al.*, 2008).

824 The average value of the  $V_f$  index computed at a distance of 250 m upstream from the  
825 Sierra Palomera fault trace ( $V_f = 0.22$ ) does not differ very much from that of the Concul fault  
826 ( $V_f = 0.30$ ; Lafuente *et al.*, 2011b), while higher and more variable values have been reported  
827 in the Maestrat grabens ( $V_f = 0.12-1.5$ ; Perea, 2006), and Betic Chains: Baza fault ( $V_f = 0.28-$   
828  $0.86$ ; García-Tortosa *et al.*, 2008); Carboneras and Lorca-Alhama faults (0.38 to 0.59; Silva *et*  
829 *al.*, 2003).

830 Plotting  $S_{mf}$  vs.  $V_f$  values on the diagram proposed by Silva *et al.* (2003) allows us  
831 assessing the relative position of the Sierra Palomera fault among extensional fault-generated  
832 mountain fronts of eastern Spain (Fig. 14). The relatively low values of both  $S_{mf}$  and  $V_f$  indices  
833 found at the Sierra Palomera mountain front (1.27 and 0.22, respectively) represent a  
834 morphotectonic signal similar to that of the Concul fault, and also consistent with extensional  
835 faults studied by Silva *et al.* (2003) in the Valencia area and Betic Chains, which draw the  
836 tendency curve plotted in Fig. 14. The position of our geomorphic indices on that diagram: (i)  
837 demonstrates that the Sierra Palomera fault fits the same tendency, and (ii) corroborates that it  
838 lies within Class 1 (active).

#### 839 ***8.4. Pleistocene fault activity and paleoseismological relevance***

840 Although morphotectonic data indicate that the Sierra Palomera fault has a significant  
841 degree of activity, no outcrop observation on the main trace has unequivocally evidenced its  
842 Quaternary activity. Therefore, it is very relevant the finding, in La Sima trench, of  
843 Pleistocene faults that accommodate extensional deformation associated to the hanging-wall  
844 rollover, since they indirectly confirm, for the first time, Pleistocene activity of the main fault.

845 As explained in section 6.4, seven deformation events (T to Z) have been recognized after  
846 detailed trench analysis, which could be conventionally considered as paleoseismic events  
847 according to usual criteria in Paleoseismology. Individual faults activated in each event have  
848 been recognized; their displacements have been quantified (individual net slip in the range of  
849 5 to 125 cm; mean = 28 cm; Table 2), and the overall faulting history has been carefully  
850 reconstructed by means of retrodeformational analysis (Fig. 12). Nevertheless, we should  
851 critically admit that the meaning of these results in relation to paleoseismicity of the Sierra  
852 Palomera fault is very imprecise, since:

853 (i) Instead of crossing the main fault, the trench only represents a short transect within the  
854 hanging-wall block, at a distance of 1.0 km from the Sierra Palomera fault trace.

855 (ii) During each event, faults widely distributed along the surveyed transect underwent  
856 both synthetic slip with Sierra Palomera fault (downthrown block to the west; positive values  
857 in Table 2) and antithetic slip (negative). The algebraic sum of those values has no meaning in  
858 relation to the real slip on the main fault.

859 (iii) The poor quality of OSL results precludes us from having an age model of the  
860 exposed sedimentary succession; therefore, the age constraints of the individual events are  
861 very limited. Only the last two events, Y and Z, could be dated to ca.  $97\pm 10$  ka and  $49\pm 5$  ka,  
862 respectively.

863 Concerning net slip accumulated by faults (see Table 2): (i) the first two events (T and U)  
864 involve significant synthetic slip (+45 and +110 cm, respectively); (ii) for V and W, synthetic  
865 and antithetic movements almost counterbalanced each other; (iii) the last three events (X, Y,  
866 Z) involve significant antithetic slip (-90, -40 and -125 cm, respectively). The cumulative  
867 global fault slip, -110 cm, considering an average fault dip of  $65^\circ$ , represents an antithetic  
868 throw of ca. 100 cm. We should add the vertical offset accommodated as continuous  
869 deformation in the bending monocline (amplitude: ca. 120 cm), not included when computing  
870 fault slip *s.s.* The total tectonic, antithetic throw at the transect should be therefore estimated  
871 at 220 cm (net slip  $\approx$  230 cm). This value reasonably approaches the total throw (190 cm) that  
872 can be directly measured from offset of the top of unit 6 (youngest sedimentary marker  
873 previous to the recorded faulting episodes). It is also consistent with the apparent height of the  
874 gentle uphill-facing scarp that breaks the natural slope of La Sima alluvial fan (260 cm;  
875 Fig. 10c). In summary, the morphological expression of the fault zone exposed in the trench  
876 fits well the antithetic sign of the displacements during the most recent faulting episodes.

877 The youngest, antithetic faulting events have associated net slip values (40 to 125 cm)  
878 that should be accommodated on faults several km long (11 to 23 km, according to the  
879 empirical relationships proposed by Wells and Coppersmith, 1994). This inference plays in  
880 favour of: (i) the interpretation of the antithetic fault exposed at La Sima trench as a large  
881 structure, comparable in length to the Sierra Palomera fault itself, as the macrostructural and  
882 geophysical data suggested (see section 7.1); (ii) the notion that faulting events recorded at the  
883 trench, in particular those dated to ca.  $97\pm 10$  ka and  $49\pm 5$  ka, very probably respond to  
884 coseismic slip events on the main fault.

885 Could the timing of those younger events be taken as a reference for approaching seismic  
886 recurrence periods and slip rates of the Sierra Palomera fault during Pleistocene times? This is  
887 a very difficult question to answer from the available information. The tempting hypothesis  
888 that the two aforementioned ages correspond to the last two major paleoearthquakes would

889 suggest a single interseismic period of around 48 ka. According to the empirical relationship  
890 by Villamor and Berryman (1999), such a recurrence period is reliable for faults moving at an  
891 average slip rate around 0.1 mm/a; therefore, it fits well the long-term slip rate estimated for  
892 the Sierra Palomera fault (in the range of 0.09 to 0.15 mm/a).

893 Nevertheless, we do not consider this as the most reliable scenario. The space and time  
894 window examined in our trench is too narrow for providing a representative  
895 paleoseismological record. Subsidiary faults similar to those exposed at La Sima could have  
896 form at other sites within the hanging-wall block in response to other slip events on the Sierra  
897 Palomera fault. Furthermore, each slip event on this main fault did not necessarily reactivate  
898 the antithetical fault exposed at La Sima trench. Accordingly, the actual slip rate on **the main**  
899 **fault** during Late Pleistocene times could be significantly higher than the long-term one, as  
900 evinced in other active faults of the region. Slip rate increased during Late Pleistocene times  
901 with respect to its average value since Late Pliocene times in the most documented structures  
902 south of Sierra Palomera: the Conclud fault (0.29 vs. 0.07-0.08 mm/a) and Teruel fault (0.19  
903 vs. 0.07 mm/a) (Lafuente *et al.*, 2014; Simón *et al.*, 2016, 2017). The same tendency has been  
904 revealed for other large faults of the neighbouring Teruel basin (Ezquerro *et al.*, 2020; see  
905 Section 2) and Calatayud basin (Peiro and Simón, 2021). We therefore consider that the Sierra  
906 Palomera fault, larger than the Conclud and Teruel faults, very probably underwent a slip rate  
907 higher than 0.09-0.15 mm/a, and an average recurrence period shorter than 48 ka, since Late  
908 Pleistocene time.

909 With this respect, the estimation of short-term slip rate that can be made for the antithetic  
910 La Peñuela fault from offset of Unit 9 in the studied trench is irrelevant. The top of that unit is  
911 dated to  $97.4 \pm 10.2$  ka, and has been displaced by the last two deformation events defined (Y  
912 and Z), totalizing a cumulative antithetic net slip of 165 cm. This results in a slip rate of  
913 0.015-0.019 mm/a, which only reflects the local deformation rate on a subsidiary fault for a  
914 very narrow, non-representative time window.

#### 915 ***8.5. Internal deformation of the hanging-wall fault block: a close look from trench*** 916 ***analysis***

917 Although the succession of deformation events identified at La Sima trench have a very  
918 limited paleoseismic meaning, it allows understanding progressive stretching within the  
919 hanging-wall block of the Sierra Palomera fault. In particular, sequential activation of  
920 synthetic and antithetic individual faults has been carefully reconstructed by means of  
921 retrodeformation analysis (Fig. 12) and can be precisely compared with faulting patterns  
922 observed in published analogue models and field examples of rollover deformation.

923 Usually, the hanging-wall rollover geometry is not entirely achieved through continuous  
924 deformation. Examples from analogue models (e.g., Withjack and Schlische, 2006), outcrops  
925 and high-resolution seismic profiles (e.g., Song and Cawood, 2001; Delogkos *et al.*, 2020)  
926 indicate that a portion of the hanging-wall deformation is accommodated by smaller-scale  
927 faults. Antithetic faults directly materialize the antithetic simple shear band that nucleates at  
928 the transition zone from the main ramp to the basal detachment (Withjack *et al.*, 1995).  
929 Therefore, they occur above, and frequently abutting, the connection line between the steep  
930 and flat segments of the main fault surface (Bruce, 1973; Song and Cawood, 2001; Withjack  
931 and Schlische, 2006). In addition, together with subsidiary synthetic faults, they can  
932 accommodate layer-parallel extension along the rollover. Such extension mainly operates at  
933 the hinge zone of the rollover, giving rise to crestral collapse grabens that are well documented  
934 from both analogue models (e.g., McClay, 1990; McClay and Scott, 1991; Buchanan and  
935 McClay, 1991; Soto *et al.*, 2007) and field examples (e.g., Imber *et al.*, 2003; Fazlikhani *et*  
936 *al.*, 2017).

937 The locus of active hanging-wall antithetic faulting, as well as that of crestral graben  
938 formation, have the appearance of having migrated landwards during development of  
939 extensional systems. Each individual antithetic fault (or fault fan) forms near the fault bend,  
940 moves passively within the hanging-wall block beyond the fault bend, and becomes  
941 inactive, while a new fault zone propagating from the same fault bend replaces it. Thus,  
942 secondary faults tend to be progressively older basinwards (Christiansen, 1983; McClay,  
943 1990; Withjack *et al.*, 1995; Withjack and Schlische, 2006). That tendency can be enhanced  
944 by repeated footwall collapse (footwall faulting sequence) at the main structure (Imber *et al.*,  
945 2003).

946 In any case, such overall time polarity of hanging-wall growth faults does not exclude  
947 significant overlap in their periods of activity (Imber *et al.*, 2003), as well as variations in the  
948 relative occurrence of synthetic and antithetic faults. The great majority of analogue models  
949 of rollovers show a faulting sequence that begins with an antithetic fault, then alternating  
950 synthetic and antithetic ones eventually joining and reciprocally offsetting at depth (McClay,  
951 1990; McClay *et al.*, 1991; T. Román-Berdiel, personal communication). Nevertheless,  
952 sandbox experiments have been reported in which alternating activation of synthetic and  
953 antithetic faults is initiated with a synthetic one (e.g., Buchanan and McClay, 1991).

954 The fault sequence interpreted at La Sima trench share some of the former evolutionary  
955 patterns typical of rollover deformation: (i) relevance and persistence of a subsidiary  
956 antithetic fault; (ii) activation of additional, younger antithetic ruptures closer to the main



957 fault; (iii) overall alternating onset of synthetic and antithetic ruptures. On the other hand, we  
958 have found a non-typical feature: the oldest recorded meso-scale faults are synthetic with the  
959 Sierra Palomera fault, despite having formed in the same area where the persistent antithetic  
960 fault will later appear. The first two deformational events (T and U) involve accumulation of  
961 significant synthetic slip (+155 cm), while in the following two (V and W) synthetic and  
962 antithetic movements almost counterbalanced each other, and the last three ones (X, Y, Z)  
963 involve substantial antithetic slip (-255 cm). Such “irregularity” suggests the existence of  
964 other controls on the hanging-wall deformation in addition to the rollover kinematics itself.

965 On the other hand, the accumulated net slip has an associated component of horizontal  
966 extension that enables another quantitative kinematical approach (see Table 2). The total  
967 extension recorded at La Sima trench is  $\approx 385$  cm, which represents about 20% of the total  
968 logged transect (local  $\beta$  factor = 1.2). The antithetic faults accommodate much more  
969 extension (200 cm) than the synthetic ones (115 cm). Considering that the bending monocline  
970 represents additional antithetic offset, it also involves additional horizontal extension, which  
971 can be estimated at 70 cm assuming a fault dip of  $65^\circ$ . Two main events (W, equally  
972 represented by synthetic and antithetic faults, and Z, mostly antithetic) accumulate about one  
973 half of the total extension (85 cm, ca. 4.5%, each one).

#### 974 **8.6. Stress regime and tectonic framework**

975 Geometry and kinematics of faults exposed in the trench, as well as of those inferred at a  
976 macrostructural scale from surface mapping and geophysical exploration, overall fits the  
977 expected deformation within the hanging-wall block of the Sierra Palomera fault. But, at the  
978 same time, it is also consistent with the regional extensional stress field, whose  $\sigma_3$  trajectories  
979 trend ENE-WSW (Simón, 1982, 1989; Arlegui *et al.*, 2005, 2006; Liesa *et al.*, 2019),  
980 orthogonal to the overall trend of the Jiloca graben, and only slightly oblique to the Sierra  
981 Palomera fault trace itself. Stress inversion from the most representative, non-rotated  
982 conjugate faults measured within the trench, according to Anderson’s model, provides local  
983 stress axes matching those regional trajectories (Fig. 15).

984

985 **[PREFERENTIALLY, FIG.15 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

986

987 It is not easy to discriminate whether the faults propagated through the hanging-wall  
988 block are kinematically or dynamically controlled, *i.e.*, they essentially accommodate  
989 extensional deformation associated to the rollover monocline, or they are directly linked to

990 regional stress conditions. The extension direction expectable for the first scenario could be  
991 constrained between N065°E (orthogonal to the average strike of the Sierra Palomera fault; an  
992 inherited feature indeed) and N050°E (transport direction). The extension trend expectable for  
993 the second scenario would approach N075°E (seeing at the average trend of the Jiloca  
994 graben), or would range from N055°E to N080°E (seeing at paleostress results reported by  
995 Arlegui *et al.*, 2005, and Liesa *et al.*, 2019). The similarity between both inferences prevents  
996 us from discriminating among those hypothetical controls based solely on the orientation of  
997 structures (stereoplots of Fig. 11 show how the strongly clustered directions of normal faults  
998 in La Sima trench fit equally well the two scenarios). Nevertheless, some details of the  
999 faulting succession suggest that both controls probably coexist. The kinematical control has  
1000 been attested and discussed in sections 8.1 and 8.5. The dynamical one could explain the early  
1001 occurrence of synthetic meso-scale fault at La Sima site.

1002 Additionally, the imprint of the regional stress field is revealed by certain fracture  
1003 features directly linked to characteristic heterogeneities of the extensional Plio-Quaternary  
1004 stress field in the eastern Iberian Chain. First, under the biaxial or multidirectional extension  
1005 regime characterizing such stress field, a strong tendency for the  $\sigma_2$  and  $\sigma_3$  axes to switch  
1006 typically results in secondary faults striking at right angles to the master faults (Simón *et al.*,  
1007 1988; Simón, 1989; Arlegui *et al.* 2005, 2006). Second, both E-W to ESE-WNW, and ENE-  
1008 WSW extension directions (characterizing the Late Miocene-Early Pliocene and the Plio-  
1009 Quaternary rift episodes, respectively) are recorded during the entire extensional period  
1010 indeed (Liesa *et al.*, 2019), suggesting stress partitioning (in the sense of Simón *et al.*, 2008)  
1011 of the composite extensional field that results from combination of intraplate NNW-SSE  
1012 compression (Africa-Iberia convergence) and WNW-ESE extension (rifting of the Valencia  
1013 trough) (Simón, 1989; Herraiz *et al.*, 2000; Capote *et al.*, 2002). Fractures observed at La  
1014 Sima trench only reveal the second type of stress heterogeneity. There is no orthogonal fault  
1015 or fracture, and hence no evidence of permutation of  $\sigma_2$  and  $\sigma_3$  axes. Nevertheless, a minority  
1016 NNE-SSW trending set can be distinguished among fractures that do not show any sign of  
1017 displacement (Fig. 11e), which records the WNW-ESE extensional component of the  
1018 regional, locally and episodically partitioned stress field.

1019

## 1020 9. Conclusions

1021 1) The NNW-SSE trending, 26 km long Sierra Palomera extensional fault probably  
1022 resulted from negative inversion of a previous contractive structure developed under the

1023 Paleogene-Early Miocene compression of the Iberian Chain.

1024 2) The Sierra Palomera extensional fault has been active during Late Pliocene-Quaternary  
1025 times. It has undergone nearly pure normal movement with mean transport direction towards  
1026 N230°E, consistent with the ENE-WSW extension trajectories of the recent to present-day  
1027 regional stress field.

1028 3) Magnetic and electromagnetic profiles, together with local geological and  
1029 geomorphological evidence, suggest that the hanging-wall block of the Sierra Palomera fault  
1030 is cut by two subsidiary parallel ruptures: (i) the synthetic Las Vallejadas fault, located at  
1031 about 1.5 km basinwards, and (ii) the antithetic La Peñuela fault, at a distance of 0.7-1.0 km,  
1032 which apparently offsets the surface of the La Sima alluvial fan giving rise to a gentle uphill-  
1033 facing scarplet.

1034 4) In the absence of recent stratigraphic markers visible in the both fault blocks, the *FES2*  
1035 planation surface (3.8 Ma) has constituted a useful marker for estimating the extensional net  
1036 slip on the main fault. The corresponding contour map has allowed calculating a maximum  
1037 value of 330 m for the fault throw *s.s.*, and 480 m for the total tectonic offset at the graben  
1038 margin (including the bending component). Assuming an average dip of 70° for the fault  
1039 plane and a pure normal movement, a net slip rate of 0.09 mm/a is inferred (0.13 mm/a  
1040 including bending). Based on the natural unevenness of the *FES2* marker, the error bar for the  
1041 calculated throws and net slip values is  $\pm 40$  m, which results in errors for slip rates around  
1042 0.01 mm/a.

1043 5) The Sierra Palomera fault is expressed in the landscape by a conspicuous fault  
1044 mountain front. Qualitative geomorphological features (trapezoidal facets; V-shaped gullies;  
1045 small, steep alluvial fans not fully connected to the axial drainage), as well as values of  
1046 geomorphic indices, are consistent with a significant degree of recent fault activity.

1047 6) Trench study has demonstrated the existence of the above-mentioned antithetic  
1048 subsidiary fault, accompanied by a number of minor synthetic and antithetic ones. Their  
1049 detailed kinematical analysis has allowed building an evolutionary model made of seven  
1050 deformation events recorded in Middle-Late Pleistocene alluvial deposits. Net slip on  
1051 individual faults ranges from 5 to 125 cm (mean = 28 cm). The cumulative global throw at the  
1052 antithetic fault zone, including fault slip *s.s.* and bending, is estimated at 220 cm, which  
1053 reasonably approaches the apparent offset of the natural slope of La Sima alluvial fan at the  
1054 uphill-facing scarplet (260 cm).

1055 7) Unfortunately, it was not feasible to achieve a consistent age model for the entire

1056 sedimentary sequence, since the majority of samples dated by Optically Stimulated  
1057 Luminescence (OSL) presented signal saturation. Only the last two deformation events have  
1058 been dated to ca.  $97\pm 10$  ka and  $49\pm 5$  ka, respectively. In addition, the surveyed trench only  
1059 represents a short transect within the hanging-wall block, not across the main fault itself, so  
1060 that its paleoseismic significance is limited. Nevertheless, it is worth highlighting the fact that,  
1061 for the first time, Pleistocene activity of the Sierra Palomera fault has been unequivocally  
1062 (although indirectly) proved from outcrop observation.

1063 8) Despite its poor paleoseismic meaning, the succession of faulting events identified at  
1064 La Sima allows unravelling the extensional deformation mechanisms within the hanging-wall  
1065 block of the Sierra Palomera fault. The total horizontal extension recorded at La Sima trench  
1066 is  $\approx 385$  cm (local  $\beta$  factor = 1.2). The evolutionary model built from retrodeformation  
1067 analysis indicates that synthetic slip prevailing in early deformation events was gradually  
1068 substituted by antithetic slip, the latter being clearly predominant during the younger ones.  
1069 Geometry and sequential development of meso-scale faults suggest the concurrence of: (1) a  
1070 kinematic control, *i.e.*, antithetic simple shear linked to rollover kinematics (mostly resulting  
1071 in the main antithetic fault zone), eventually accompanied by layer-parallel extension  
1072 orthogonal to the rollover axis, and (2) a dynamic control, *i.e.*, response to the regional stress  
1073 field.

1074

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1085

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1087

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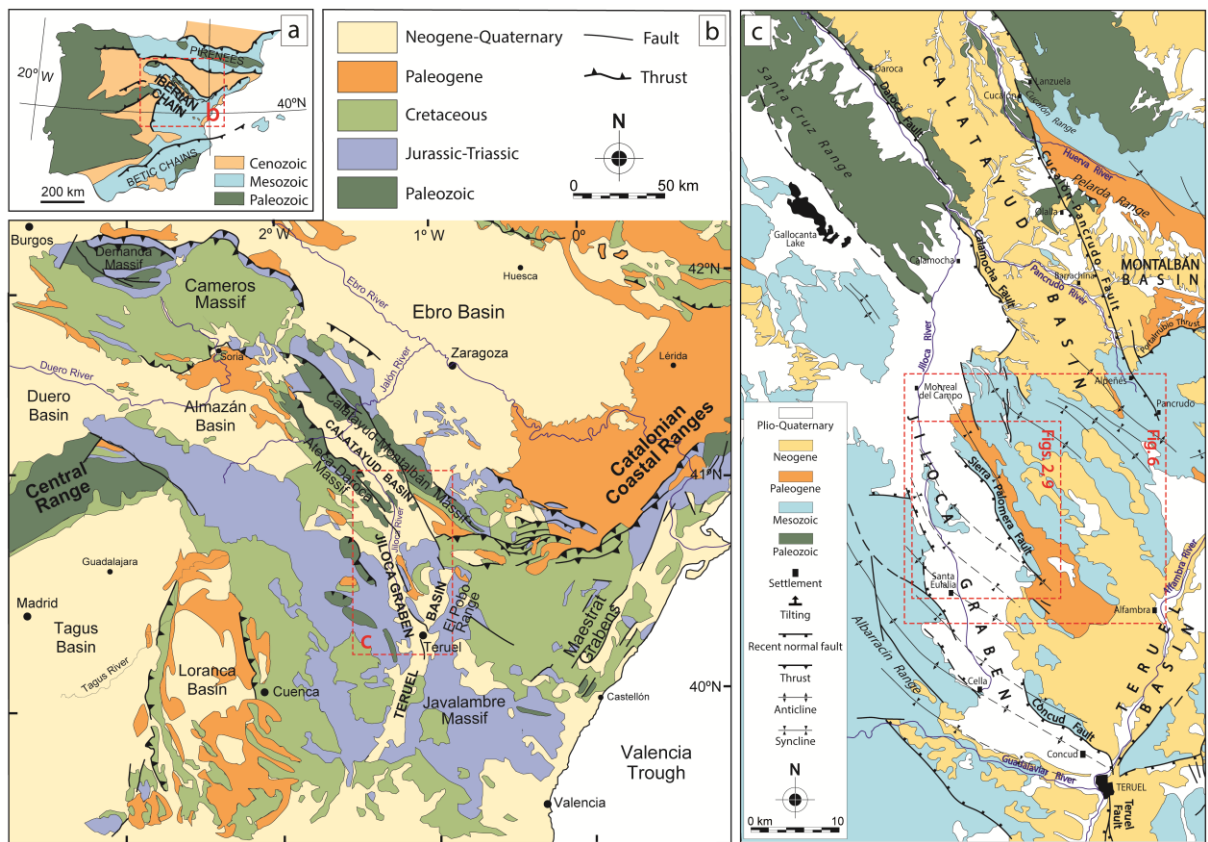
1361 The authors declare that they have no known competing financial interests or personal  
1362 relationships that could have appeared to influence the work reported in this paper.

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1364 FIGURES AND FIGURE CAPTIONS:

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1366 **Figure 1:**



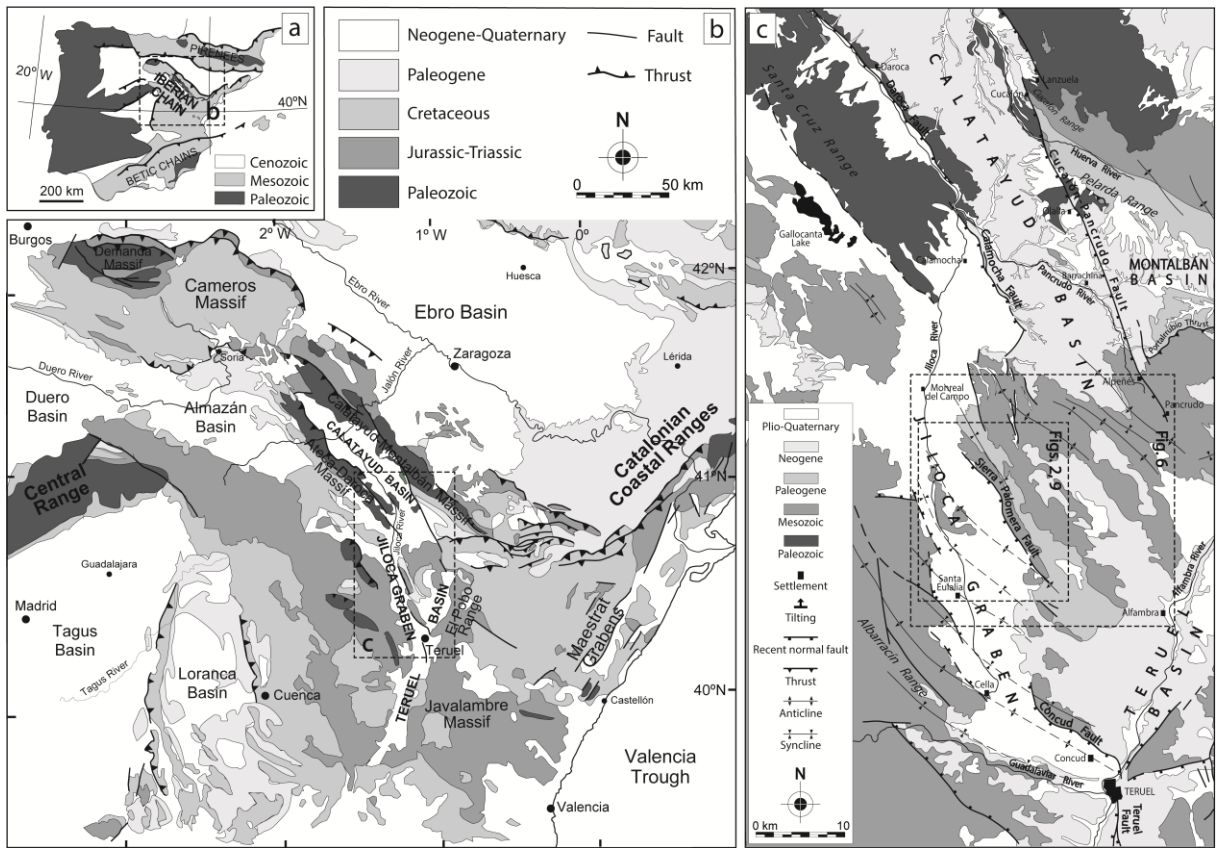
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1389 **Figure 1:**

1390 (a) Location of the Iberian Chain within the Iberian Peninsula. (b) Geological sketch of the Iberian  
1391 Chain, with location of the main Neogene-Quaternary extensional basins. (c) Simplified geological  
1392 map of the Jiloca graben, with location of Figures 2, 6 and 9.

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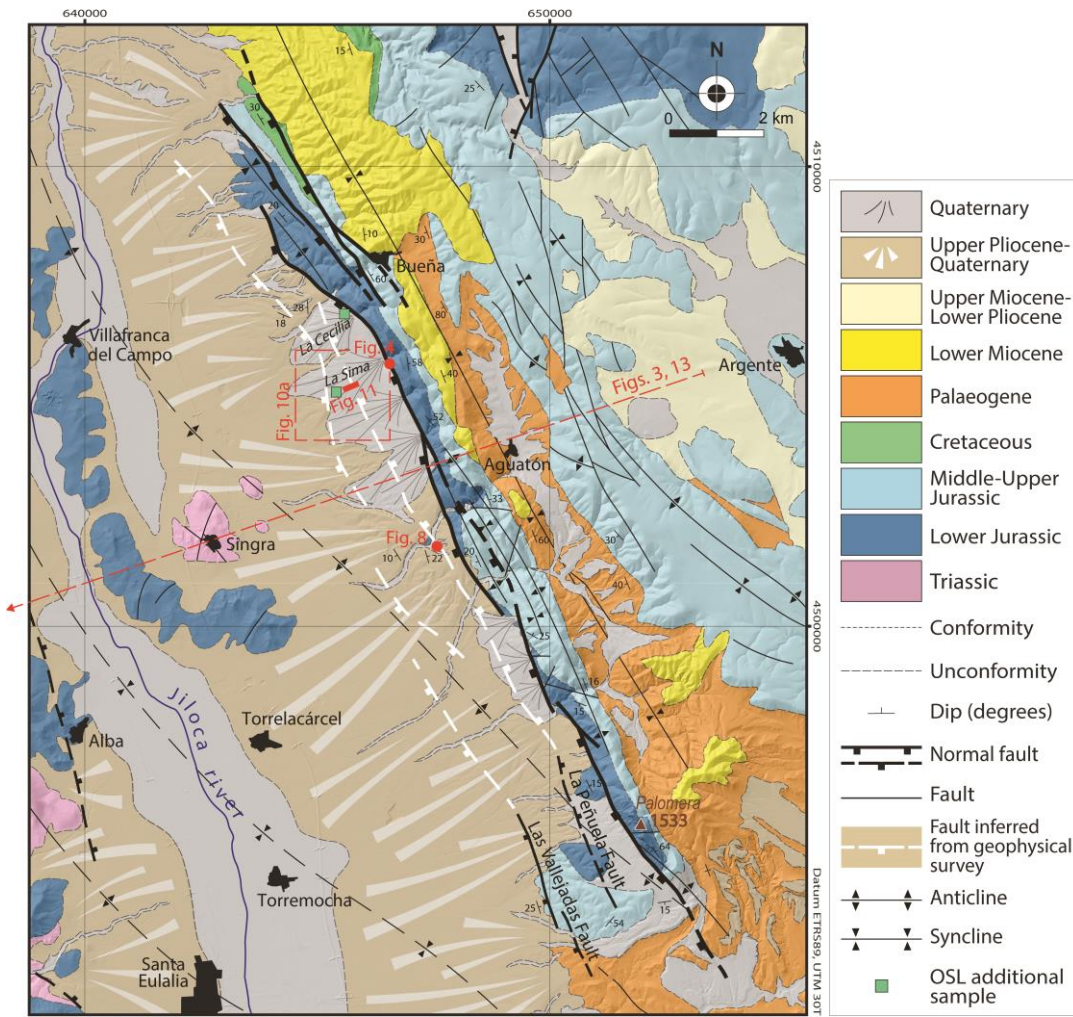
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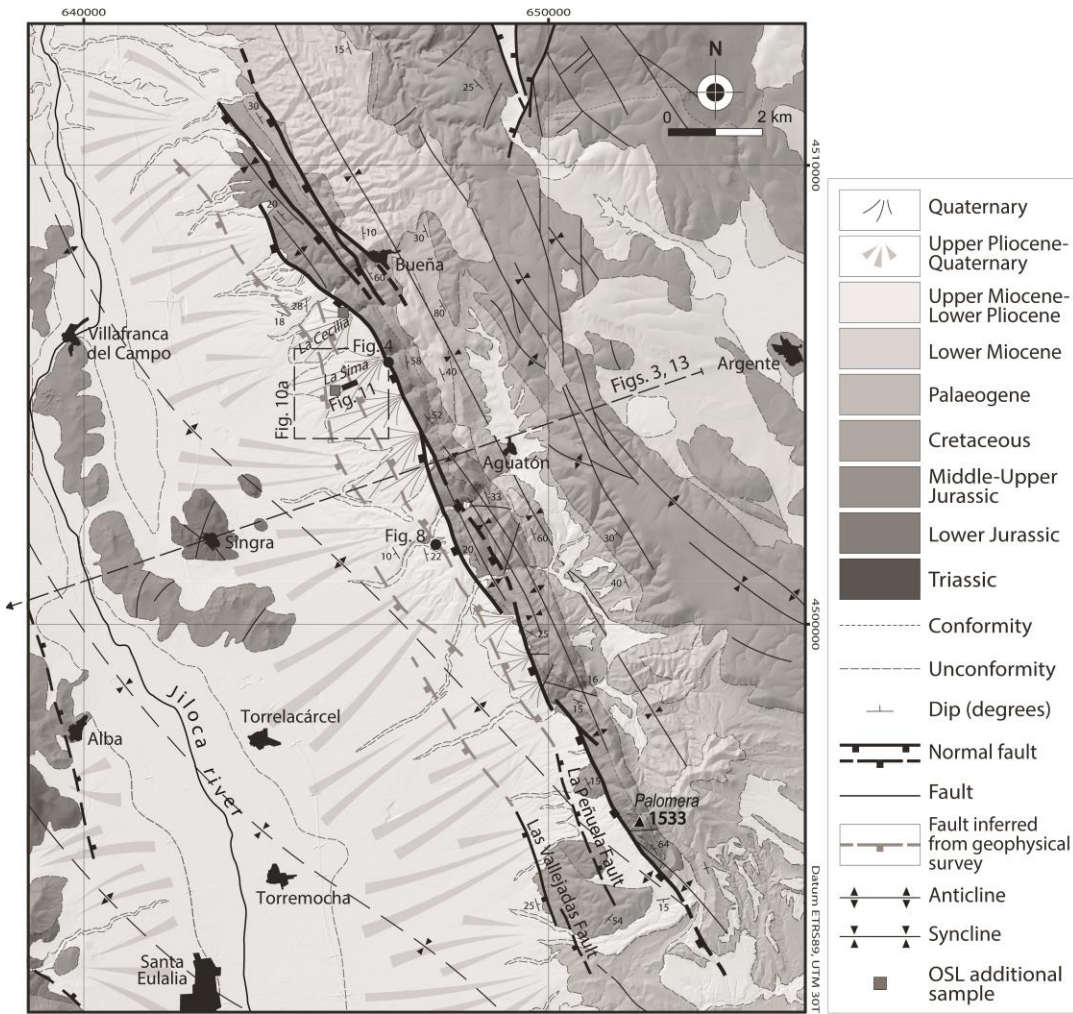
1418 **Figure 2:**



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1437 **Figure 2:**

1438 Geological map of the Sierra Palomera area (on DEM image from Instituto Geográfico Nacional)  
1439 showing the main structures associated to the Sierra Palomera fault. Location of Figures 3, 4, 8, 10a,  
1440 11 is indicated, as well as that of OSL samples in La Cecilia and La Sima alluvial fans (see Table 1).

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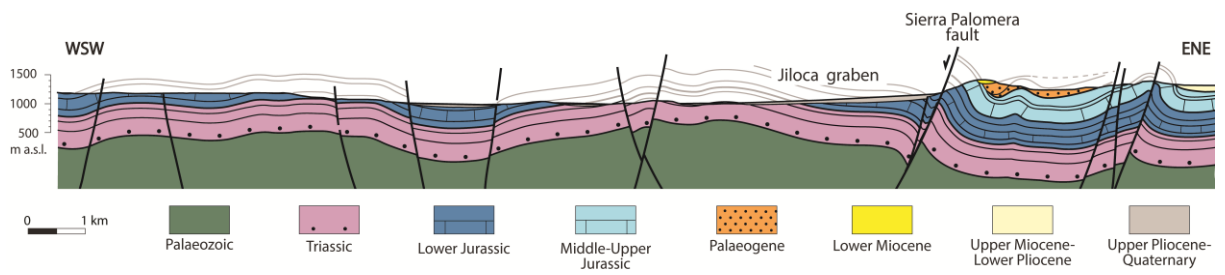
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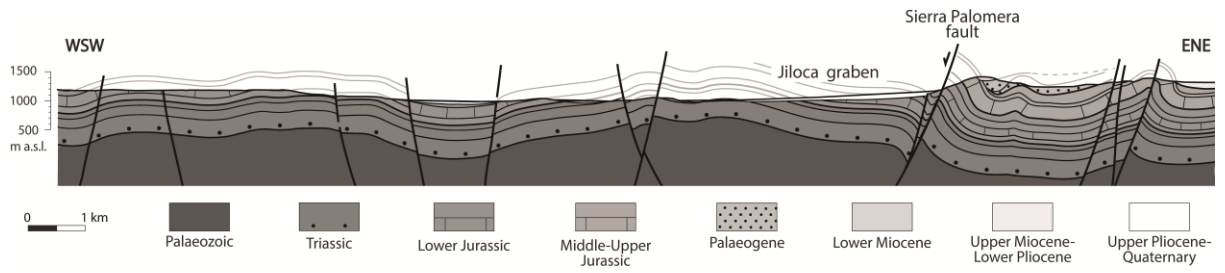
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1466 **Figure 3:**



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1488 **Figure 3:**

1489 Cross section of the Jiloca Graben at its central sector, initially reconstructed from surface geology and  
1490 shallow borehole data (modified from Rubio and Simón, 2007). See location in Figure 2.

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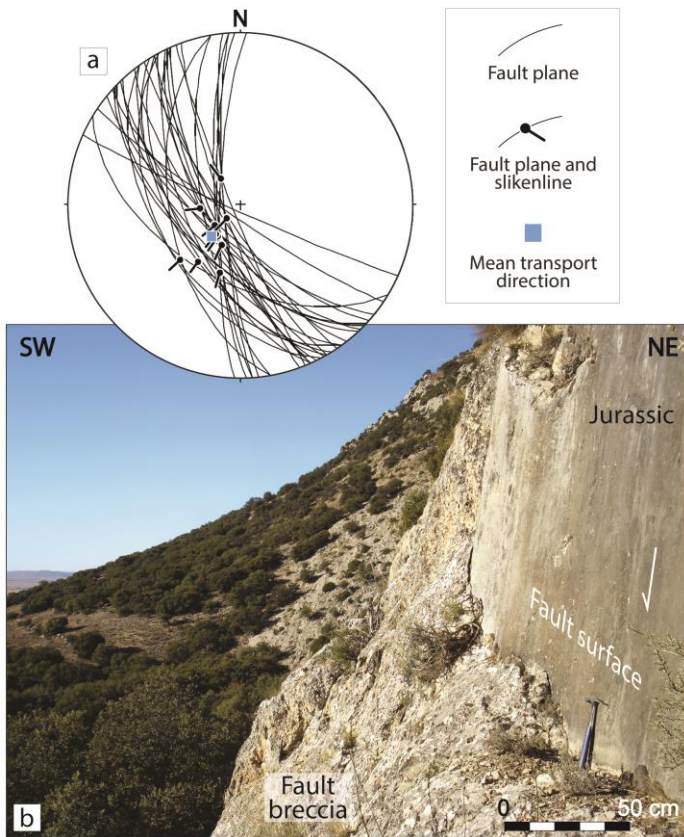
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1517 **Figure 4:**

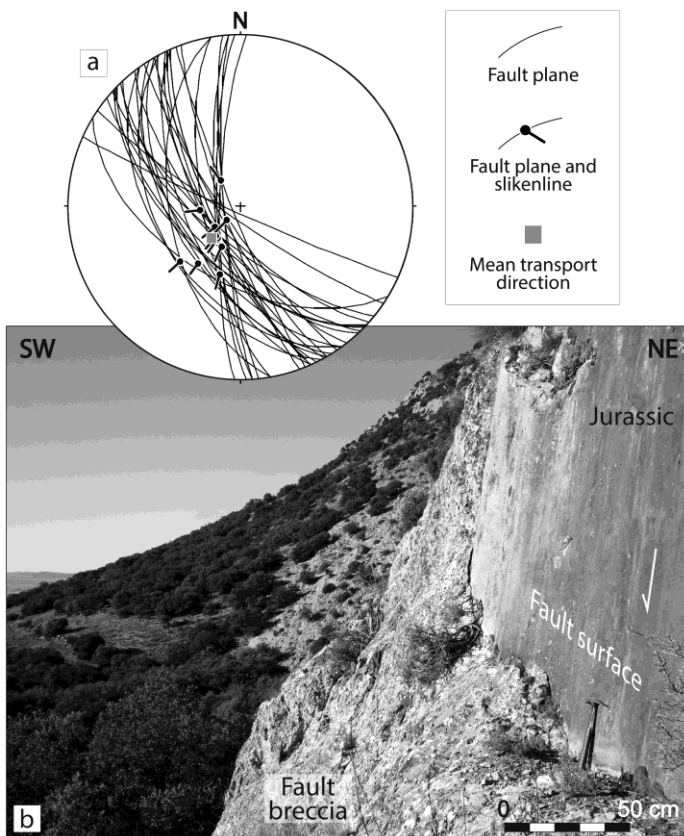


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1523 **Figure 4:**

1524 (a) Field view of one of the rupture surfaces within the damage zone of the Sierra Palomera fault; it  
1525 cuts Lower Jurassic limestones and shows associated fault breccia. (b) Stereoplot (equal area, lower  
1526 hemisphere) showing orientations of fault planes and slickenlines collected in that zone.

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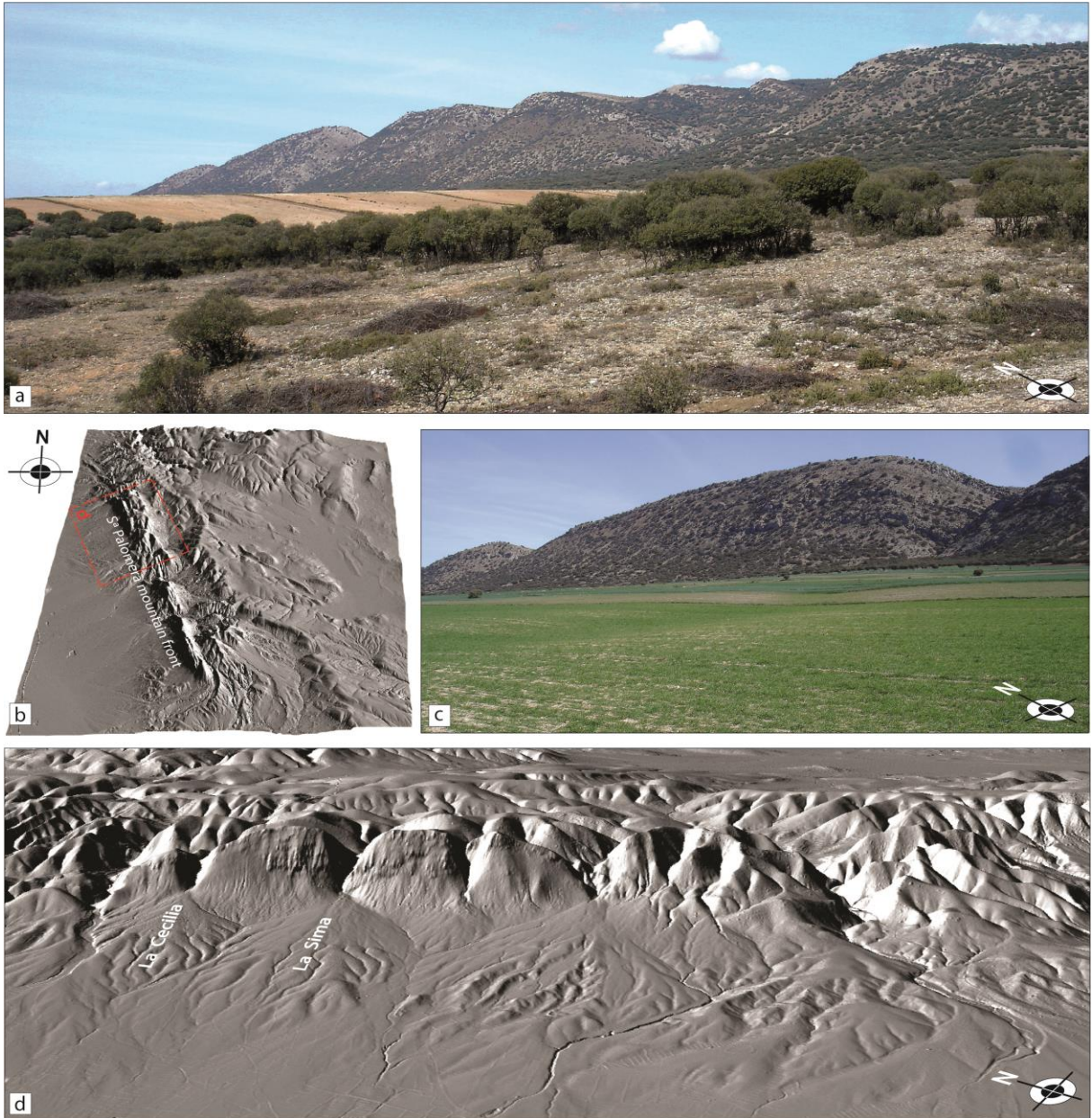
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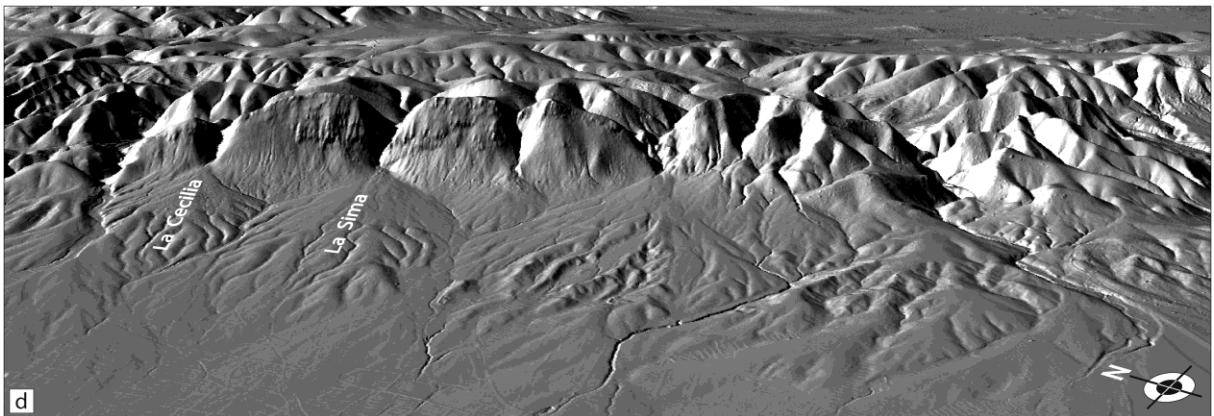
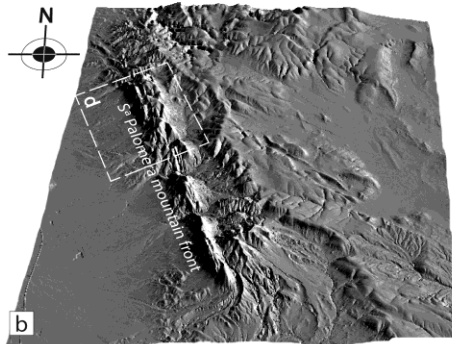
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1552 **Figure 5:**



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1578 **Figure 5:**

1579 The Sierra Palomera mountain front. (a) Field panoramic view. (b) Hillshade oblique image rendered  
1580 from Digital Elevation Model (5 m grid) of Instituto Geográfico Nacional (IGN). (c) Detail of a  
1581 trapezoidal facet within the fault scarp. (d) Hillshade oblique image (5-m-grid DEM, IGN) showing a  
1582 close view to the alluvial fans sourced at the mountain front; La Cecilia and La Sima alluvial fans are  
1583 identified.

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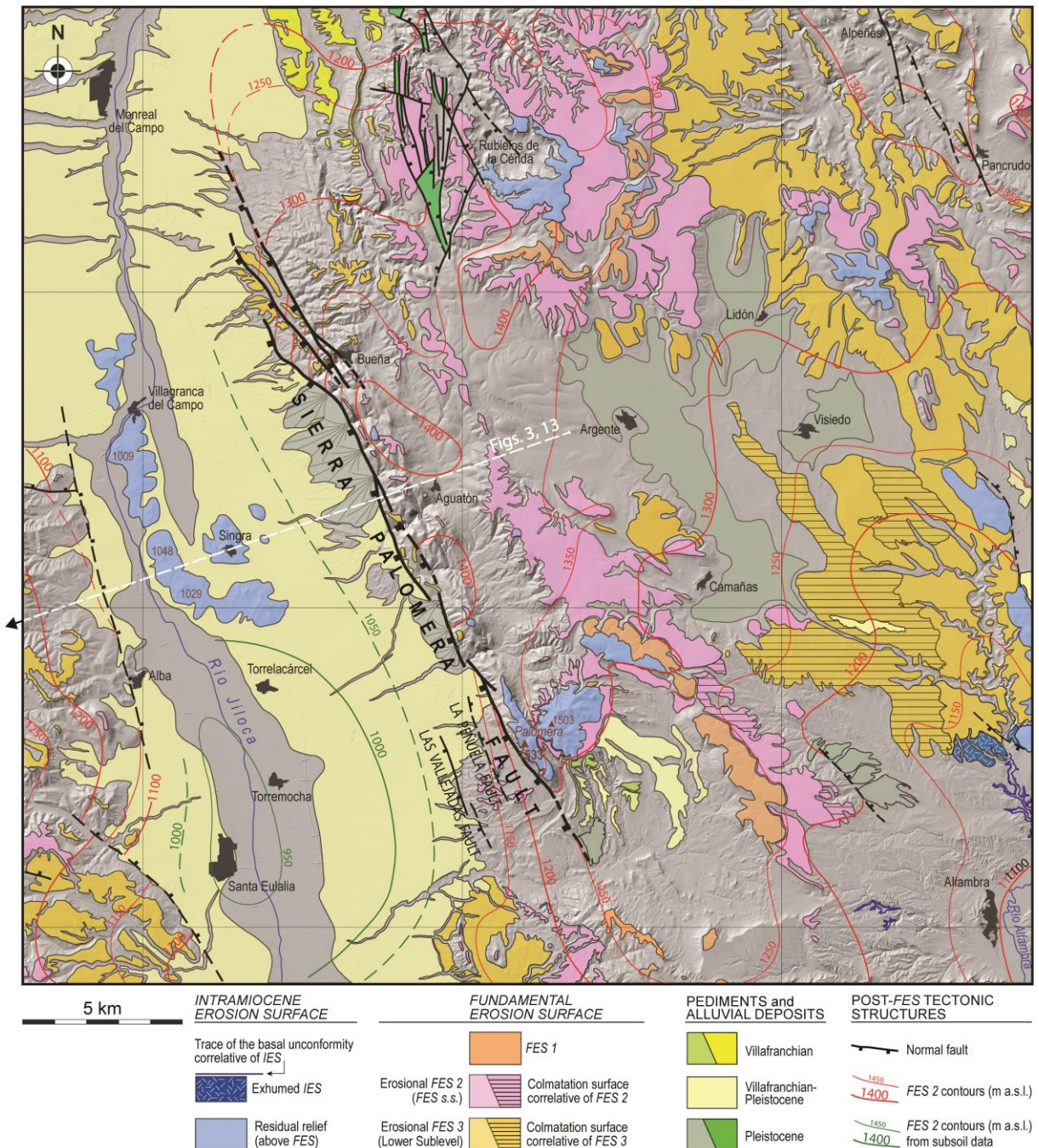
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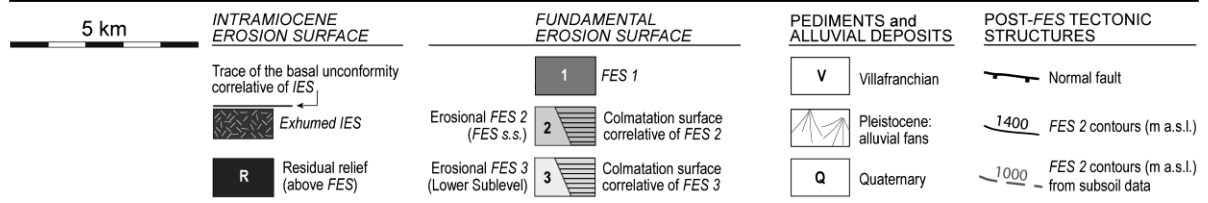
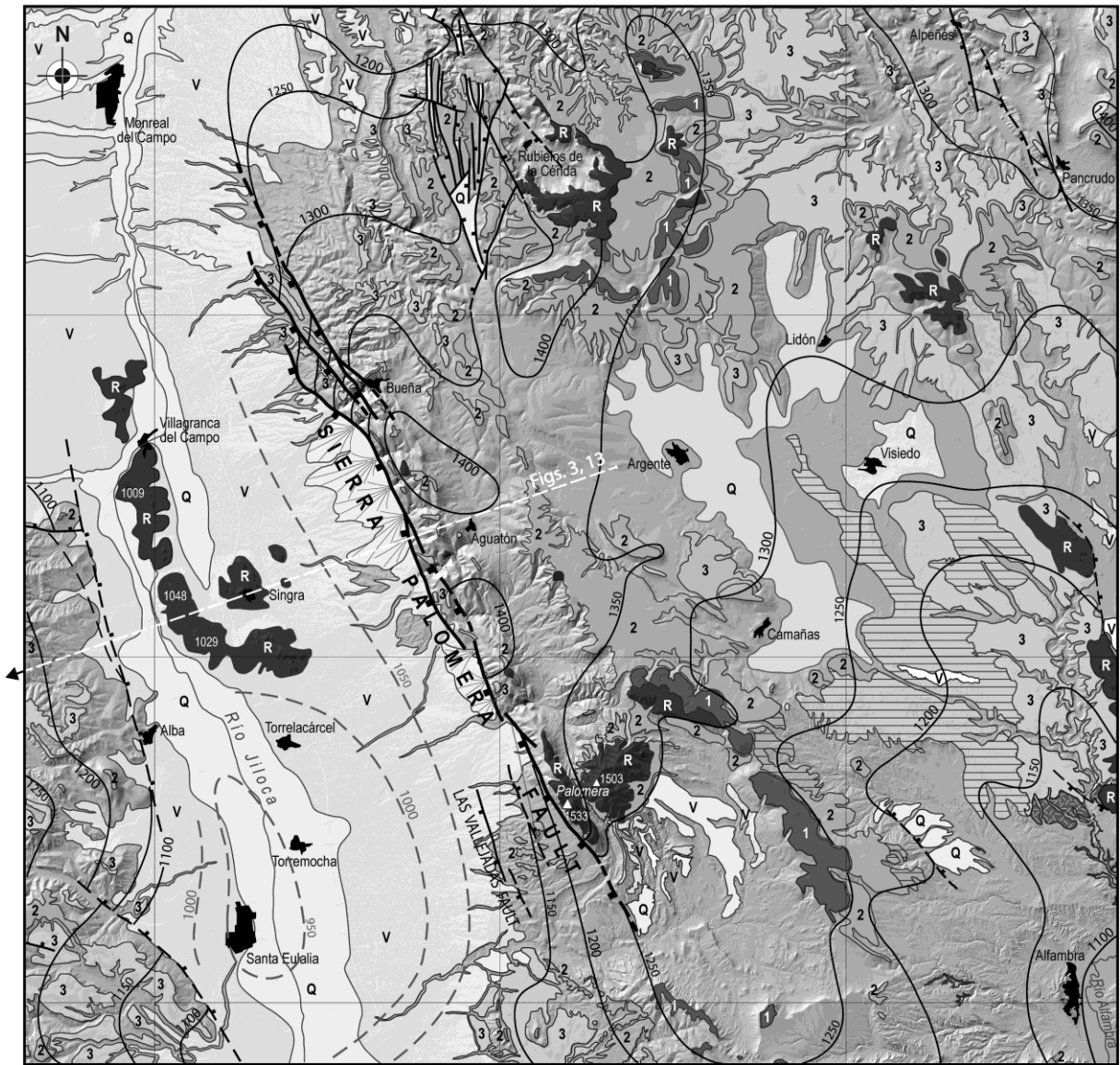
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1608 **Figure 6:**



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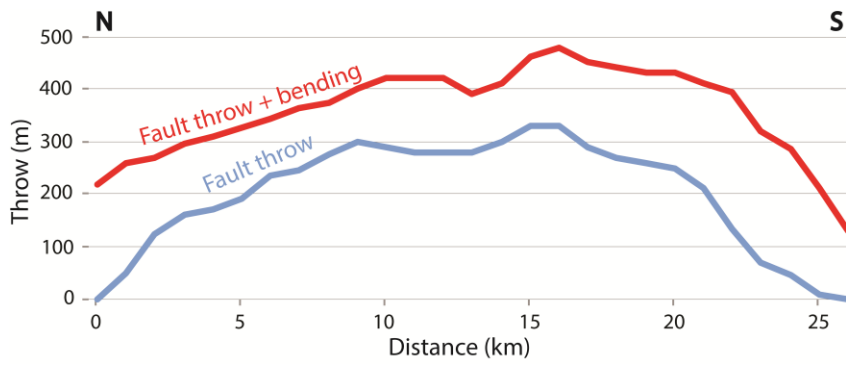
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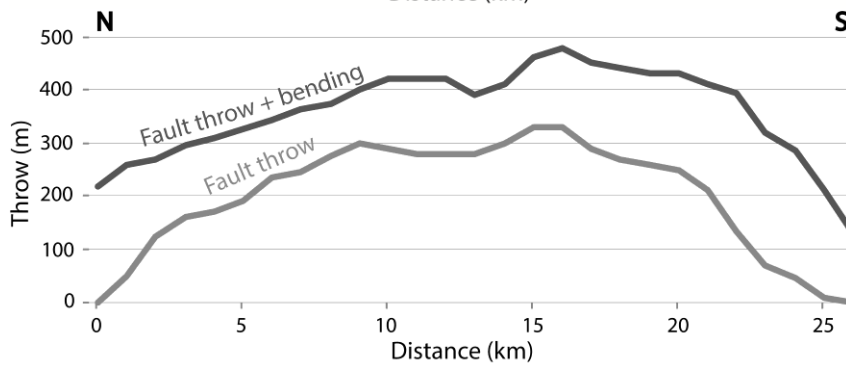
1626 **Figure 6:**  
1627 Morphotectonic map of the Sierra Palomera area.  
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1655 **Figure 7:**

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1675 **Figure 7:**

1676 Throw vs. distance (T-D) graph along the Sierra Palomera fault. Lower curve: fault throw s.s. recorded  
1677 by the *FES2* marker. Upper curve: total tectonic offset of *FES2* including the bending component.

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1704 **Figure 8:**



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1719 **Figure 8:**

1720 Villafranchian alluvial deposits deformed by an accommodation monocline in the footwall block of La  
1721 Peñuela fault. See location in Figure 2.

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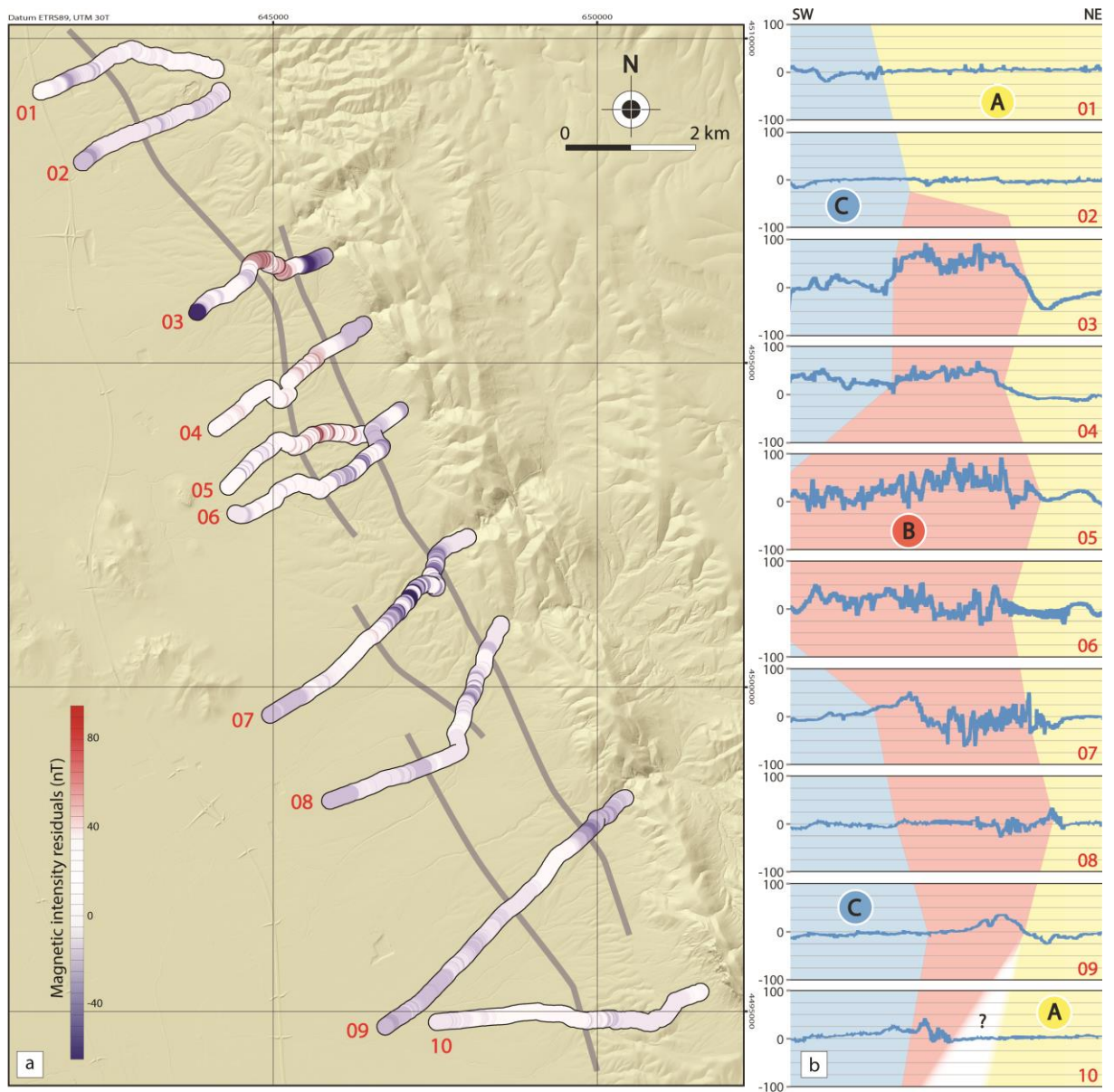
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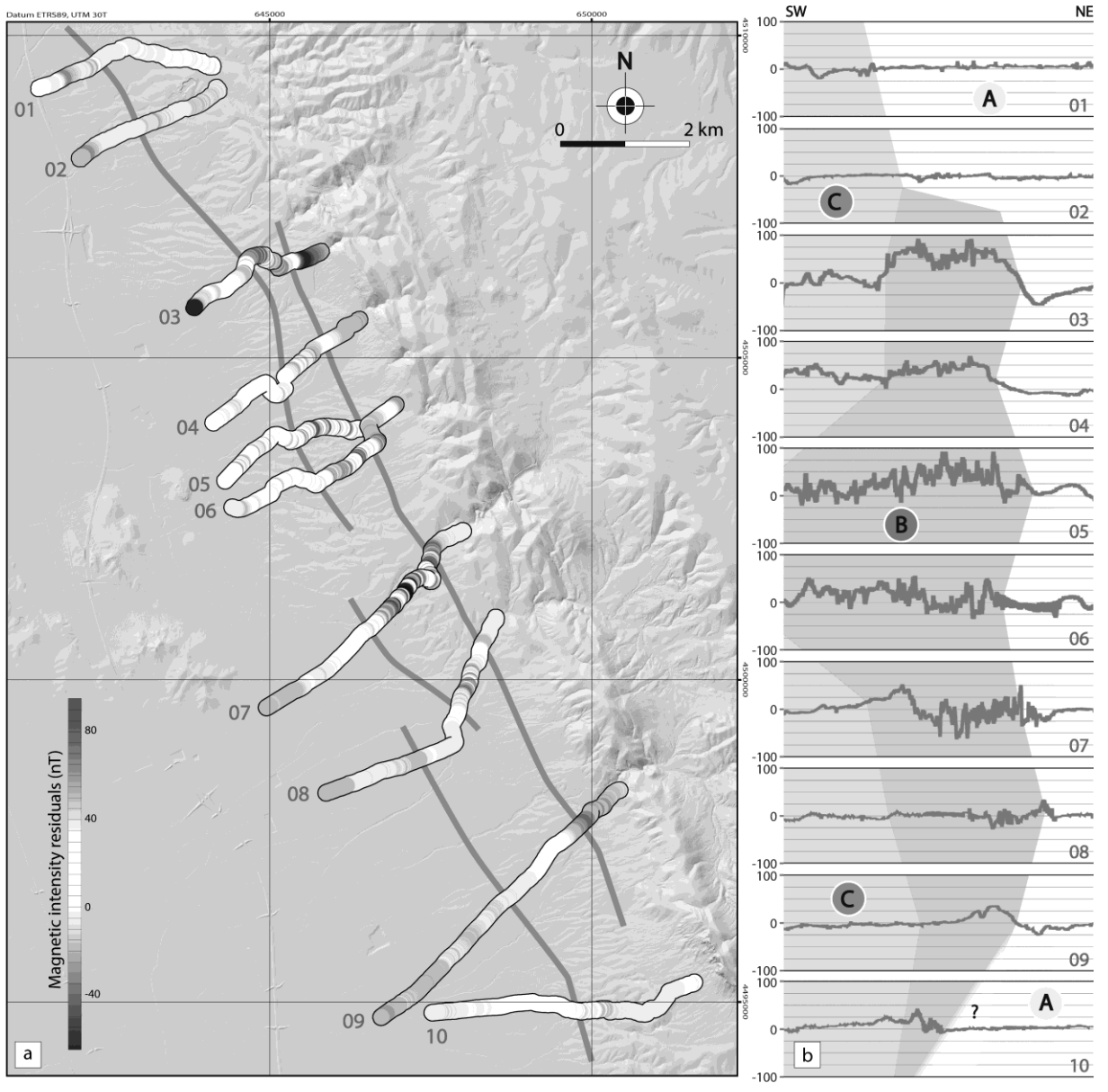
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1748 **Figure 9:**



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1773 **Figure 9:**

1774 Results of the geomagnetic survey covering the Sierra Palomera piedmont. (a) Location of magnetic  
1775 profiles 01 to 10, with the residual values of field intensity (nT) plotted as a colour palette. (b)  
1776 Magnetic profiles plotted with a normalized horizontal length, in which domains A, B and C roughly  
1777 parallel to the Sierra Palomera fault are defined (see text for details).

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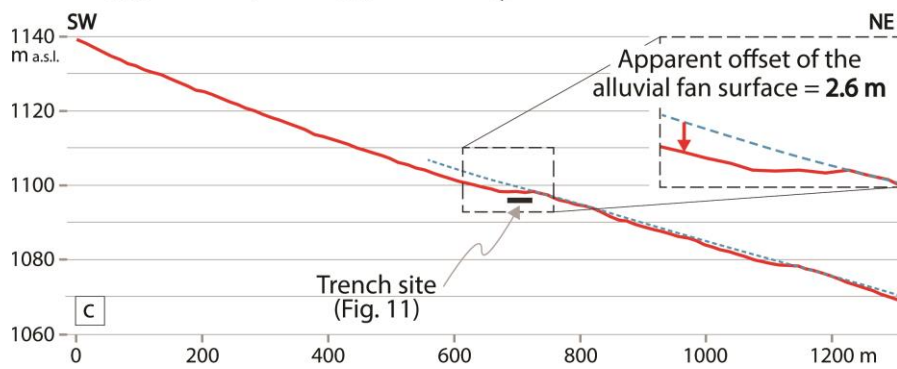
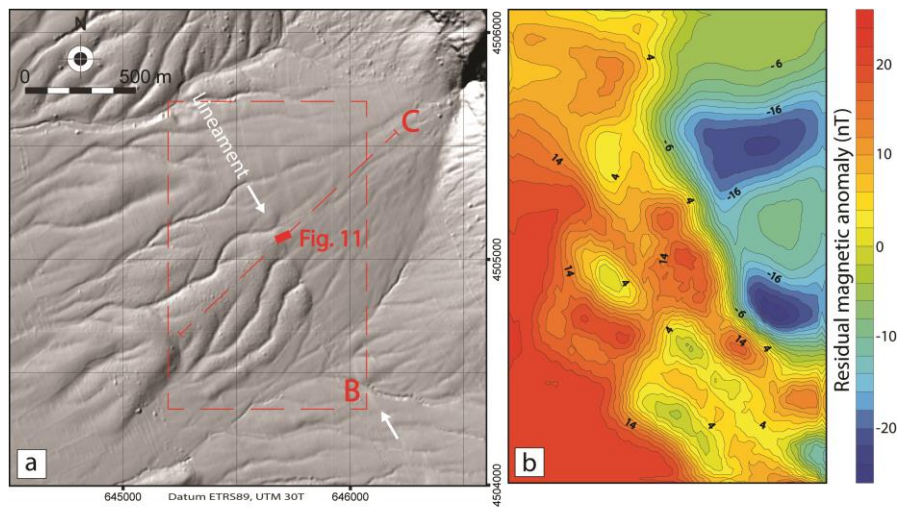
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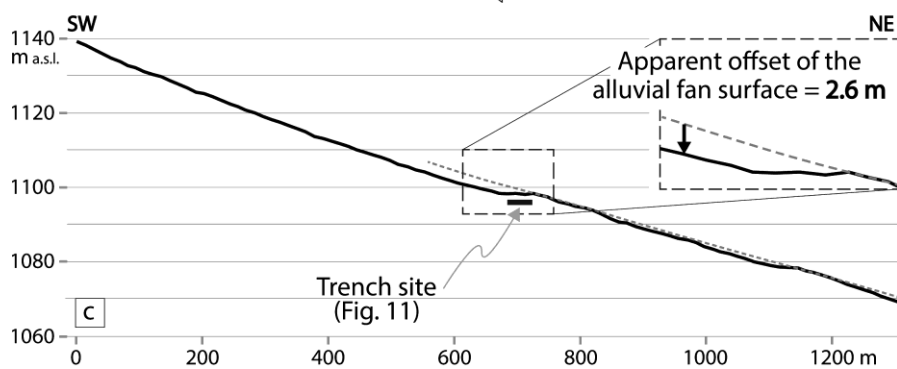
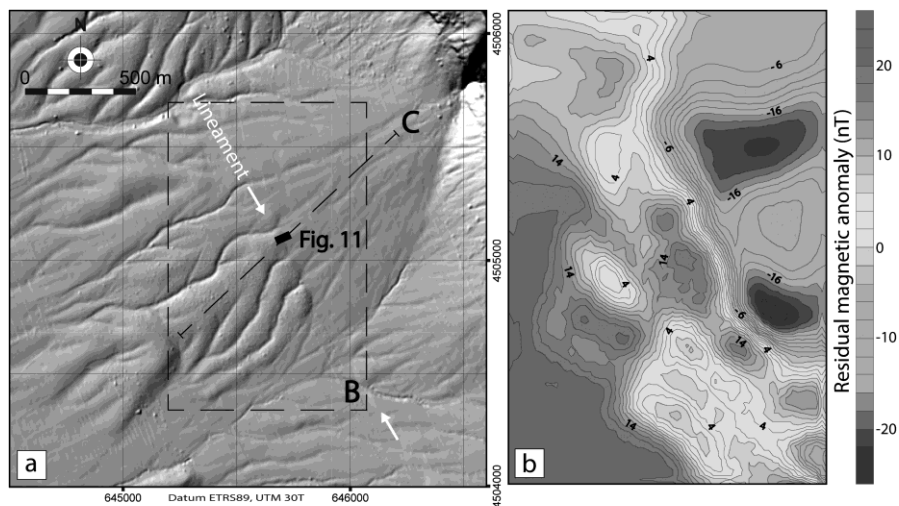
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1808 **Figure 10:**

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1813 **Figure 10:**

1814 (a) Hillshade relief map of the barranco de la Sima alluvial fan rendered from digital elevation model  
1815 (DEM, 5 m grid) of the Instituto Geográfico Nacional. See location in Figure 2. (b) Residual magnetic  
1816 field anomalies at the central sector of the alluvial fan. (c) Detailed topographic profile showing a  
1817 slope anomaly in the longitudinal profile of the alluvial fan surface, from which an apparent antithetic  
1818 throw of 2,6 m can be inferred.

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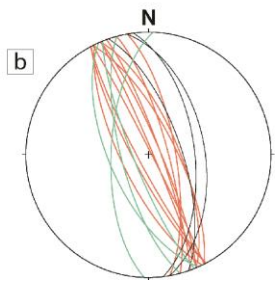
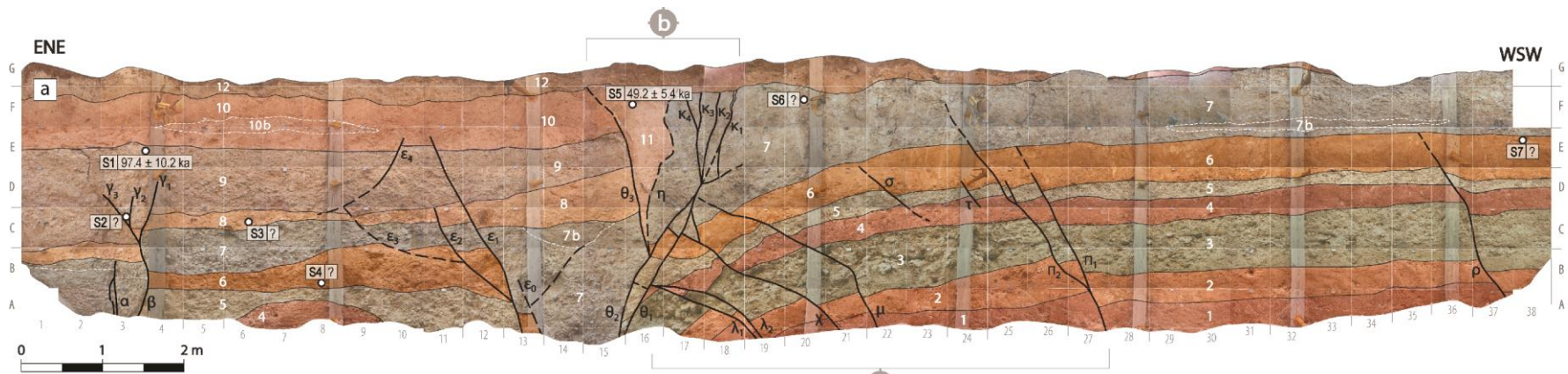
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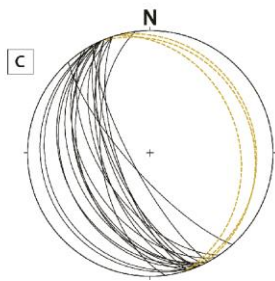
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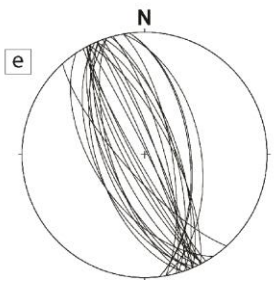
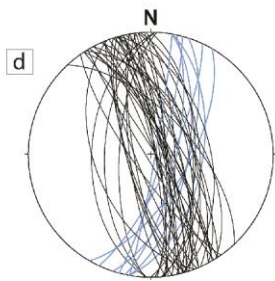
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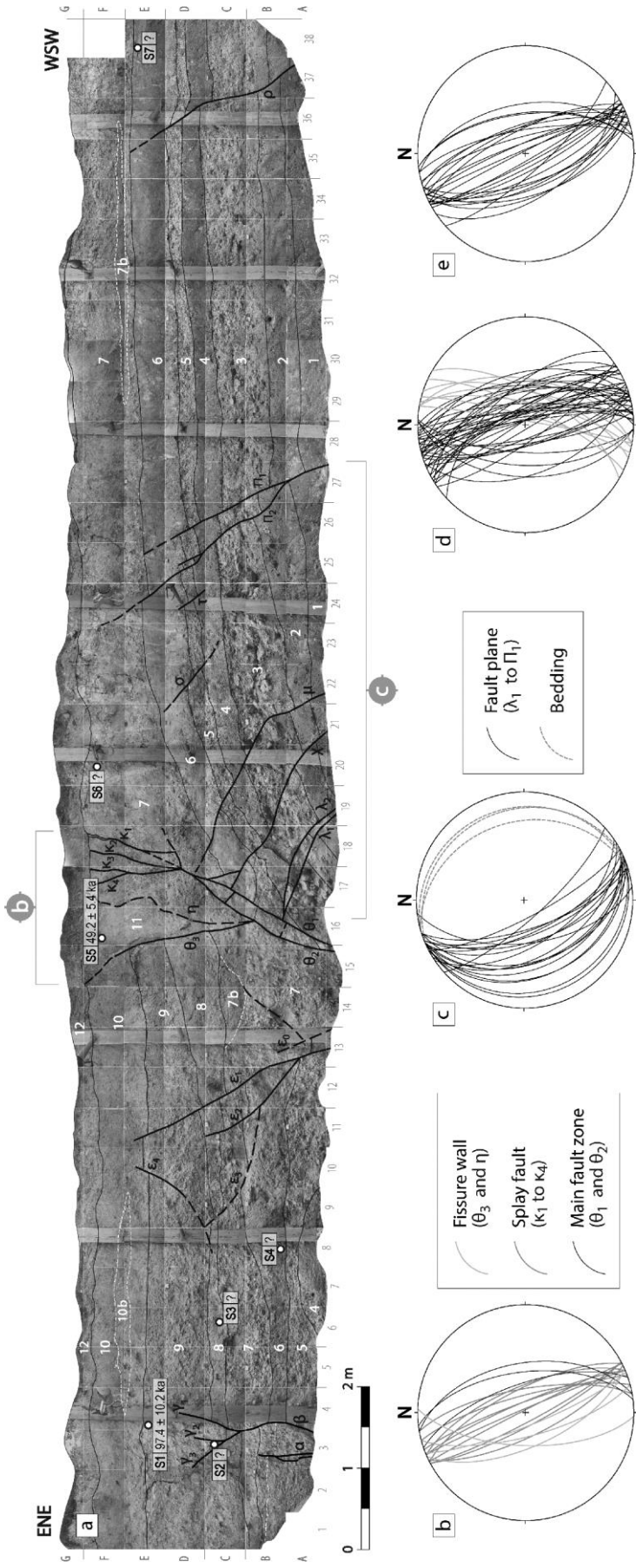
- Fissure wall ( $\theta_3$  and  $\eta$ )
- Splay fault ( $\kappa_1$  to  $\kappa_4$ )
- Main fault zone ( $\theta_1$  and  $\theta_2$ )



- Fault plane ( $\lambda_1$  to  $\pi_1$ )
- Bedding







1849 **Figure 11:**

1850 (a) Detailed log of La Sima trench. See location in Figure 2. 1 to 12: Quaternary units described in the  
1851 text. Greek characters: faults referred in the text. The location and age of samples dated by OSL is  
1852 indicated. Stereoplots (equal area, lower hemisphere) show orientations of faults and fractures  
1853 measured within the trench: (b) Central fault zone. (c) Footwall block, including monocline. (d)  
1854 Synthetic stereoplot of fault planes; those rotated at the central monocline have been restored to their  
1855 original orientation. (e) Synthetic stereoplot of fractures without displacement.

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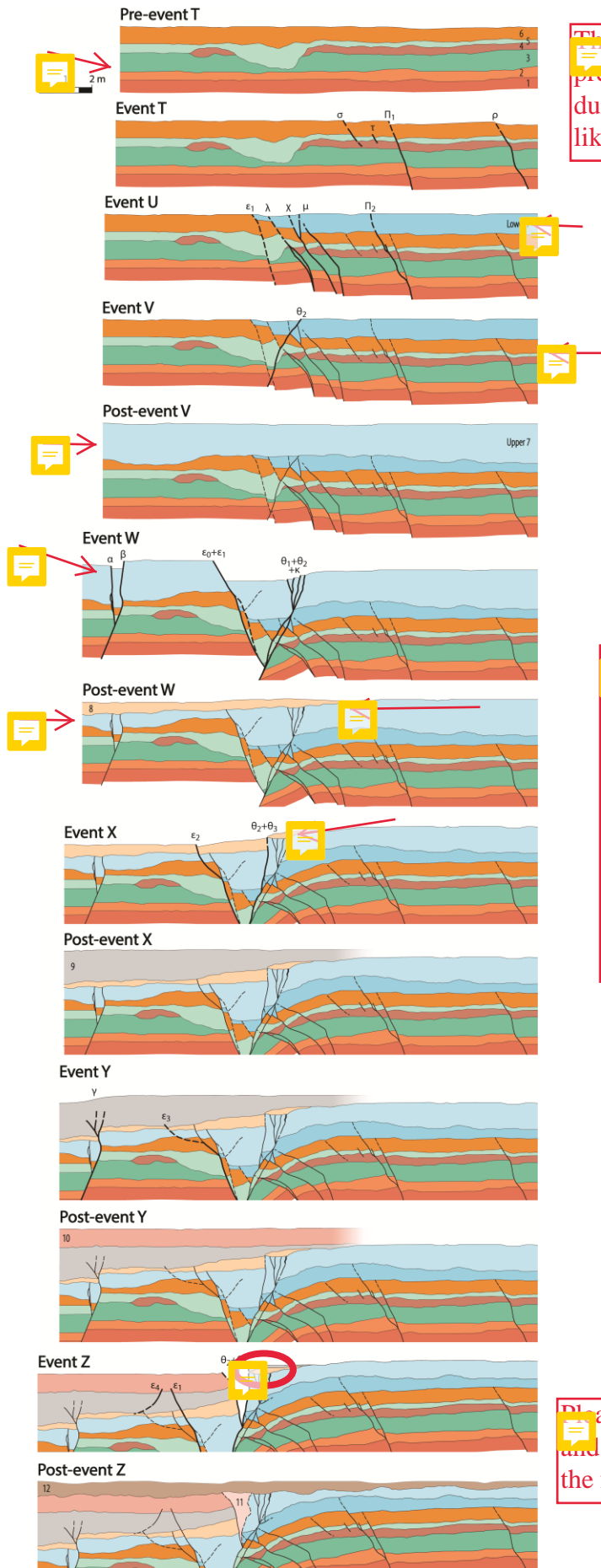
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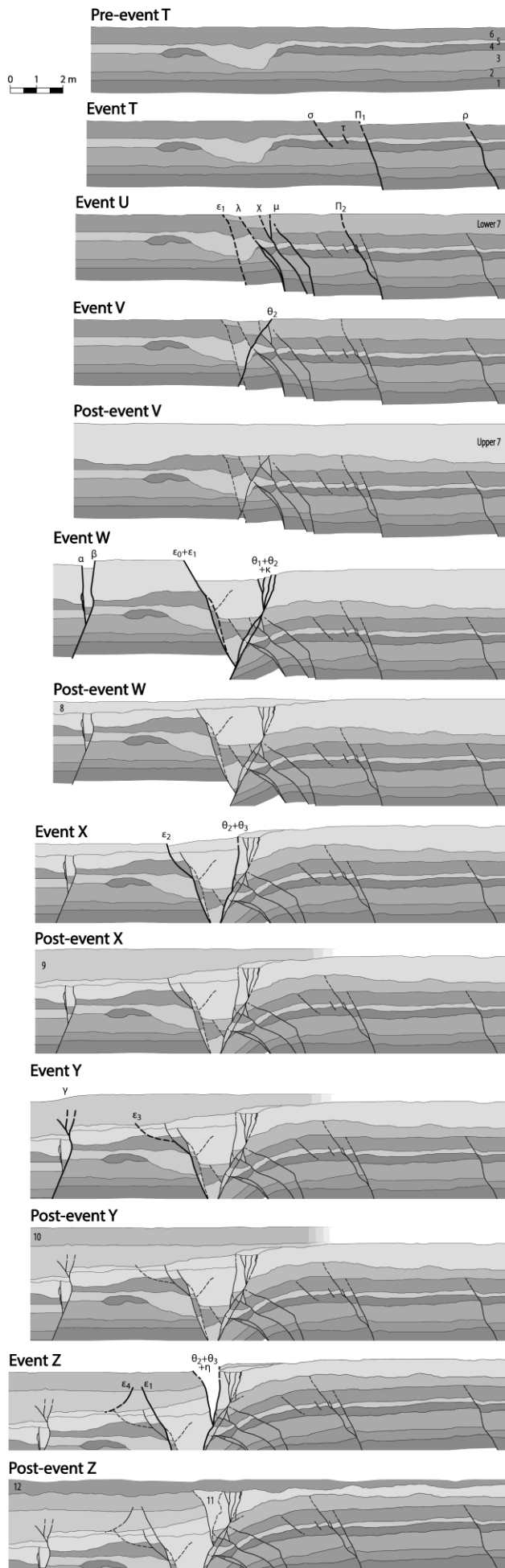
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Three first cartoon show that units 1-6 are pre-kinematic and fault activity starts during deposition of unit 7 and most likely fault E1 is the main structure here.

I think this evolutionary model can be simplified into: 1-Pre-kinematic phase (units 1-6); 2-main synthetic (dominantly) fault activity, block rotation and rollover formation (unit 7); 3- Dominantly antithetic fault activity, when faults  $\theta_1, 2, \eta, K1-4$  and  $\beta, \alpha, Y1-3$  are active (units 8-11, perhaps also latest unit 7) and 4- post-kinematic (unit 12).

Please explain what thin, thick and dashed lines represent in the figure caption.



1887 **Figure 12:**

1888 Evolutionary model of sedimentation and deformation recorded at the La Sima trench from  
1889 retrodeformational analysis. Each sketch represents a stage subsequent to the paleoseismic event (and,  
1890 in some cases, to deposition of sedimentary units) labelled above.

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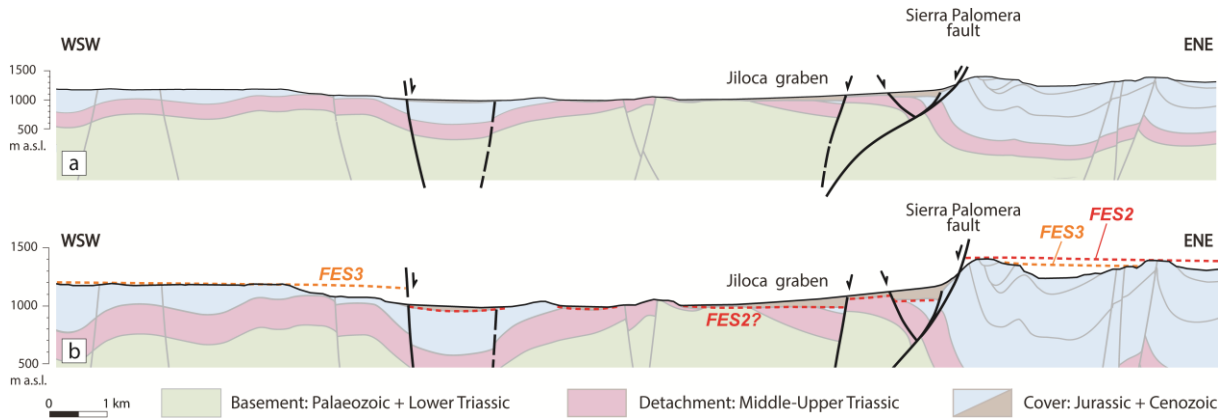
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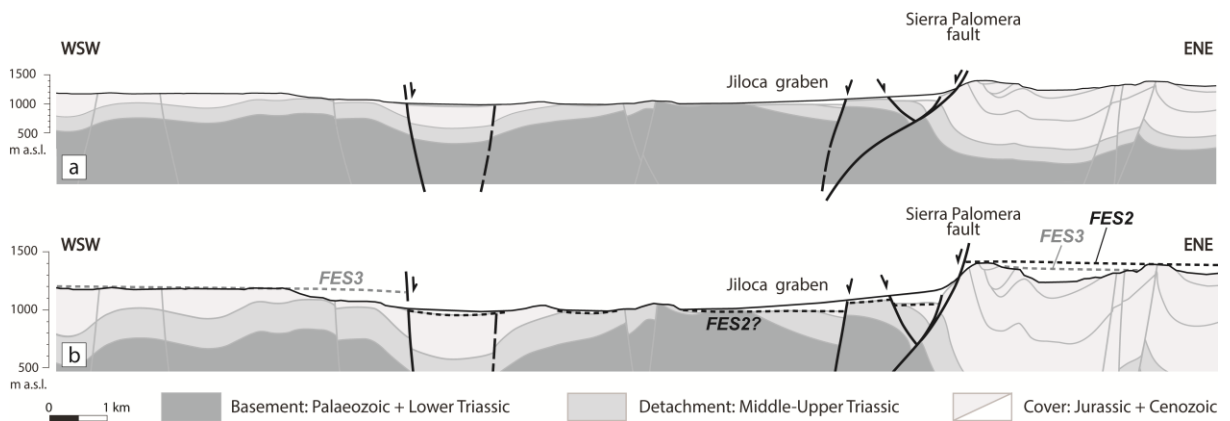
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1922 **Figure 13:**



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1943 **Figure 13:**

1944 (a) Refined cross section of the Jiloca graben at its central sector, in which the new inferred, subsidiary  
1945 faults have been incorporated. (b) Upper fringe of the same cross section (vertical scale x2) showing  
1946 offset of planation surfaces *FES2* and *FES3*.

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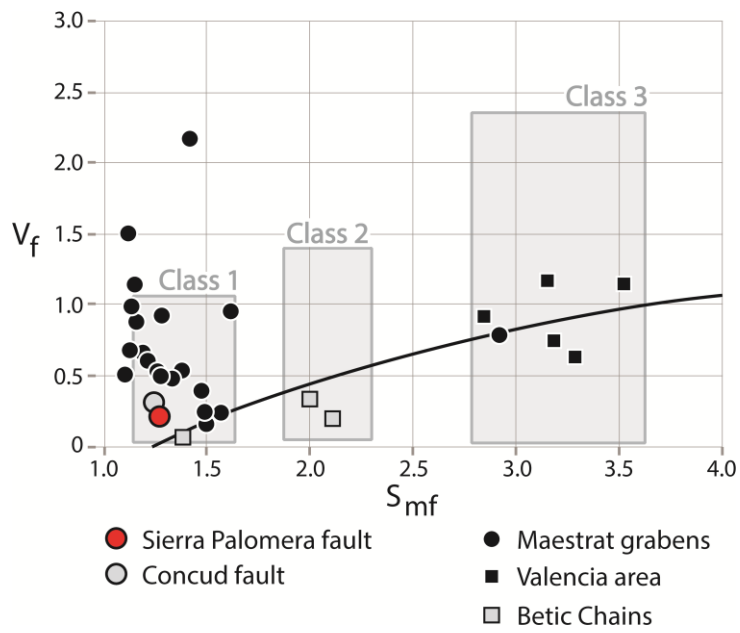
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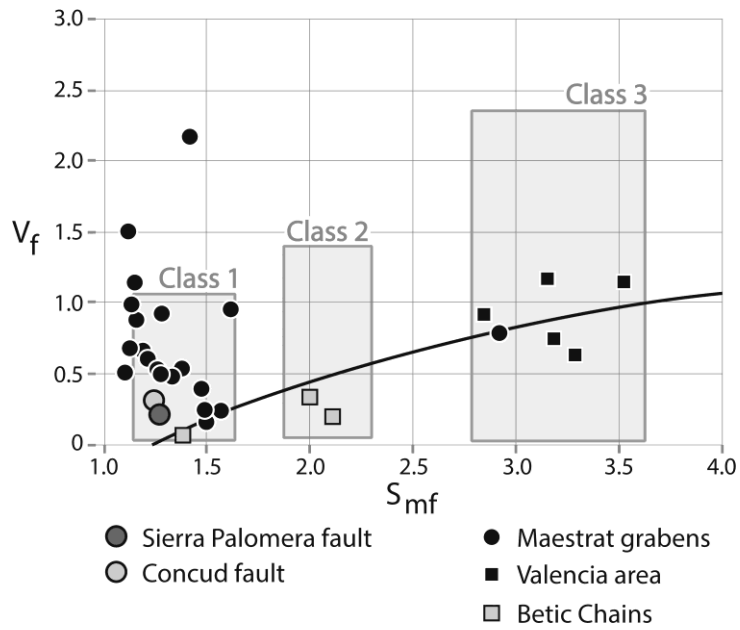
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1978 **Figure 14:**

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1992 **Figure 14:**

1993 Plot of  $S_{mf}$  (mountain-front sinuosity index) vs.  $V_f$  (valley width/height ratio, measured 250 m  
1994 upstream from the fault trace), showing the relative position of the Sierra Palomera Fault among  
1995 extensional fault-generated mountain fronts of eastern Spain. For comparison, the  $S_{mf}$ - $V_f$  plots for the  
1996 neighbouring Concul fault (Lafuente et al, 2011b), faults bounding the Maestrat grabens (eastern  
1997 Iberian Chain; Perea, 2006), and Valencia region and Betic chains (Silva *et al.*, 2003) are also  
1998 included. Class 1, 2, 3: activity classes (active, moderate and inactive, respectively); the curve  
1999 represents the tendency for normal faults in SE Spain according to Silva *et al.* (2003).

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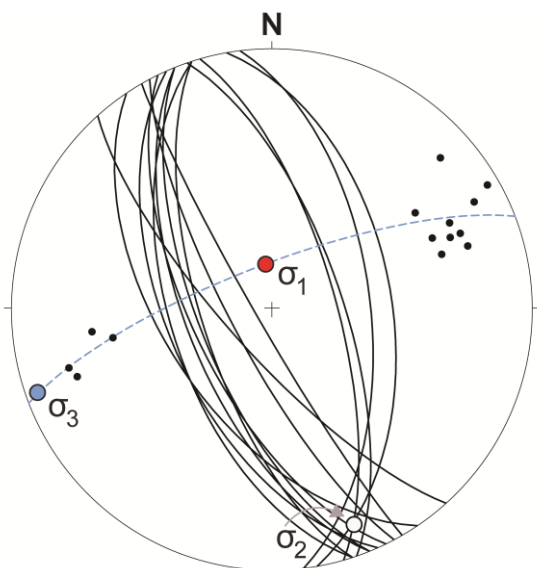
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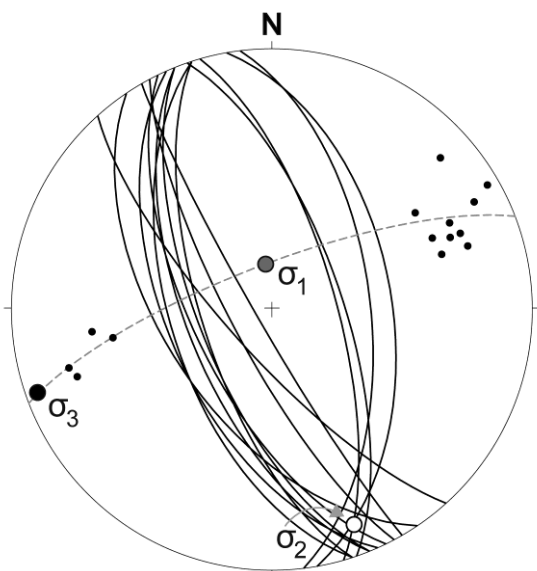
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2027 **Figure 15:**



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2043 **Figure 15:**

2044 Interpretation of paleostress axes from orientation of non-rotated, conjugate fault planes measured  
2045 within La Sima trench. Stress inversion based on model by Anderson (1951).

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2072 **Table 1:**

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Sample	Laboratory reference	Stratigraphic location	Depth (m)	H <sub>2</sub> O (%)	Quartz Grain (µm)	<sup>238</sup> U (ppm)	<sup>232</sup> Th (ppm)	K (%)	Dose rate (Gy/ka)	Equivalent dose (Gy)	Age (ka)
S1	UGA15OSL-1013	Unit 9 (top)	1.0	5±2.5	80-125	1.42±0.33	5.86±1.14	0.6±0.1	1.50±0.15	146.0±3.9	97.4±10.2
S2	UGA15OSL-1014	Unit 9b	2.1	5±2.5	80-250	0.73±0.12	2.24±0.46	0.2±0.1	0.68±0.10	>256	>378
S3	UGA15OSL-1015	Unit 8	1.6	5±2.5	125-250	0.95±0.15	2.45±0.54	0.3±0.1	0.84±0.11	>300	>355
S4	UGA15OSL-1017	Unit 6 (base)	2.8	5±2.5	150-250	1.35±0.25	5.42±0.88	0.5±0.1	1.27±0.13	>300	>236
S5	UGA15OSL-1018	Unit 11	0.4	5±2.5	125-250	1.29±0.20	4.15±0.71	0.5±0.1	1.26±0.12	62.0±3.4	49.2±5.4
S6	UGA15OSL-1019	Unit 7 (top)	0.7	5±2.5	125-250	0.96±0.20	4.73±0.71	0.5±0.1	1.21±0.12	>300	>248
S7	UGA15OSL-1020	Unit 6 (top)	1.2	5±2.5	80-125	1.41±0.21	4.54±0.75	0.8±0.1	1.56±0.13	>300	>193
La Cecilia	MAD-6326BIN	Alluvial fan	3.0	2.31	2-10	2.97	1.54	0.01±0.1	1.63	47.1±2.5	28.9±2.0
La Sima	MAD-6327BIN	Alluvial fan	0.4	6.25	2-10	3.73	1.90	0.18±0.1	2.31	44.3±1.4	19.2±1.1

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2079 **Table 1:**

2080 Parameters and results of OSL dating of samples collected at the La Sima trench (S1 to S7;  
2081 Luminescence Dating Laboratory of University of Georgia, USA), and La Cecilia and La Sima alluvial  
2082 fans (Laboratorio de Datación y Radioquímica de la Universidad Autónoma de Madrid, Spain).

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2108 **Table 2:**

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Event	Active faults	Net slip (cm)	Horizontal extension (cm)	Net slip by event <sup>(1)</sup> (cm)	Horizontal extension by event <sup>(2)</sup>
T	$\sigma$	+ 10	5	+ 45	20 cm (1%)
	$\tau$	+ 5	5		
	$\pi 1$	+ 15	5		
	$\rho$	+ 15	5		
U	$\varepsilon 1$	+ 15	5	+ 110	45 cm (2%)
	$\lambda 1$	+ 25	10		
	$\lambda 2$	+ 20	5		
	$\chi$	+ 20	10		
	$\mu$	+ 15	10		
	$\pi 2$	+ 15	5		
V	$\theta 2$	- 5	5	- 5	5 cm (0%)
W	$\alpha$	+ 10	0	- 5	85 cm (5%)
	$\varepsilon 0$	+ 45	15		
	$\varepsilon 1$	+ 45	25		
	$\beta$	- 30	5		
	$\theta 1 + \theta 2 + \kappa 1$ to $\kappa 4$	- 75	40		
X	$\varepsilon 2$	+ 5	5	- 90	65 cm (3%)
	$\theta 2 + \theta 3$	- 95	60		
Y	$\varepsilon 0$	0	0	- 40	10 cm (1%)
	$\gamma 1$	- 20	10		
	$\gamma 2 + \gamma 3$	- 20	0		
Z	$\varepsilon 1$	+ 10	5	- 125	85 cm (5%)
	$\varepsilon 4$	- 10	5		
	$\theta 2 + \theta 3 + \eta$ (open fissure)	- 125	75		
<i>Total synthetic faults</i>		+270			115 cm (6.1%)
<i>Total antithetic faults</i>		-380			200 cm (10.6%)
<i>Monocline</i>		-120			≈70 cm (3.7%)
<i>Total structures</i>		-230			≈385 cm (20.4%)

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<sup>(1)</sup> Fault net slip *s.s.*, excluding vertical displacement associated to the monocline.

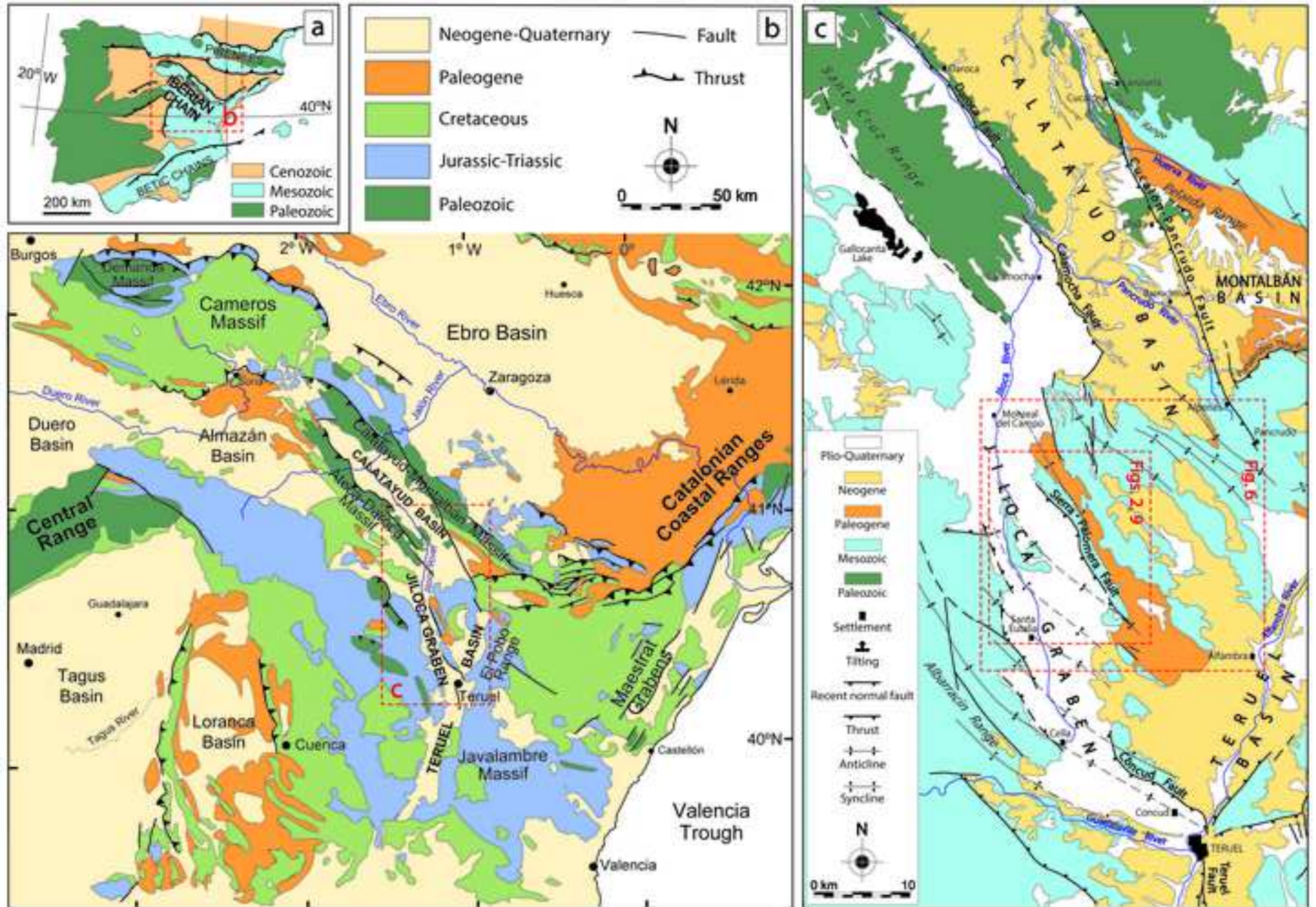
<sup>(2)</sup> Initial (restored) log length= 1890 cm.

2126 **Table 2:**

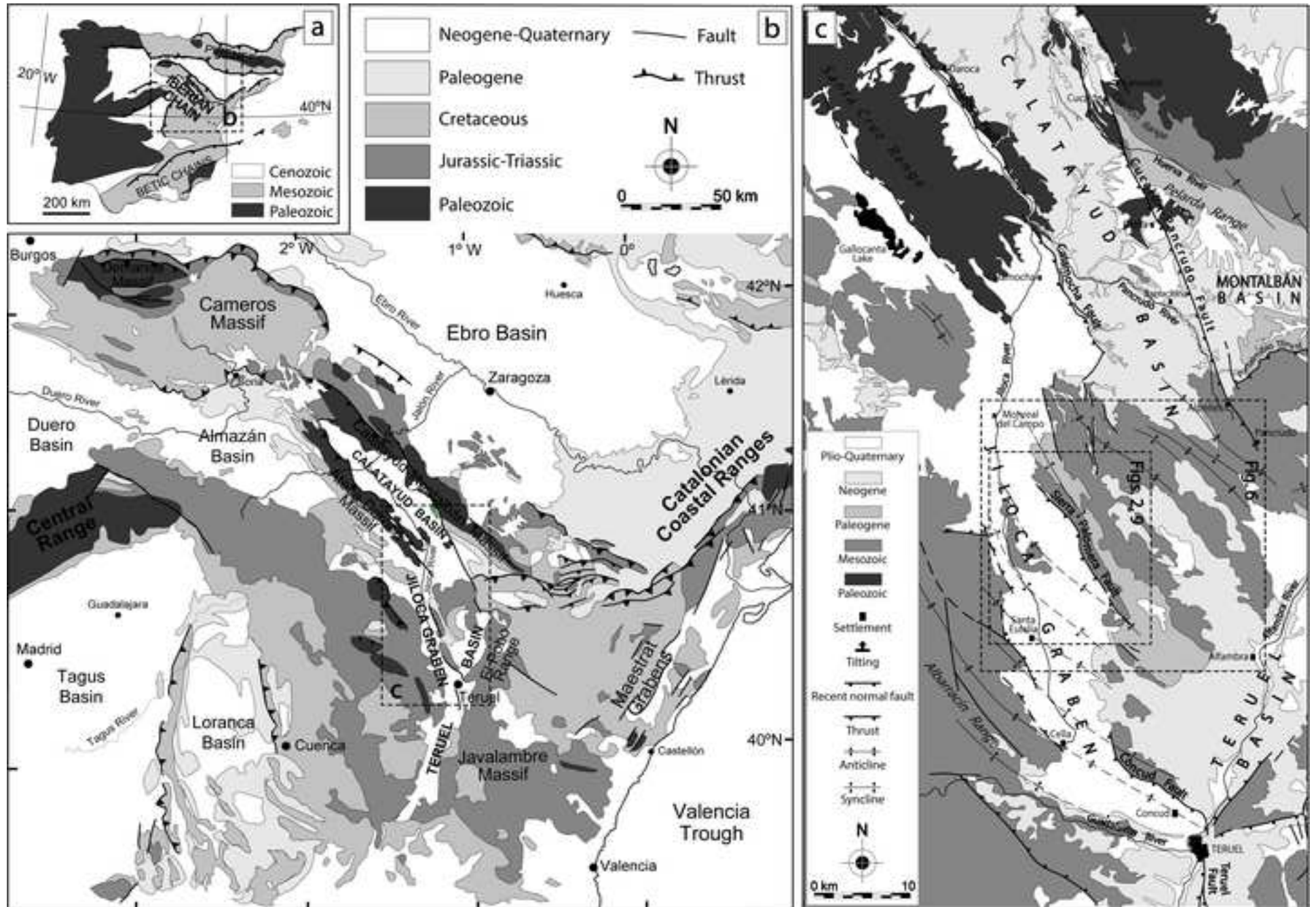
2127 Synthesis of deformation events inferred at La Sima trench: faults activated during each event, net slip  
2128 values calculated from the trench log (positive: synthetic with the Sierra Palomera fault; negative:  
2129 antithetic), and associated values of horizontal extension.

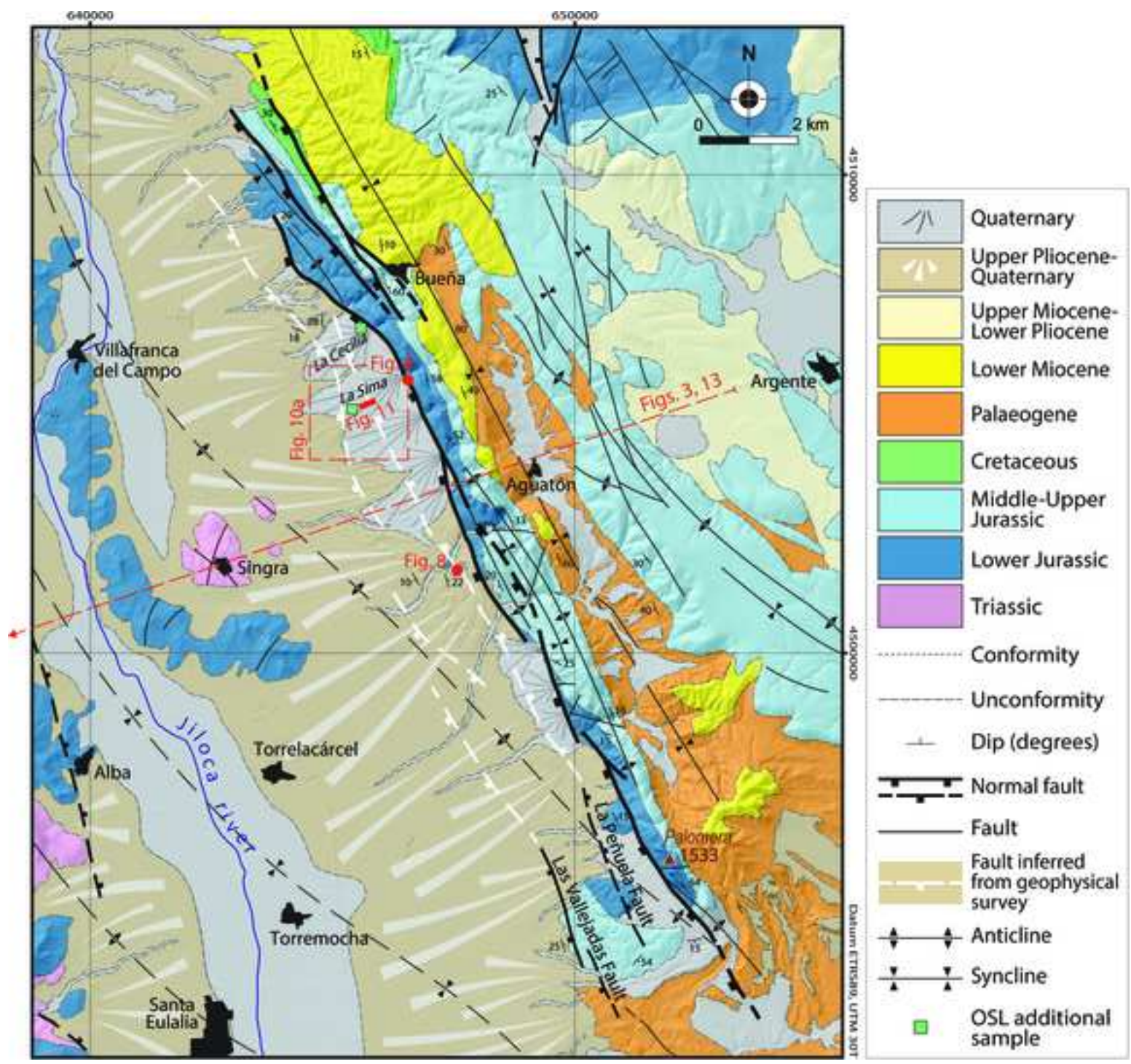
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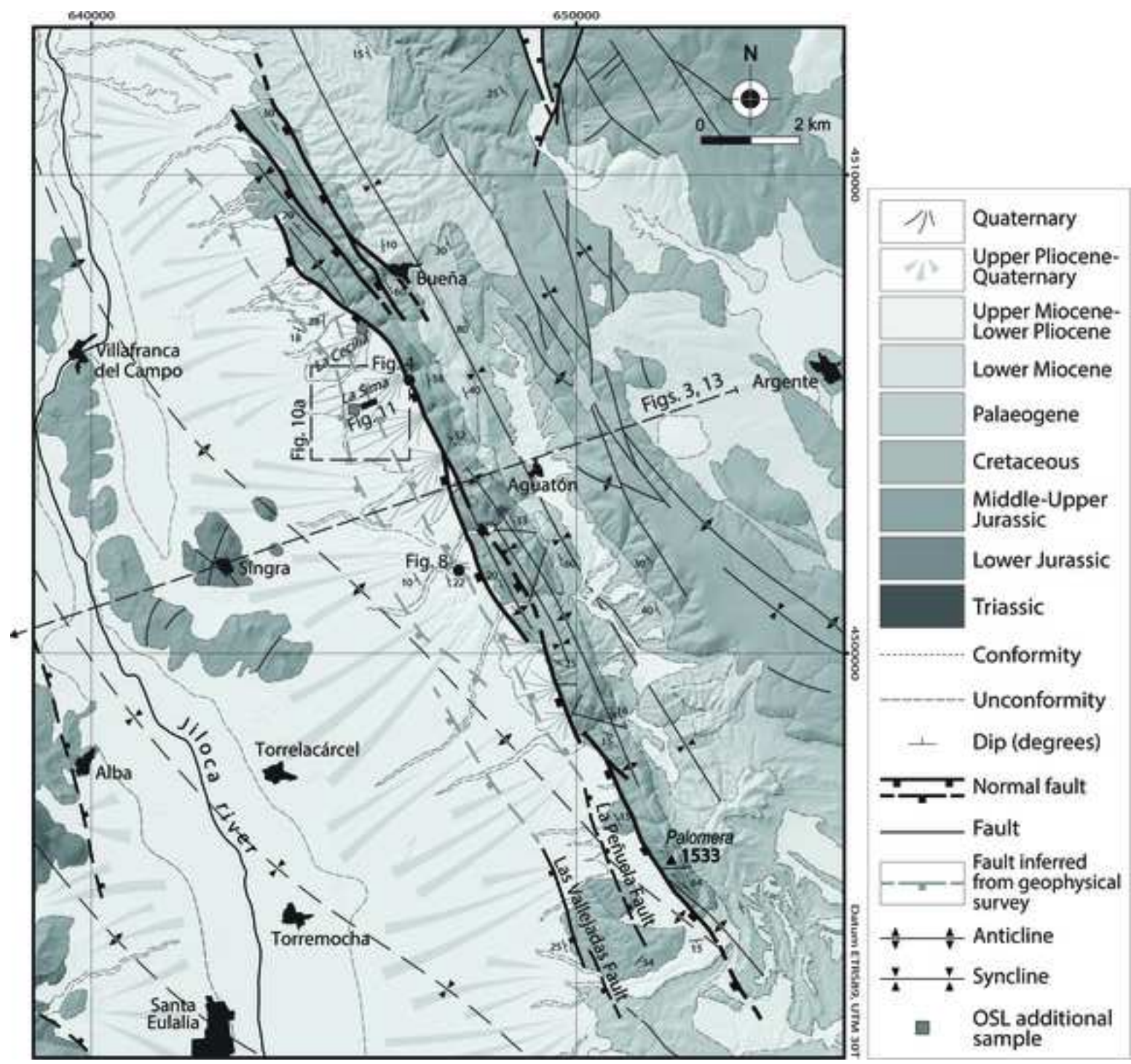
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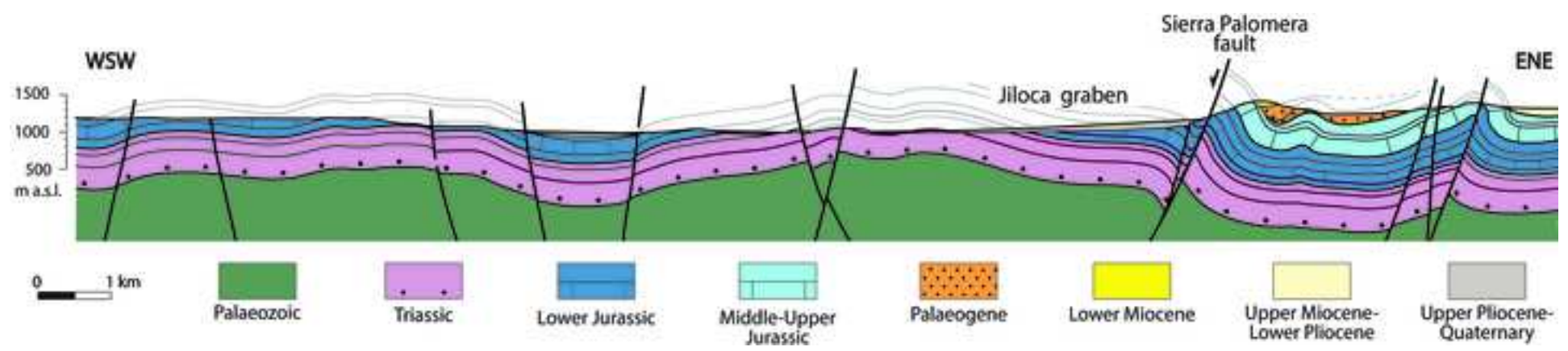


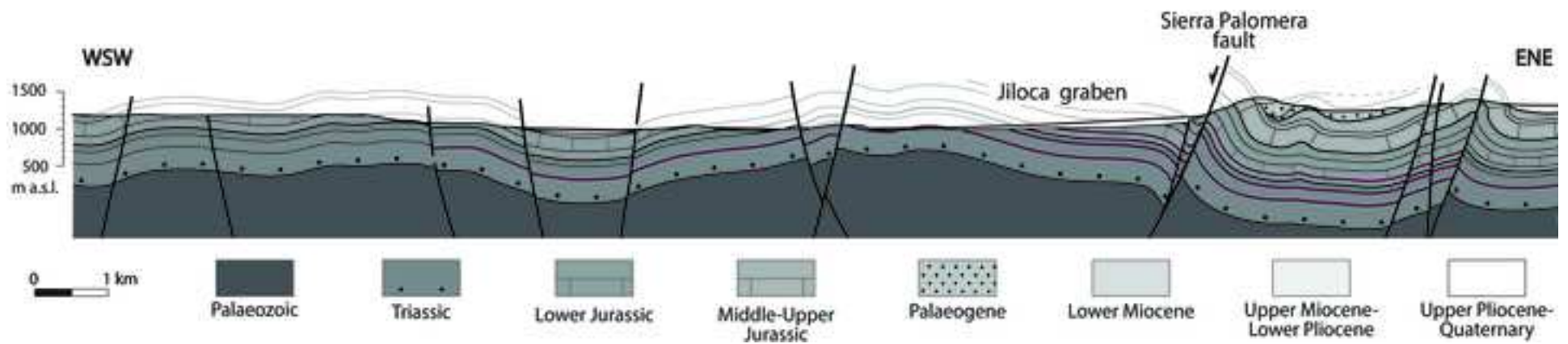


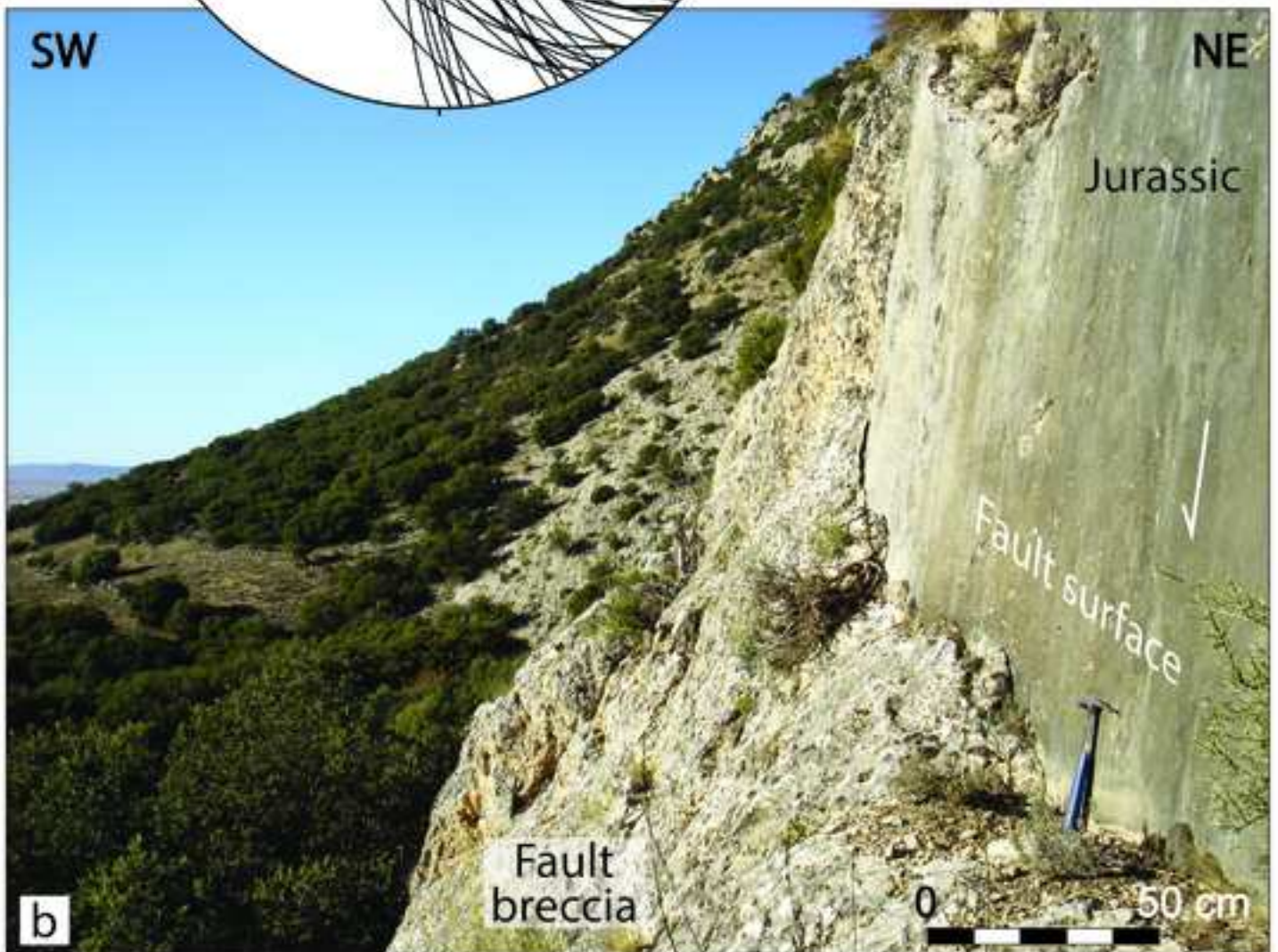
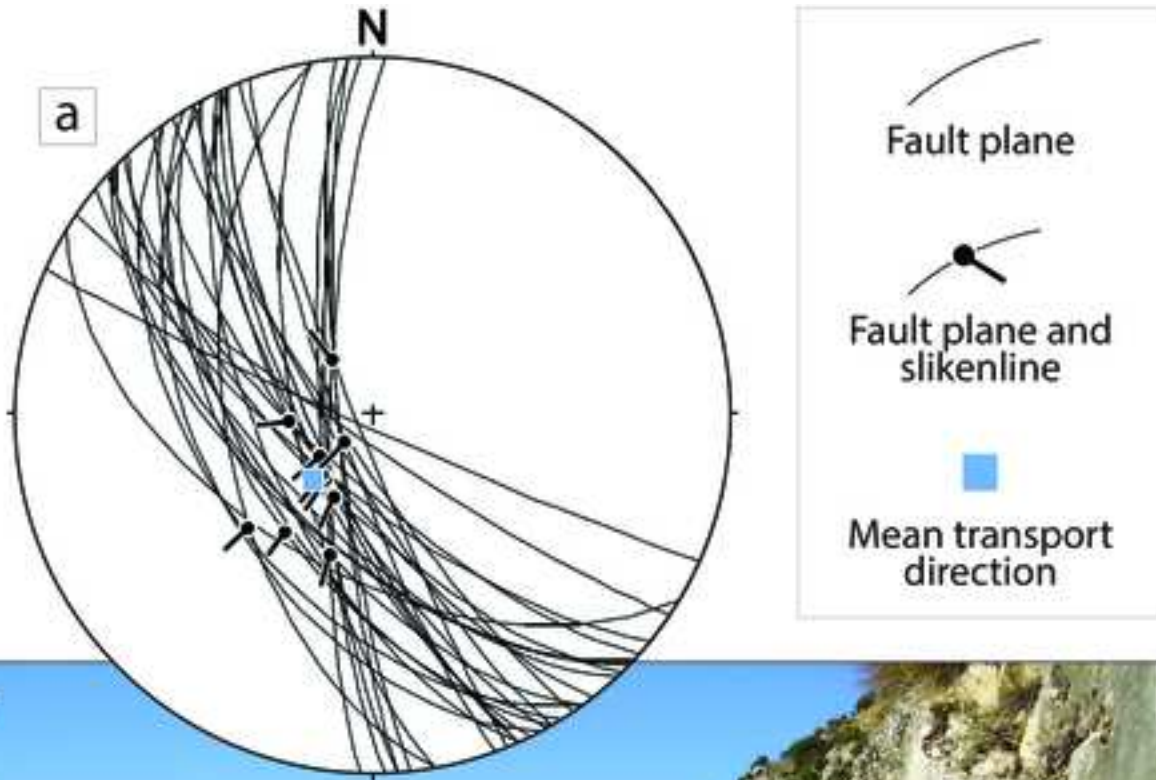


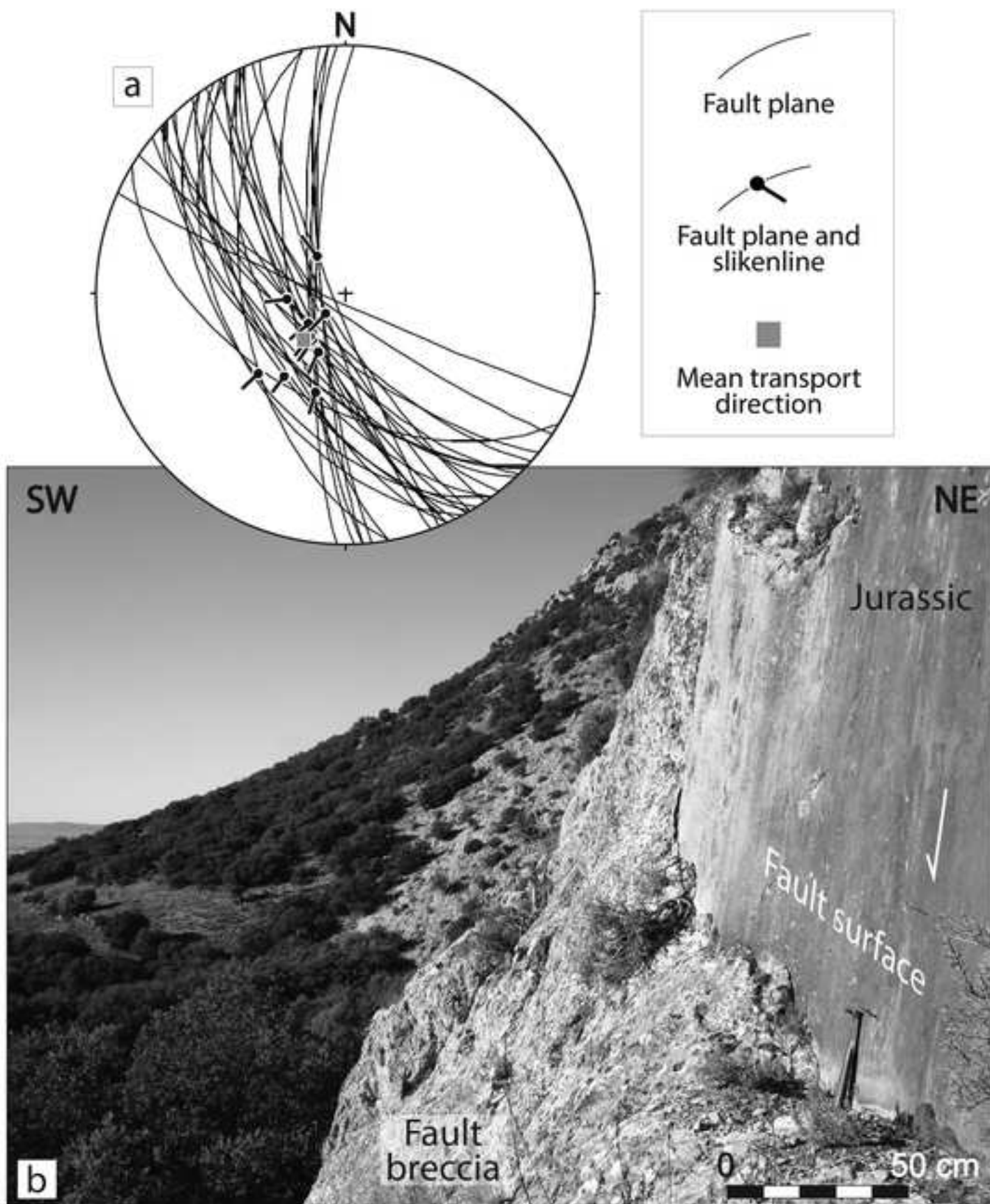


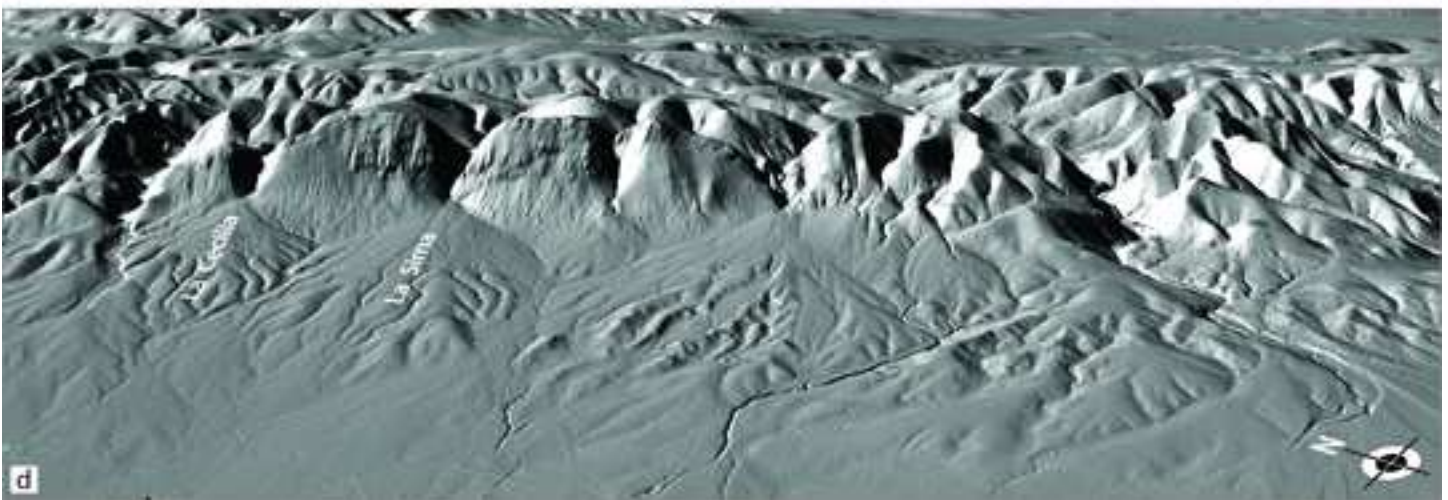
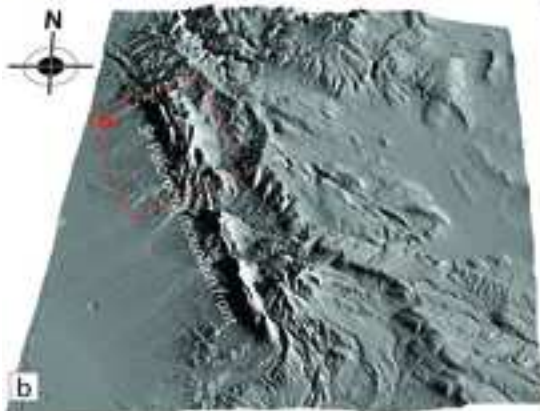




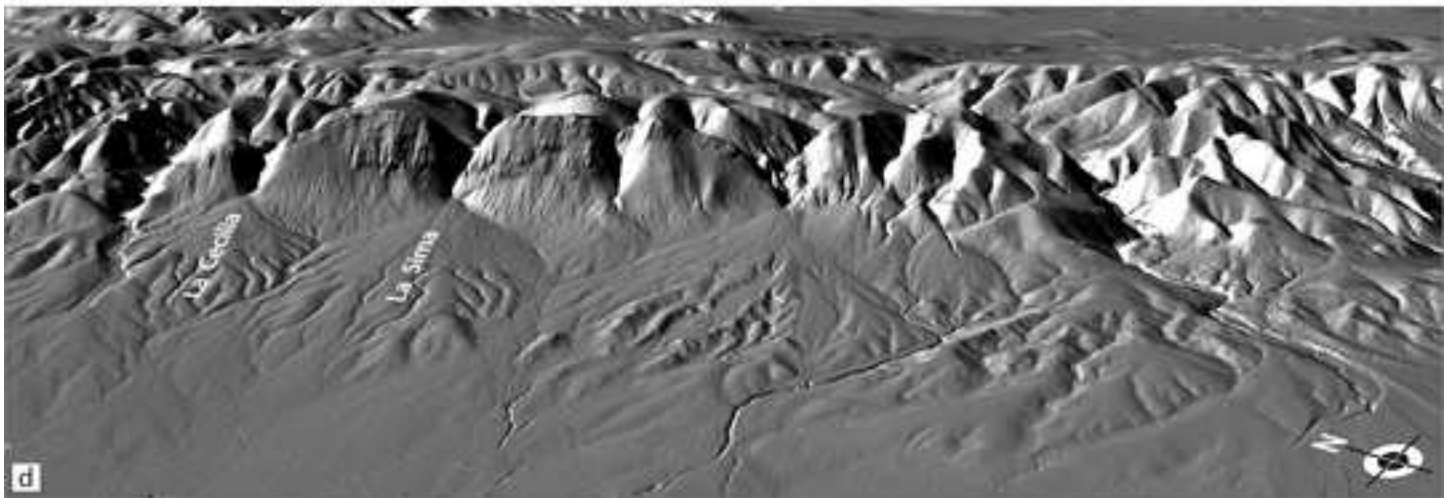
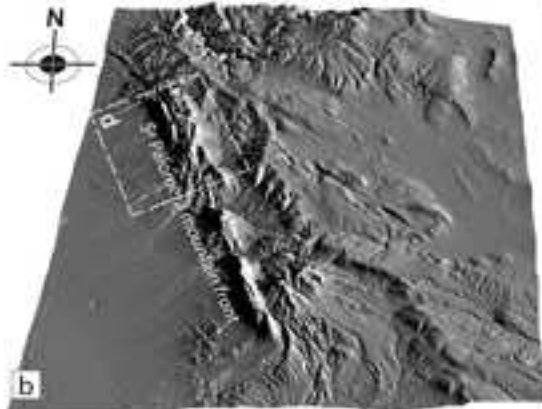


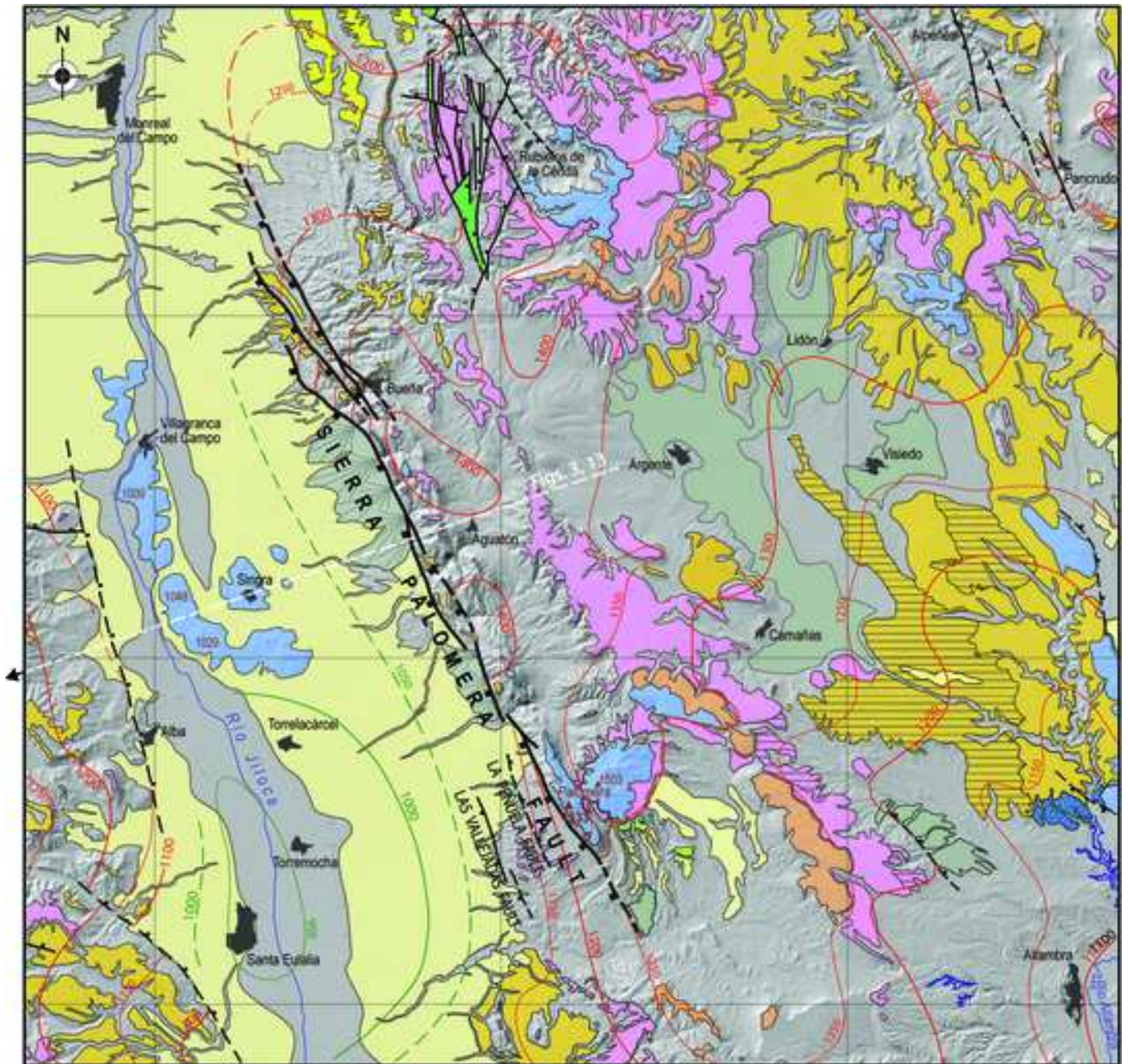


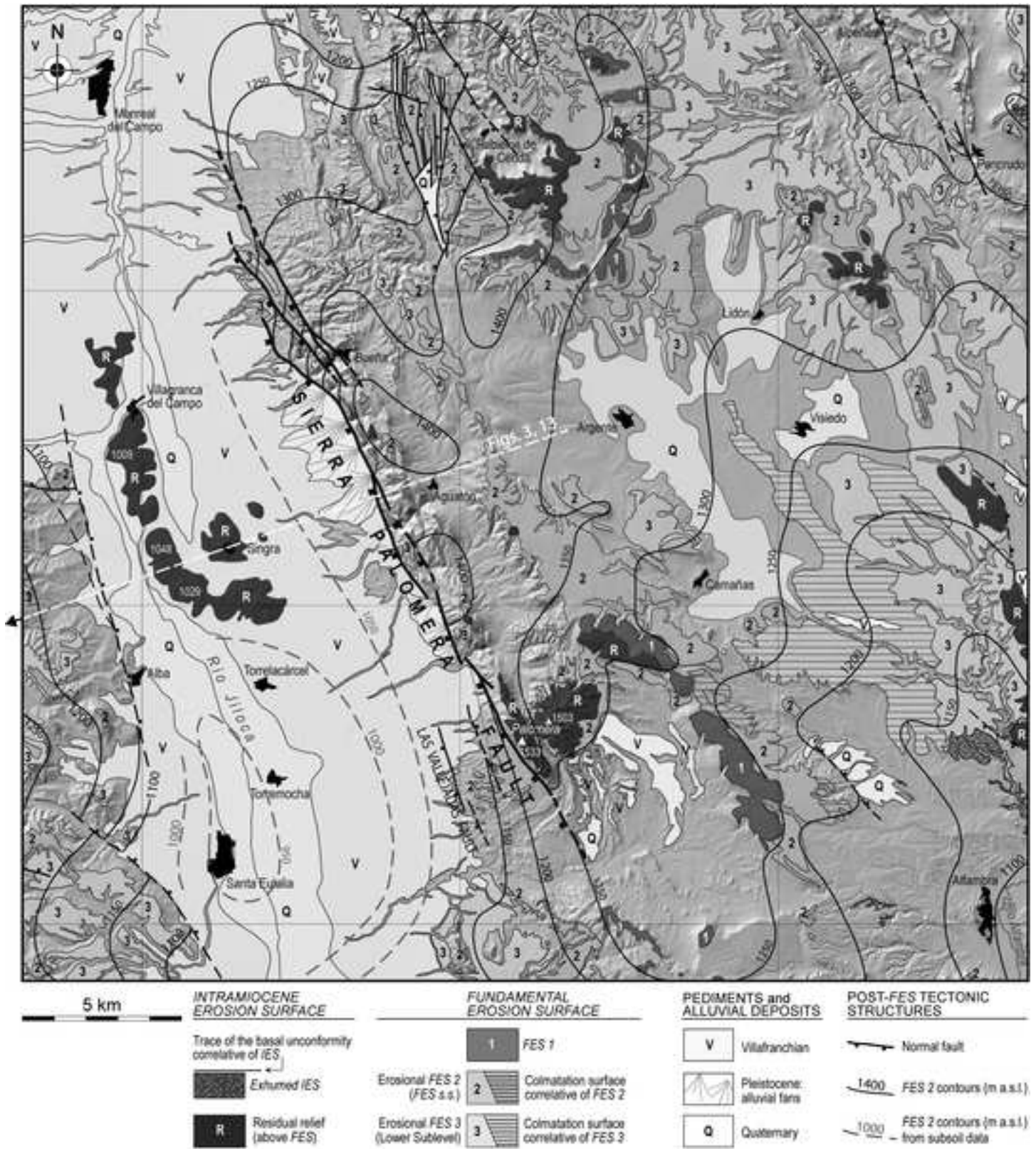


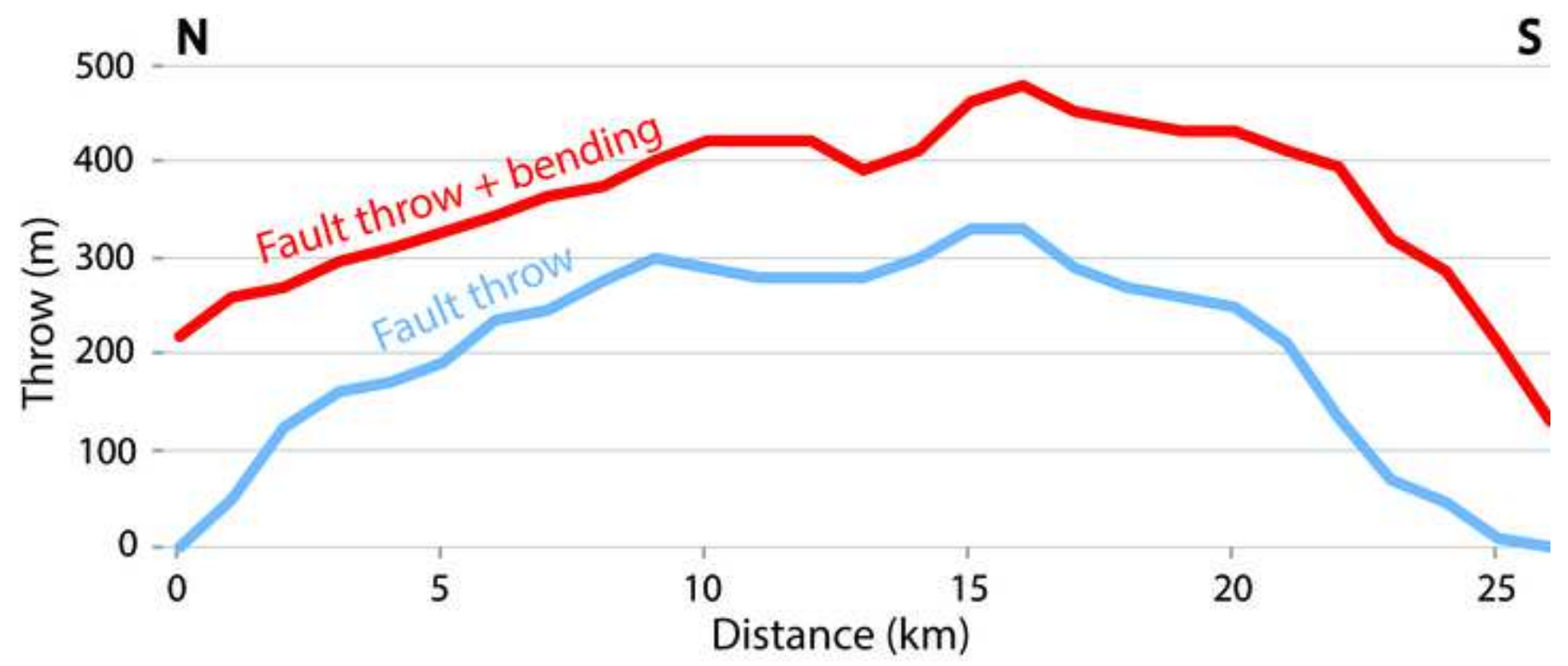


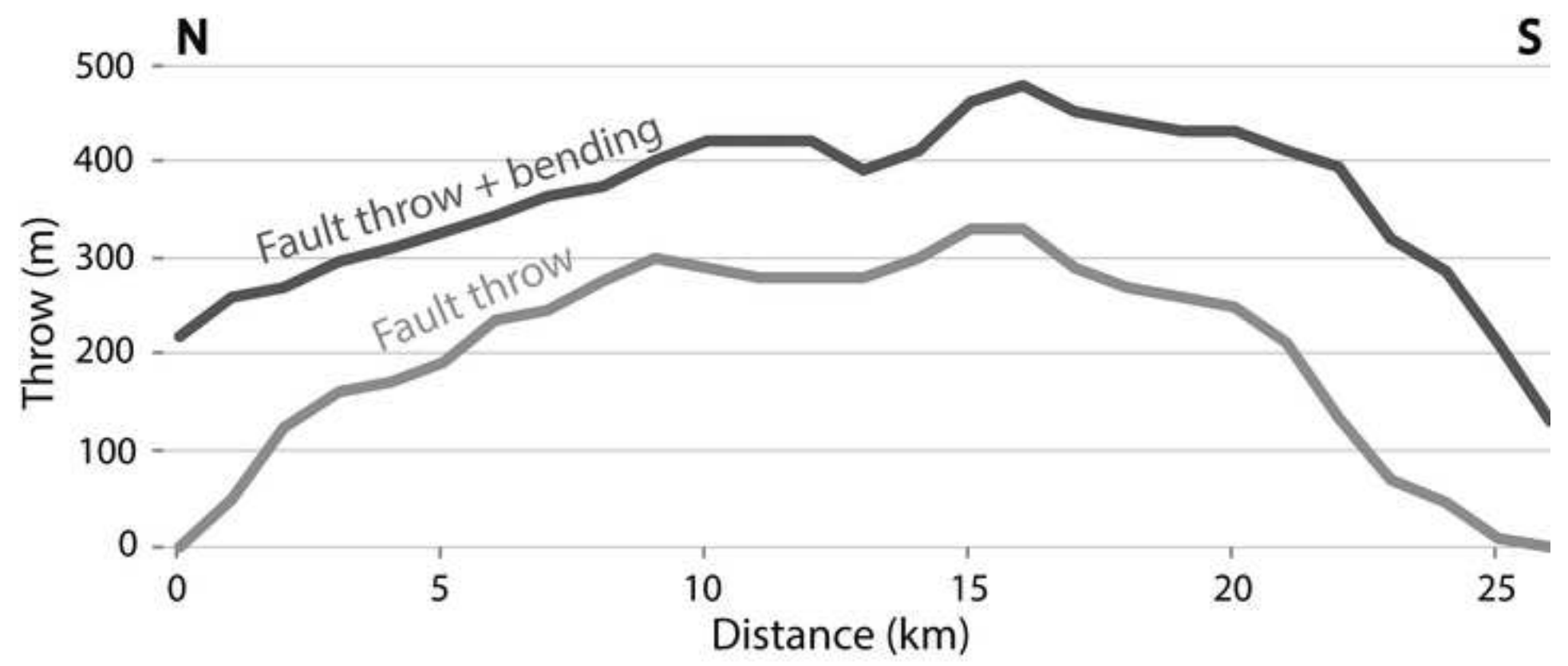






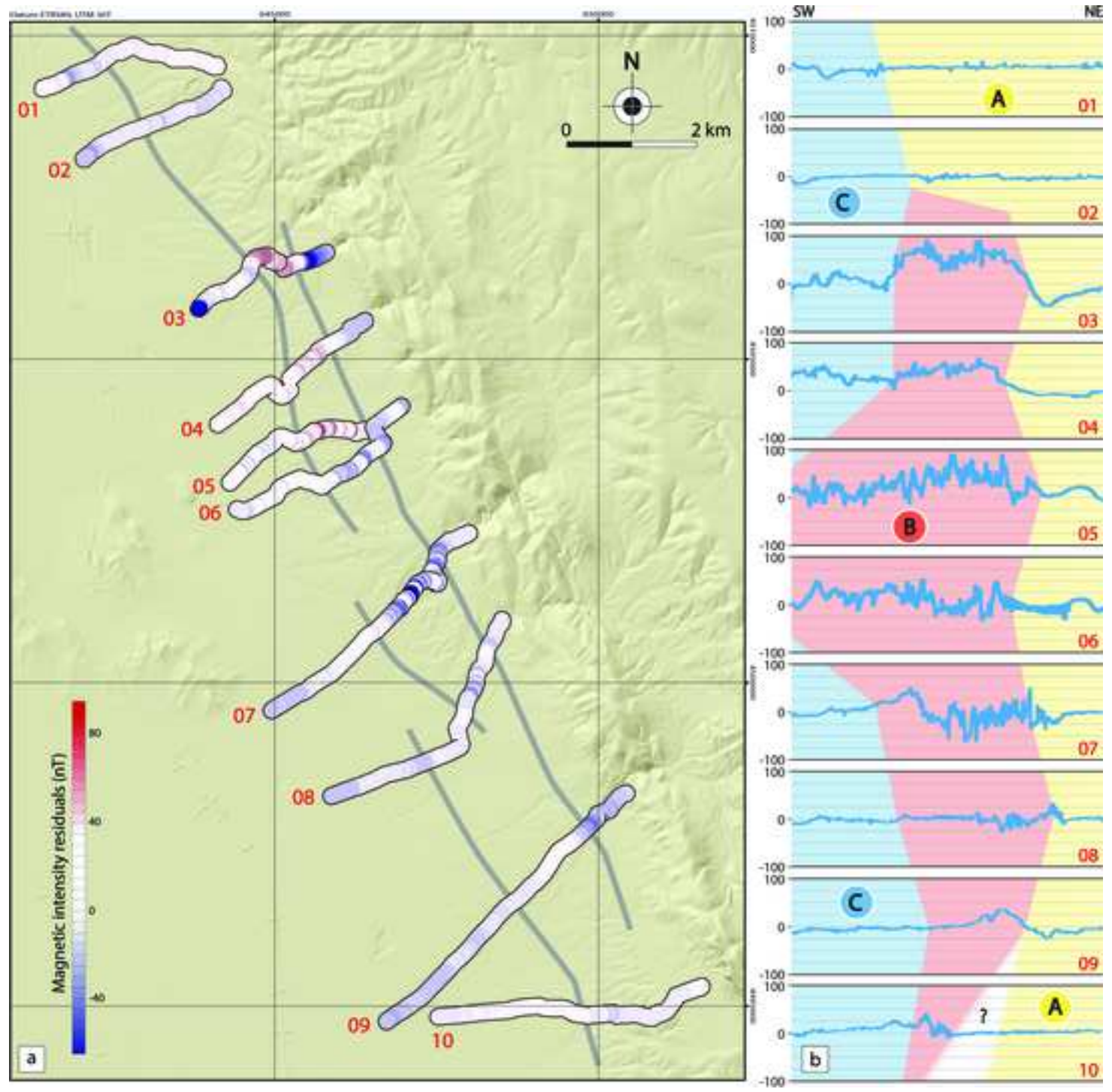




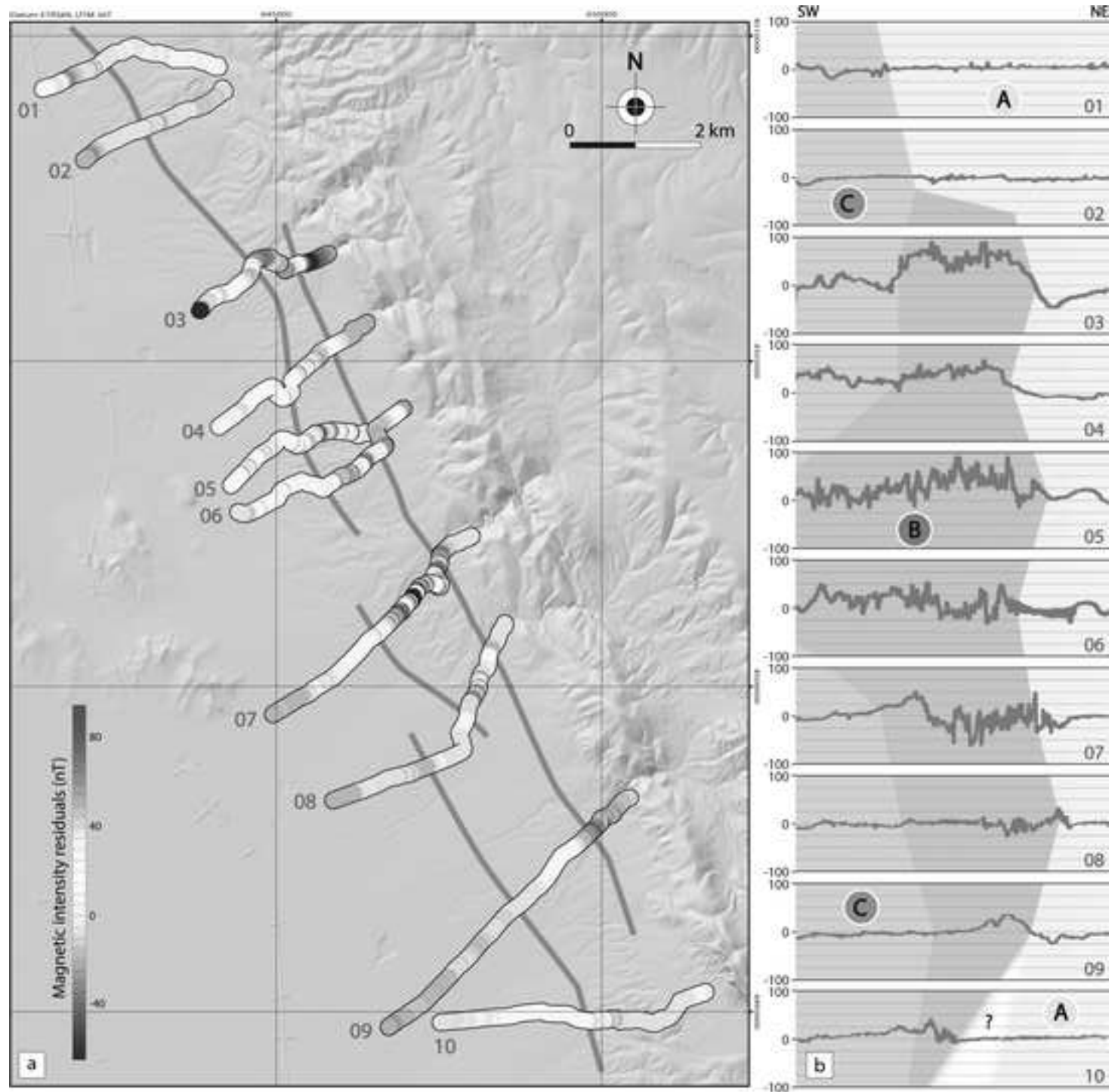


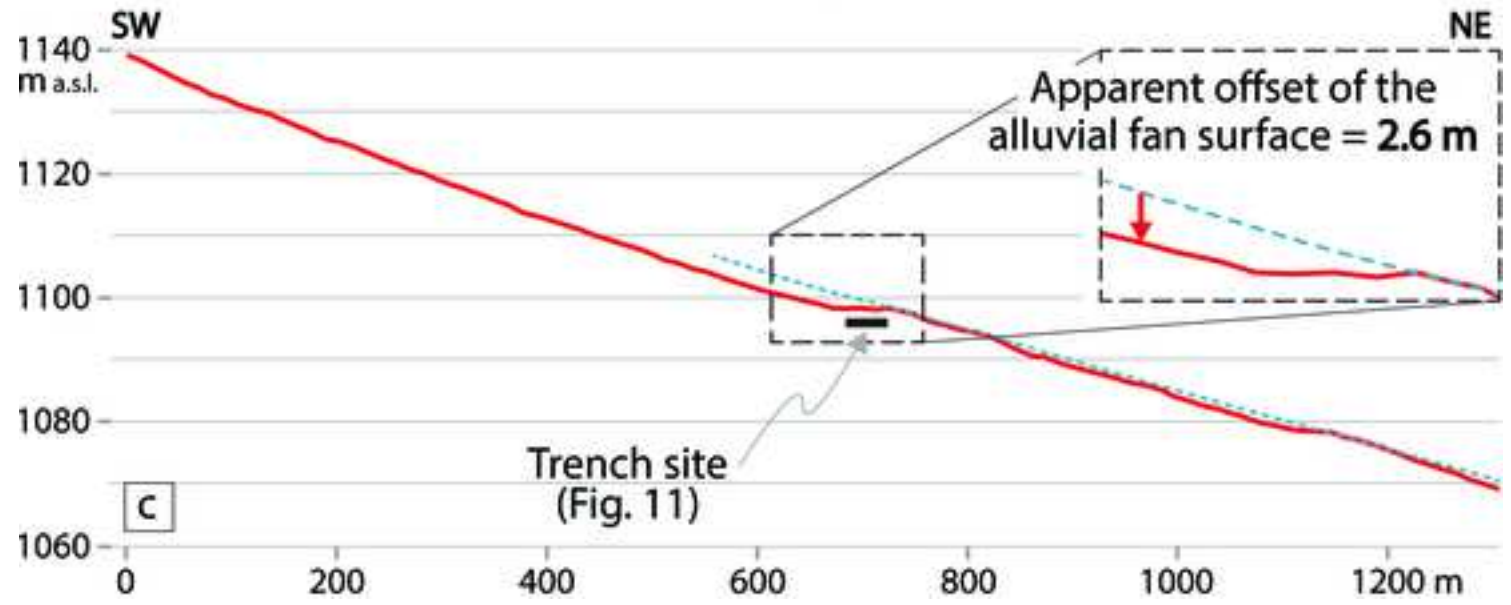
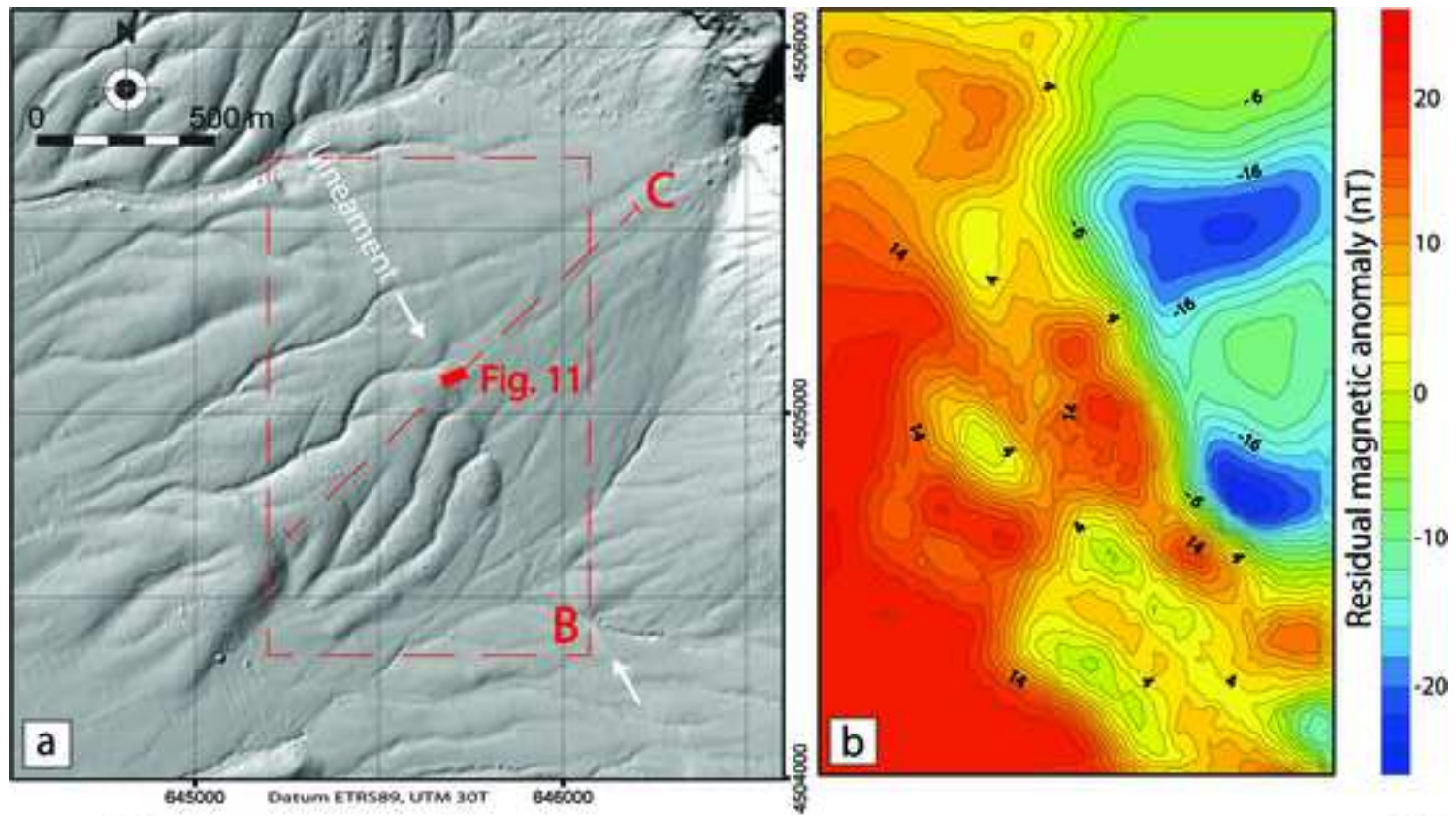


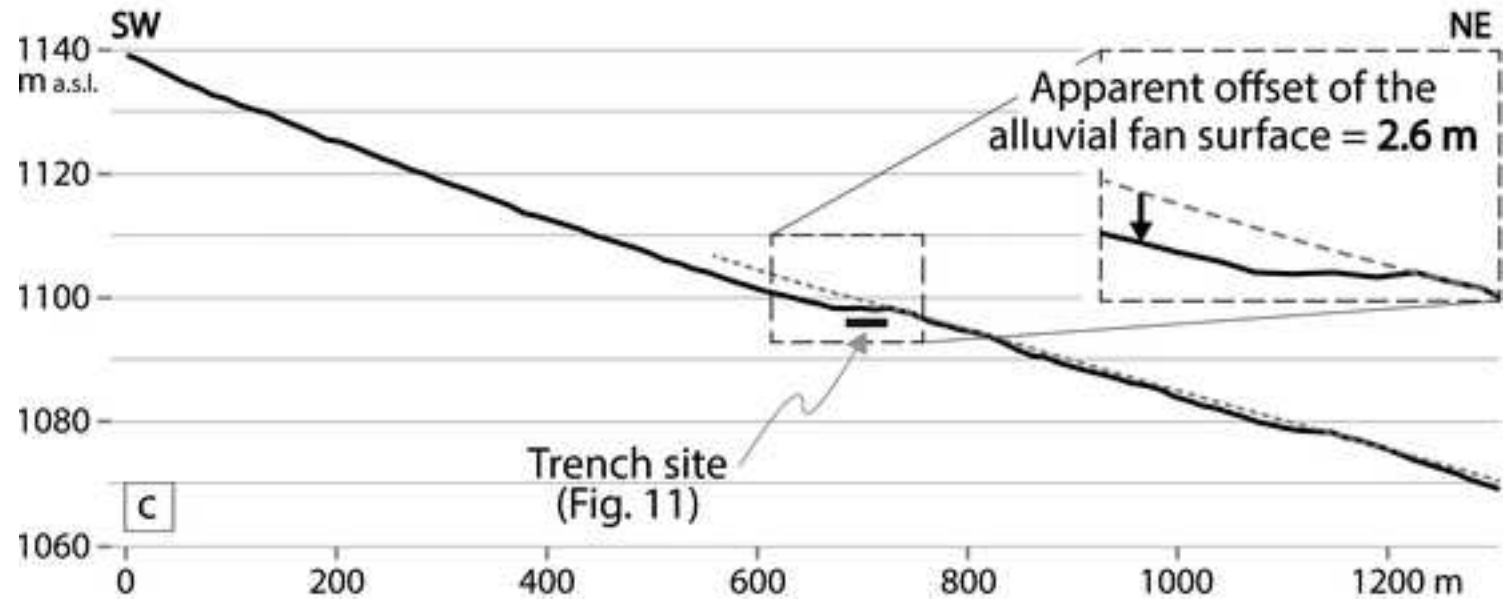
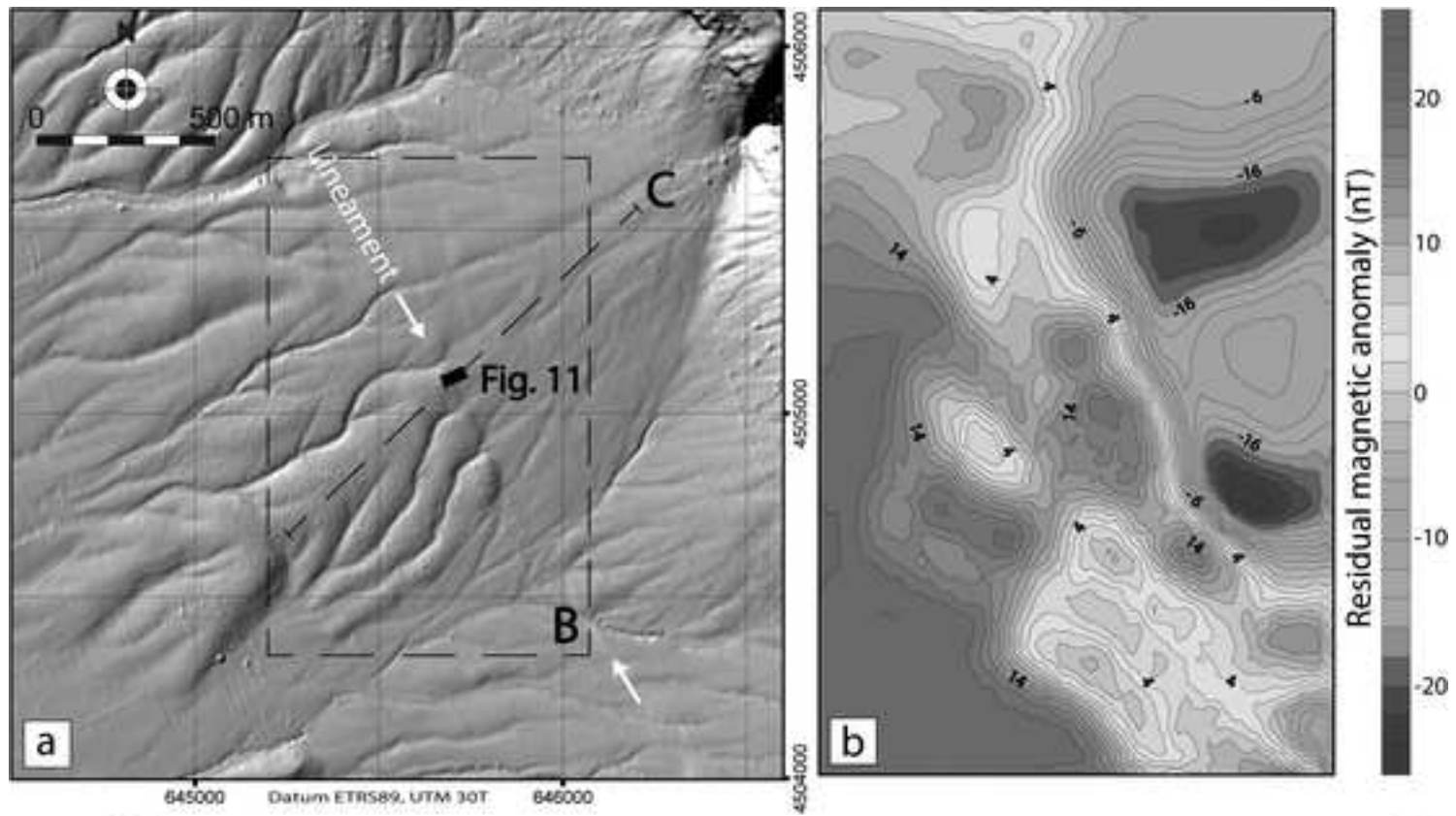


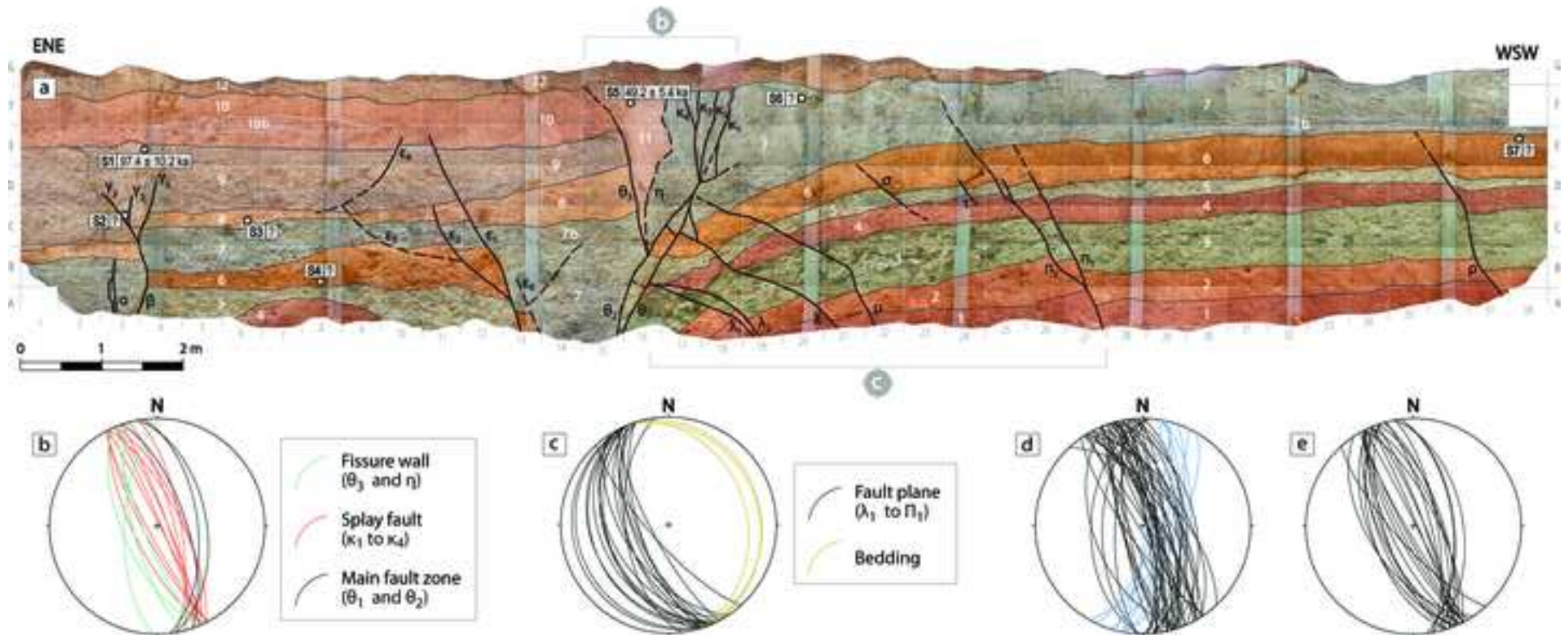


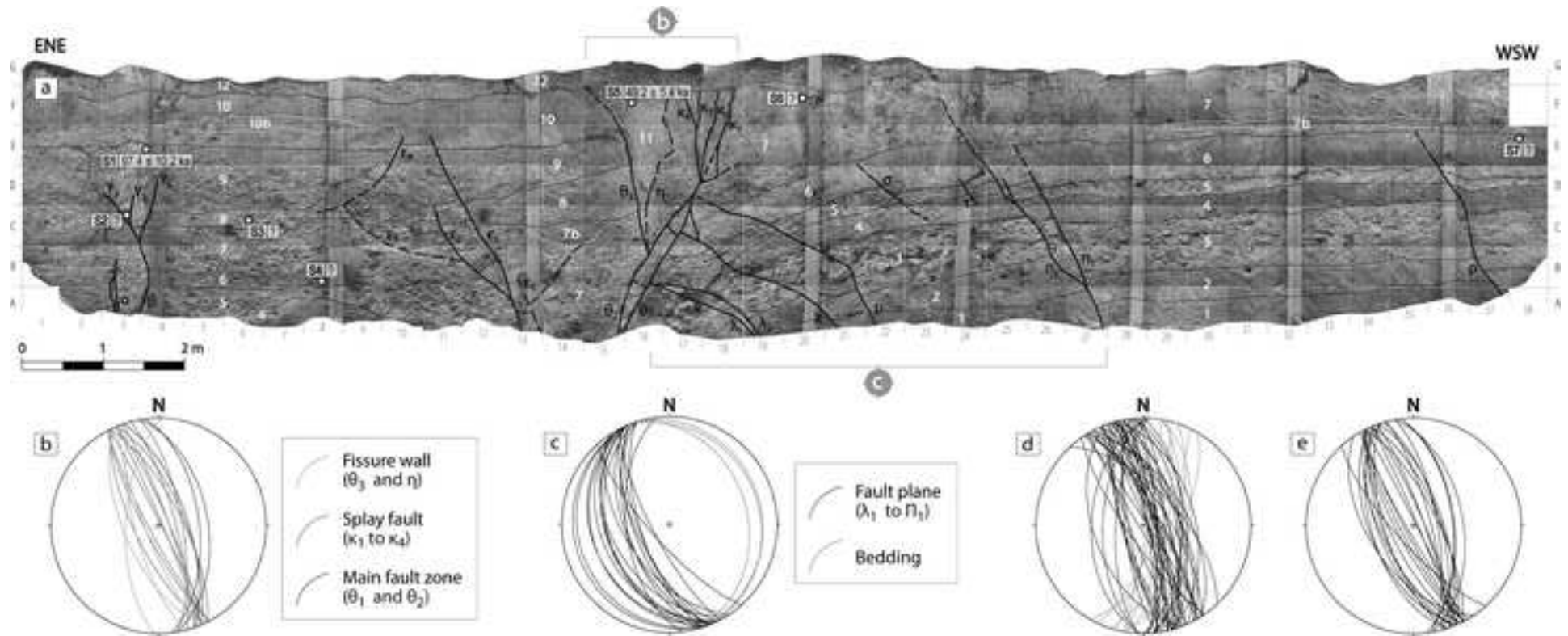


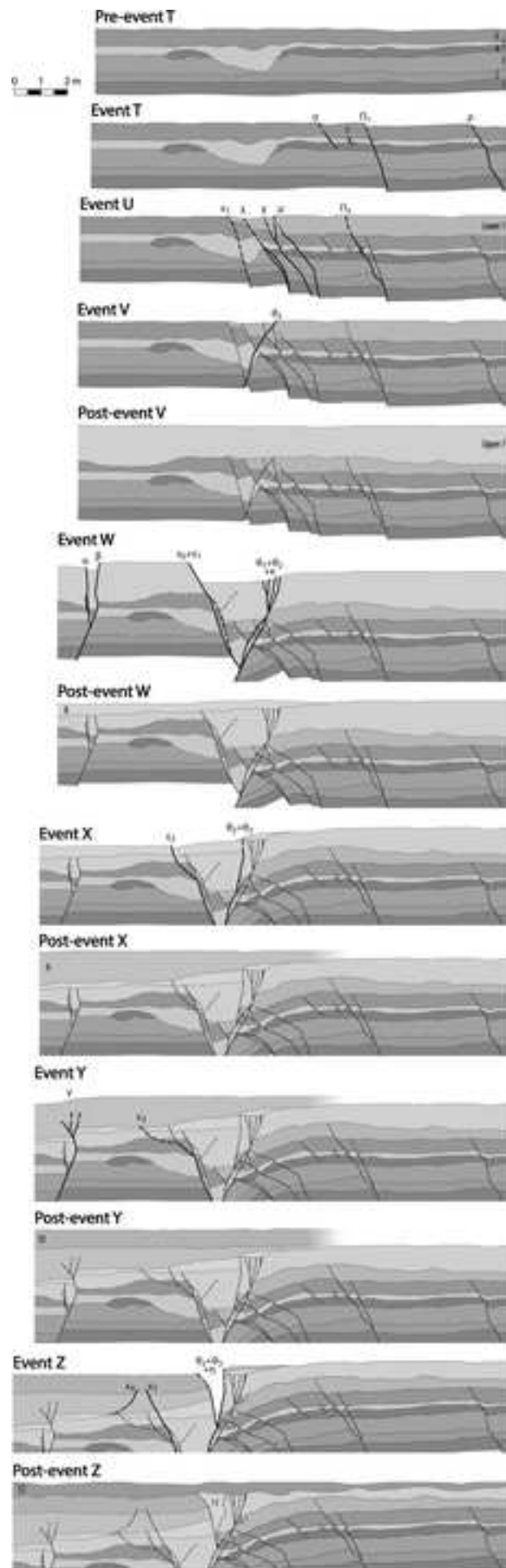


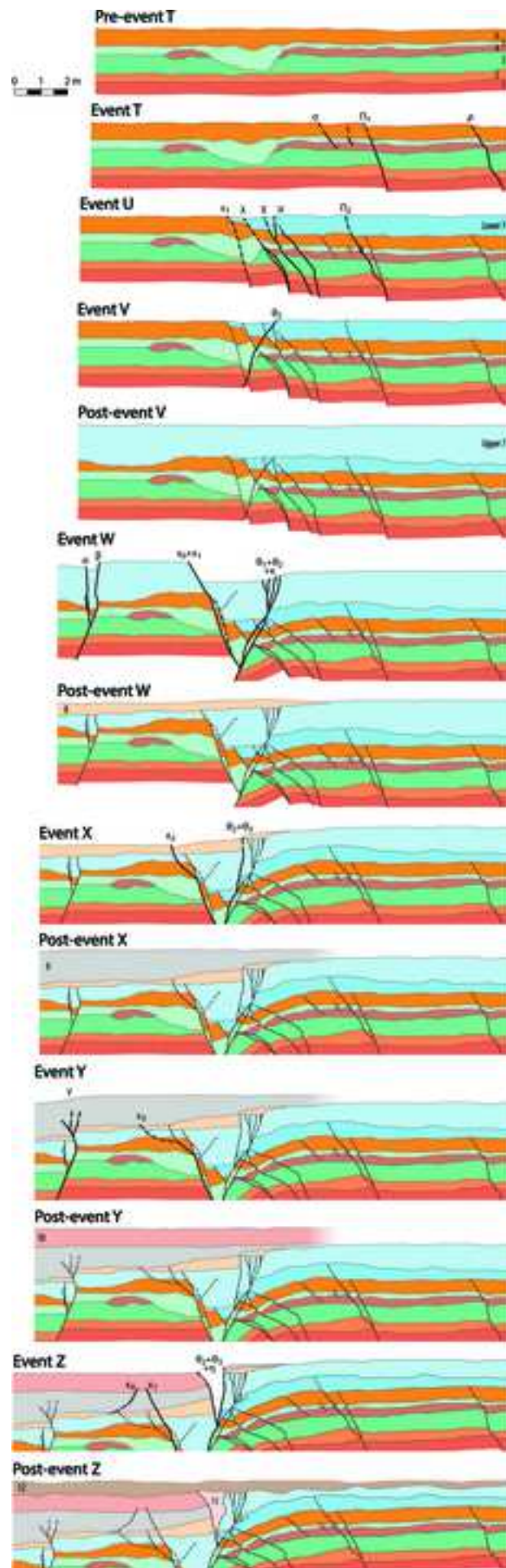


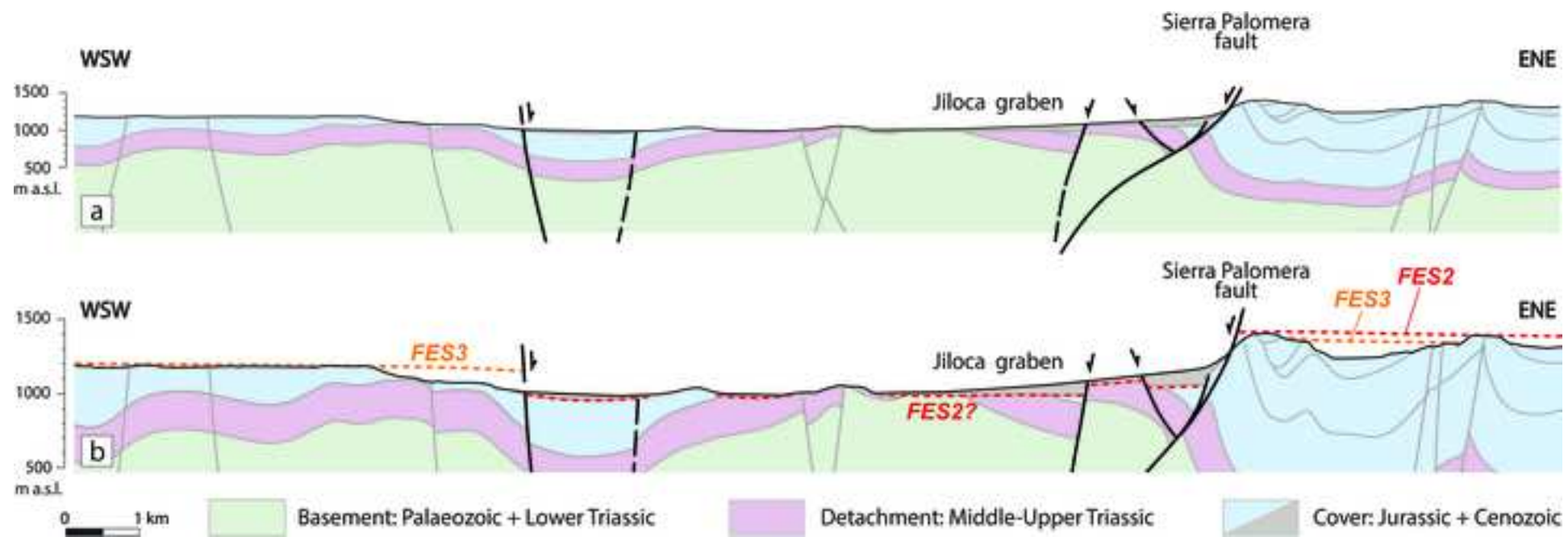




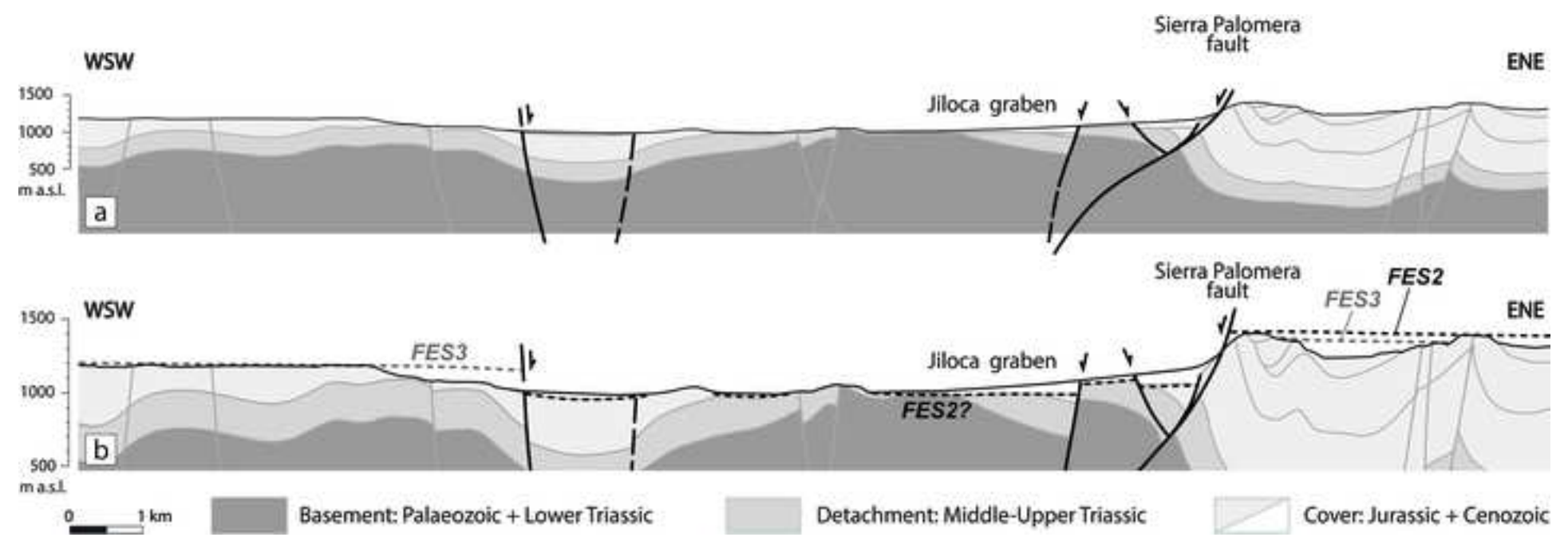


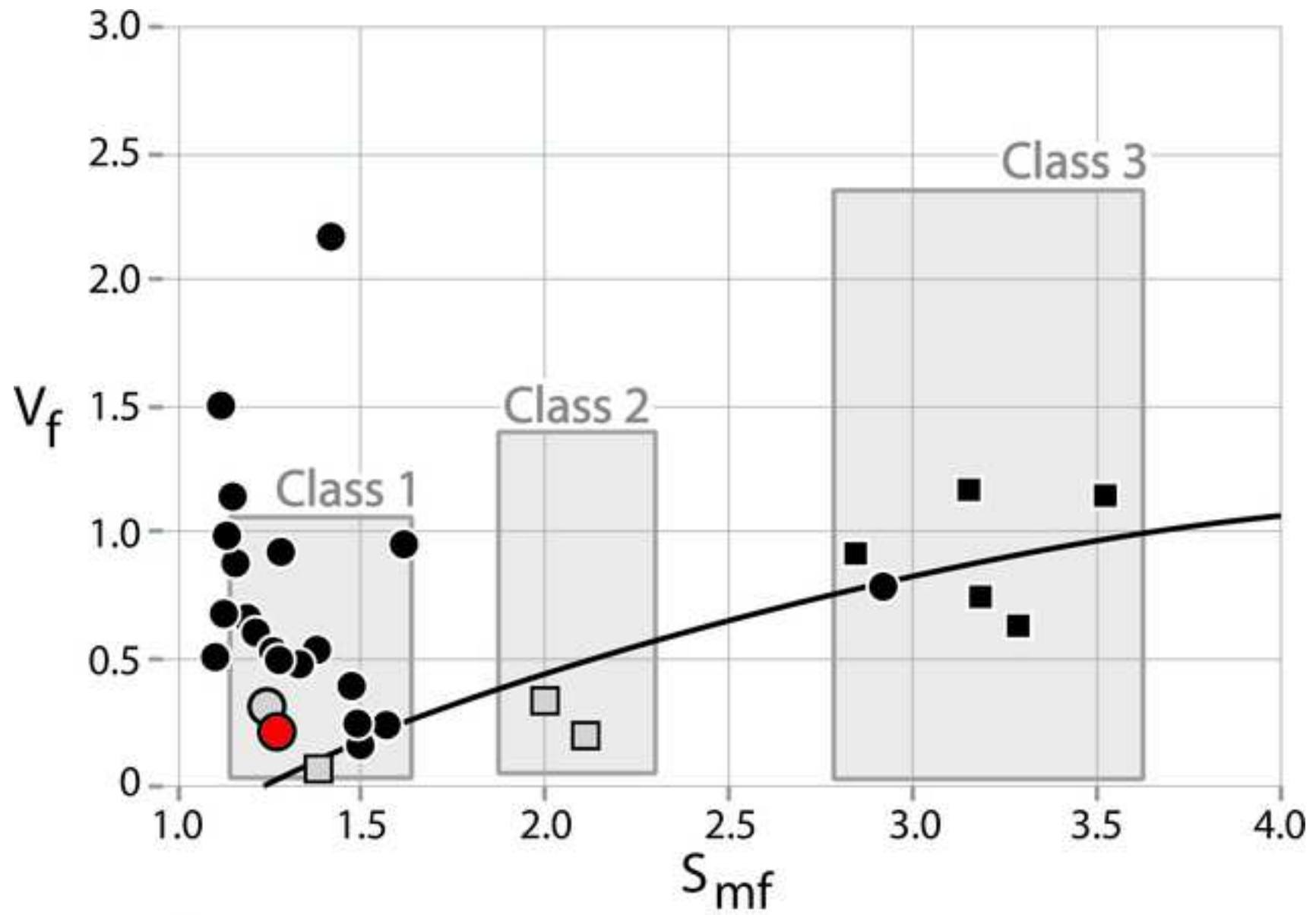






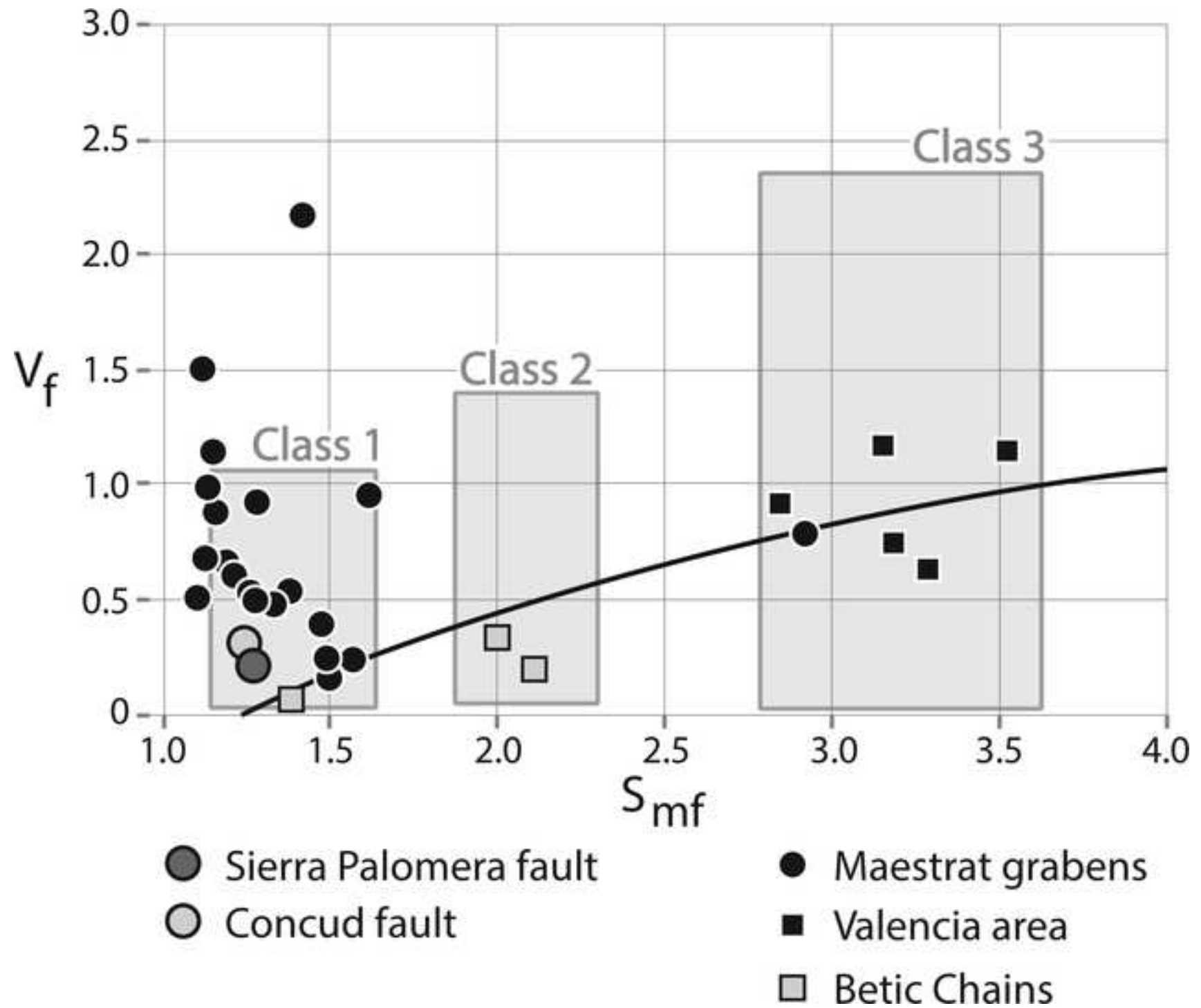


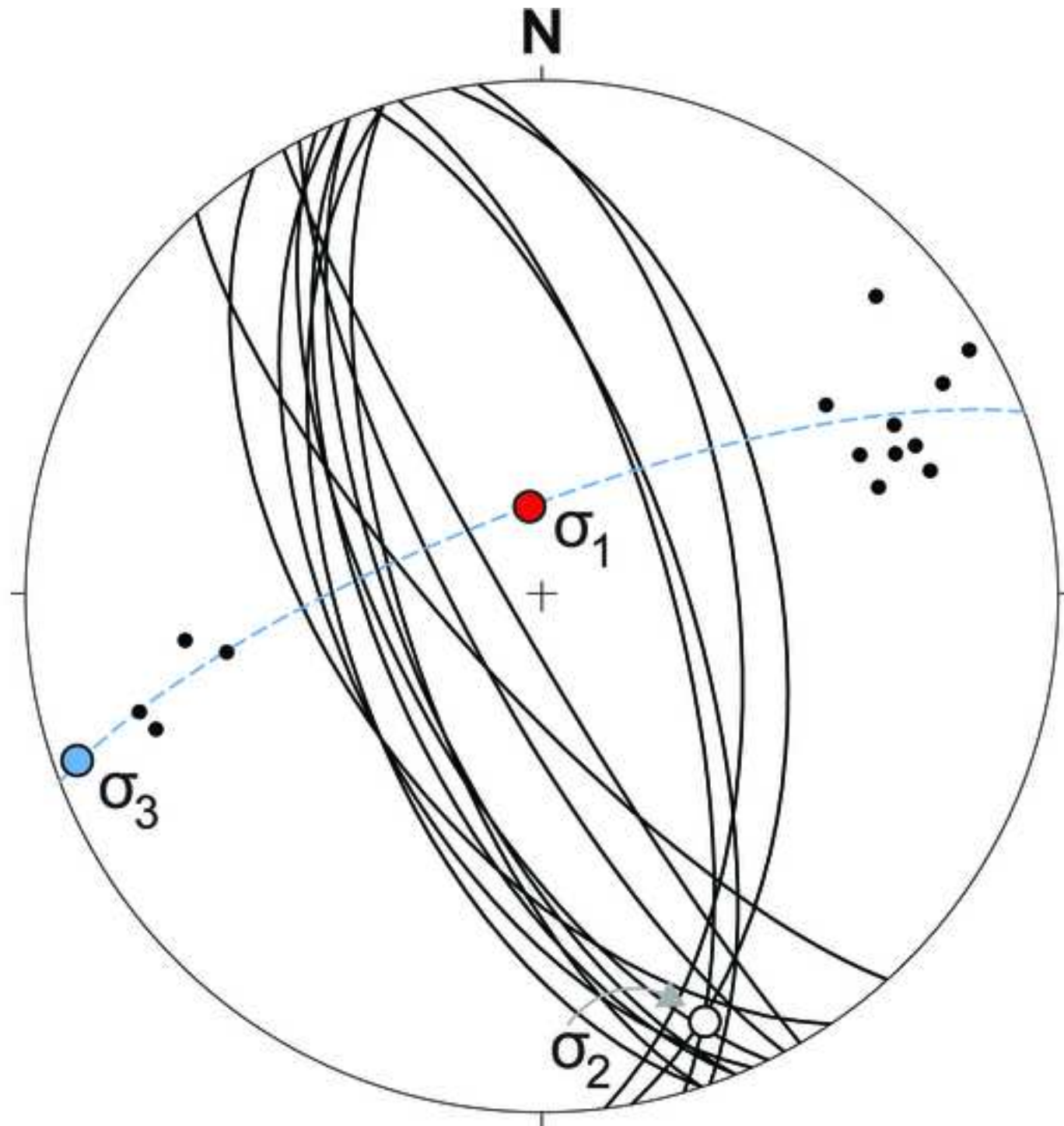


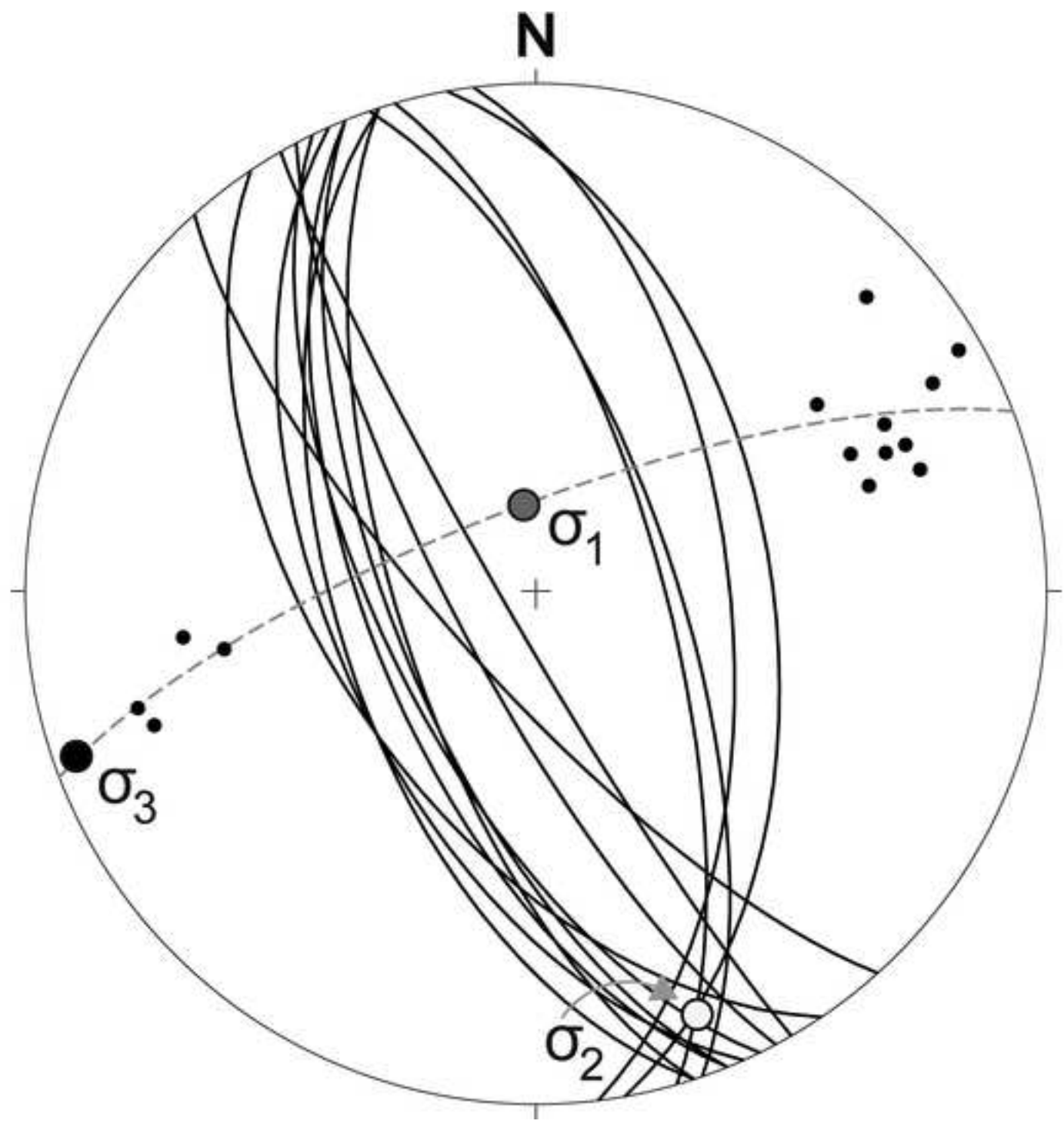


● Sierra Palomera fault  
○ Conclud fault

● Maestrat grabens  
■ Valencia area  
□ Betic Chains







## HIGHLIGHTS

- The Sierra Palomera fault bounds the central sector of the active Jiloca Graben
- This fault offsets ca. 480 m a mid-Pliocene (3.5 Ma) planation surface
- A large antithetic fault in the hanging-wall block accommodates simple shear associated to roll-over
- The antithetic fault was active during Late Pleistocene time
- Hanging-wall subsidiary faulting is controlled by both roll-over kinematics and the regional extensional stress field

1 *Hanging-wall deformation at the active Sierra Palomera extensional fault*  
2 *(Jiloca basin, Spain) from structural, morphotectonic, geophysical and trench*  
3 *study*

4

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18

19 **Abstract**

20 The NNW-SSE trending Sierra Palomera fault is characterized as an active, nearly pure  
21 extensional fault with mean transport direction towards N230°E, consistent with the ENE-  
22 WSW extension trajectories of the recent to present-day regional stress field. Its  
23 macrostructure is described from surface geology and magnetometric and electromagnetic  
24 surveys, which have allowed identifying two subsidiary, nearly parallel normal faults  
25 (antithetic and synthetic, respectively). The structural contour map of an extensive planation  
26 surface, dated to 3.8 Ma, provides a maximum fault throw *s.s.* of 330 m for the main fault  
27 (480 m including bending), and a net slip rate of 0.09 mm/a (0.13 mm/a including bending).  
28 Trench study focussed on the subsidiary antithetic fault shows evidence of its activity during  
29 Middle-Late Pleistocene times, offsetting ca. 2.56 m the slope of a well-preserved alluvial fan.  
30 Detailed analysis and retrodeformation of the antithetic fault and other minor ruptures in the  
31 trench has allowed defining seven deformation events. The lack of a consistent age model for

32 the involved sedimentary sequence makes them almost meaningless in terms of paleoseismic  
33 history. However, geometry and sequential development of meso-scale faults (intermediate  
34 between seismic-scale and analogue models) allows unravelling the extensional deformation  
35 mechanisms-history within the hanging-wall block of the Sierra Palomera fault. Progressive  
36 rupture patterns reveal shifting from dominantly synthetic to dominantly antithetic faulting,  
37 suggesting both kinematical control linked to rollover growth, and dynamical control by the  
38 regional stress field.

39 **Keywords:** Active fault, antithetic fault, rollover, magnetometry, Pleistocene, Iberian Chain.

## 40 1. Introduction

41 Our understanding of geometry and kinematics of extensional fault systems has been  
42 significantly improved thanks to analytical and scaled analogue models, particularly  
43 concerning deformation of the hanging-wall block of listric faults. Such models provide  
44 interesting inferences about controls that the shape of the main fault surface exerts on the  
45 development of hanging-wall folds and fractures. Fault surfaces with irregular geometry  
46 induce antithetic simple shear along a deformation band that nucleates at shallowing fault  
47 bends, while synthetic shear is induced at steepening fault bends (McClay and Scott, 1991;  
48 Xiao and Suppe, 1992; Withjack *et al.*, 1995; Delogkos *et al.*, 2020). Depending on the  
49 mechanical properties-behaviour of materials, such overall simple shear mechanism results in  
50 either fault-related folding (rollover and drag folds, respectively) or faulting (antithetic and  
51 synthetic, respectively). Analogue models provide insights into both differential behaviours,  
52 *e.g.*, by comparing experimental materials as clay and sand (*e.g.*, Withjack *et al.*, 1995).  
53 Nevertheless, as discussed by Xiao and Suppe (1992), models give limited information about  
54 the actual small-scale mechanisms that accommodate deformation. Therefore, contribution of  
55 data directly supplied by field examples is necessary for full understanding of kinematics of  
56 extensional systems.

57 ~~Methodology of trench analysis, extensively used and standardized for~~  
58 ~~paleoseismological studies (e.g., McCalpin, 1996), offers new insights for detailed analysis of~~  
59 ~~progressive extensional deformation. Each identified paleoseismic event can be considered as~~  
60 ~~an incremental or ‘infinitesimal’ deformation episode, and hence the reconstructed~~  
61 ~~paleoseismic sequence provides a realistic view of extension kinematics (although ineludibly~~  
62 ~~constrained to a given space and time window).~~

63 The Sierra Palomera fault, at the central sector of the Jiloca basin, is one of the most  
64 conspicuous recent, hypothetically active extensional faults in the central Iberian Chain  
65 (Spain; Fig. 1), but less known than other neighbouring structures. The Calamocha and



66 Concud faults, which bound the northern and southern sectors of the Jiloca basin (Fig. 1c),  
67 offset early Pliocene lacustrine deposits of the Calatayud and Teruel basins, respectively. This  
68 allows calculating their total throws at about 210 m for the Calamocha fault (Martín-Bello *et*  
69 *al.*, 2014), and 260 m for the Concud fault (Ezquerro *et al.*, 2020). On the contrary, no recent  
70 stratigraphic marker is available for the Sierra Palomera fault. The tectonic nature of the basin  
71 boundary itself, and particularly the relative role of erosive lowering and fault displacement in  
72 the creation of the mountain scarp, has been the object of controversy indeed. After Cortés  
73 and Casas (2000), its topography is essentially a result of erosive incision in response to  
74 orogenic uplift during the Paleogene. Gracia *et al.* (2003) reinterpret the Jiloca depression as a  
75 polje developed during the Late Pliocene-Quaternary. Rubio and Simón (2007) and Rubio *et*  
76 *al.* (2007) provide new sedimentary, geomorphological and hydrogeological evidence on the  
77 tectonic origin of the Jiloca depression, concluding that the Sierra Palomera fault has a  
78 maximum throw approaching 350-400 m. Nevertheless, in contrast with other neighbouring  
79 faults (Concud, Teruel, Valdecebro, Calamocha, Munébrega faults), in which numerous  
80 trench studies have been carried out in the last two decades (Gutiérrez *et al.*, 2009; Lafuente,  
81 2011; Lafuente *et al.*, 2011a, 2014; Martín-Bello *et al.*, 2014; Simón *et al.*, 2016, 2017, 2019),  
82 no paleoseismological analysis has been developed in the Sierra Palomera fault owing to lack  
83 of appropriate sites for digging a trench at the main fault zone.

84 The Sierra Palomera fault belongs to the Jiloca graben, the youngest Neogene-Quaternary  
85 basin of the central-eastern Iberian Chain (eastern Spain; Fig. 1) linked to rifting of the  
86 Valencia Trough (Vegas *et al.*, 1979). In overall, it is a half-graben that exhibits a NNW-SSE  
87 trend resulting from en-échelon, right lateral arrangement of NW-SE striking normal faults at  
88 its eastern, active border. This basin has developed since Late Pliocene time, under a nearly  
89 biaxial or multidirectional extension regime ( $\sigma_2 \approx \sigma_3$ ) with maximum extension trajectories  
90 ( $\sigma_3$ ) oriented ENE-WSW (Simón, 1983, 1989; Arlegui *et al.*, 2005; Liesa *et al.*, 2019).

91  
92 **[PREFERENTIALLY, FIG.1 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

93  
94 The northern and southern sectors of the Jiloca basin are bounded by the Calamocha and  
95 Concud faults, respectively (Fig. 1c). Both faults cut and offset the uppermost, early Pliocene  
96 lacustrine deposits of the neighbouring Calatayud and Teruel basins, respectively. Based on  
97 clearly recognized stratigraphic markers, the corresponding maximum throws are calculated at  
98 about 210 m for the Calamocha fault (Martín-Bello *et al.*, 2014), and 260 m for the Concud  
99 fault (Ezquerro *et al.*, 2020).

100 In the central segment of the basin (Fig. 2), the displacement at the Sierra Palomera fault  
101 cannot be calculated in the same way since no recent stratigraphic marker is available. The  
102 tectonic nature of the boundary itself, and particularly the discrimination between the role of  
103 erosive lowering and vertical tectonics in the creation of the mountain scarp has been the  
104 object of controversy indeed. After Cortés and Casas (2000), its topography is essentially a  
105 result of erosive incision in response to orogenic uplift. Gracia *et al.* (2003) reinterpret the  
106 Jiloca depression as a polje, developed during Late Pliocene-Quaternary times on an incipient  
107 half graben. Rubio and Simón (2007) and Rubio *et al.* (2007) analyse these arguments and  
108 provide new sedimentary, geomorphological and hydrogeological evidence on the tectonic  
109 origin of the Jiloca depression, from both surface and subsoil data. These authors conclude  
110 that: (i) the basin is a tectonic graben limited by Plio-Quaternary faults; (ii) the Sierra  
111 Palomera fault has a maximum throw approaching 350-400 m; and (iii) although the basin is  
112 noticeably underfilled, its sedimentary infill shows thickness and facies distribution consistent  
113 with such basin model.

114  
115 ~~IPREFERENTIALLY, FIG.2 SHOULD BE INSERTED HERE, AS A 1.5-COLUMN FIGURE!~~

116  
117 Concerning the signs of Quaternary activity, these are again conspicuous in the northern  
118 and southern sectors of the Jiloca graben but not in the central one. The Conclud fault has been  
119 object of intense paleoseismological research ~~at both natural outcrops and trenches~~, which  
120 ~~have has~~ allowed reconstructing a ~~wide paleoseismic~~ succession of eleven events since ca. 74  
121 ka BP ~~to the present day~~, with average recurrence period of 7.1-8.0 ka, total accumulated net  
122 ~~accumulated~~ slip of about 20 m, and average slip rate of 0.29 mm/a (Lafuente, 2011; Lafuente  
123 *et al.*, 2011a,b, 2014; Simón *et al.*, 2016). Quaternary activity of the Calamocha fault is  
124 revealed by the mechanical contact between Neogene units of the Calatayud basin and Late  
125 Pleistocene alluvial deposits that infill the northernmost Jiloca basin. ~~Three distinct fault~~  
126 ~~branches are well exposed at the slopes of the A-23 highway and an industrial area in the~~  
127 ~~neighbourhoods of Calamocha town~~ (Martín-Bello *et al.*, 2014). Other neighbouring faults  
128 (Munébrega, Teruel, Valdecebro) have also been object of trench studies in the last two  
129 decades (Gutiérrez *et al.*, 2009; Simón *et al.*, 2017, 2019).

130 On the contrary, no exposure of the Sierra Palomera fault cutting Quaternary deposits  
131 has been ~~described~~ reported, and no paleoseismological analysis has been carried out. This is  
132 mainly due to the fact that the Quaternary fluvial incision is virtually absent, and there is a  
133 lack of appropriate sites for digging trenches across the main fault. ~~Endorheic conditions in~~  
134 ~~this sector have remained until historical times, with development of a palustrine area at the~~

135 ~~basin centre (ancient Cañizar lake; Rubio and Simón, 2007). Observation of Quaternary~~  
136 ~~surficial ruptures has not been possible, thus their evidence is only indirect.~~

137 In such a situation, the study of the Sierra Palomera fault should be focussed on obtaining  
138 indirect evidence of its recent activity from hanging-wall deformation. This can be achieved  
139 by (i) exploring the subsoil of the associated pediment by means of geophysical techniques,  
140 (ii) analysing the effects of fault activity on the relief through morphotectonic analysis, and  
141 (iii) recognizing deformation of Quaternary materials in trenches. Methodology of trench  
142 analysis, extensively used and standardized for paleoseismological studies (e.g., McCalpin,  
143 2009), offers new insights for detailed analysis of progressive extensional deformation.  
144 Concerning scale, trenches have the advantage of delivering valuable information on faults at  
145 an intermediate scale between seismic profiles and laboratory analogue models. Concerning  
146 timing, each identified event can be considered as an incremental or ‘infinitesimal’  
147 deformation episode, and hence the reconstructed paleoseismic succession provides a detailed  
148 and realistic view of extension kinematics (although ineludibly constrained to a given space  
149 and time window).

150 ~~The purpose of the present work has been carried out in that perspective. is contributing~~  
151 ~~to fill this gap, with three~~Our specific objectives are: (1) improving our overall knowledge on  
152 the structure and evolution of the Sierra Palomera fault and the Jiloca basin; (2) reporting  
153 evidence on the activity of the Sierra Palomera fault during the Quaternary, and (3)  
154 characterizing the style-patterns of progressive extensional deformation within its hanging-  
155 wall block. ~~Especial attention will be paid to structural features that indicate recent activity of~~  
156 ~~the Sierra Palomera fault and other structures associated to it, showing how geophysical~~  
157 ~~exploration provides complementary subsoil information with that respect. We will go deeper~~  
158 ~~into the morphotectonics of the area, analysing the effects of fault activity on the relief. In the~~  
159 ~~absence of stratigraphic markers, extensive Late Neogene planation surfaces existing in the~~  
160 ~~region will be especially useful as geomorphological markers of deformation. Finally, we will~~  
161 ~~address a detailed analysis of ruptures within a portion of the hanging wall block of the Sierra~~  
162 ~~Palomera fault by using trenching techniques.~~

## 164 **2. Geological setting**

165 The Iberian Chain is a NW-SE trending, 450 km long intraplate mountain range located  
166 in the eastern Iberian Peninsula (Fig. 1a). This chain developed in Paleogene to Early  
167 Miocene times due to positive inversion of the extensional Mesozoic Iberian basin, under the

168 convergence between the Africa and Eurasia plates, ~~under which an heterogeneous ensemble~~  
169 ~~of fold and thrust belts, depicting a roughly double vergence structure, was built by positive~~  
170 ~~inversion of the extensional Mesozoic Iberian basin~~ (Álvaro *et al.*, 1979; Guimerà and Álvaro,  
171 1990; Capote *et al.*, 2002; Liesa *et al.*, 2018). After a transition period during the Early  
172 Miocene, in which the longitudinal Calatayud basin developed under a transpressional regime  
173 (Colomer and Santanach, 1988; Simón *et al.*, 2021), a new extensional stage associated to  
174 rifting of the Valencia Trough took place.

175 Extensional deformation propagated onshore towards the central part of the Iberian Chain  
176 (Álvaro *et al.* 1979, Vegas *et al.*, 1979) in two stages, inducing both reactivation of the main  
177 inherited Mesozoic faults and formation of new normal faults, and generating a number of  
178 diversely oriented intracontinental grabens and half-grabens (Simón, 1982, 1989; Gutiérrez *et*  
179 *al.*, 2008, 2012; Ezquerro, 2017; Liesa *et al.*, 2019).

180 ~~Relationships of extensional macrostructures with geomorphic features and stress~~  
181 ~~evolution in the Iberian Chain allow defining two main extensional phases.~~ During the first  
182 ~~phase stage~~ (Late Miocene to Early Pliocene in age), the 90-km-long, NNE-SSW to N-S  
183 trending Teruel half-graben basin developed, filled with terrestrial sediments up to 500 m  
184 thick (Simón, 1982, 1983; Moissenet, 1983; Anadón and Moissenet, 1996; Ezquerro, 2017;  
185 Ezquerro *et al.*, 2019, 2020). ~~Throughout this period, the Teruel basin propagated northwards,~~  
186 ~~acquiring a N-S trend at its northern sector (El Pobo fault zone; Fig. 1b; Ezquerro *et al.*, 2019,~~  
187 ~~2020), while other N-S trending half-grabens were settled in its footwall block (western and~~  
188 ~~eastern El Pobo basins; Simón Porcar *et al.*, 2019). The~~ The second extensional ~~phase stage~~  
189 ~~that started by~~ in the Late-mid-Pliocene and shows has produced a more widespread  
190 deformation i. In the central Iberian Chain, a large number of ~~compressional and~~  
191 ~~extensional inherited~~ structures were reactivated, producing new NNW-SSE trending grabens  
192 and half-grabens that are inset or cross-cut the pre-existent Teruel and Calatayud basins  
193 (Simón, 1983, 1989; Gutiérrez *et al.*, 2008, 2020; Liesa *et al.*, 2019). They include, among  
194 others (Fig. 1c), ÷ (i) the 80-km-long Jiloca graben, which results from en-échelon, right  
195 releasing arrangement of the NW-SE striking Conclud, Sierra Palomera and Calamocha faults  
196 (Simón, 1983; Rubio and Simón, 2007; Simón *et al.*, 2012, 2017; Peiro *et al.*, 2019, 2020);  
197 (ii) the 30 km long Daroca half graben (Colomer, 1987; Gracia, 1992; Gutiérrez *et al.*, 2008,  
198 2020; Casas *et al.*, 2018); (iii) the 88 km long Río Grío Panerudo Fault Zone, made of two  
199 ~~main faults, Río Grío Lanzuela and Cuealón Panerudo (Peiro and Simón, 2021).~~ In the first  
200 extensional phase, the direction of maximum extension ( $\sigma_3$ ) was E-W to ESE-WNW (under a  
201 triaxial extensional regime), ~~whereas while~~ 'multidirectional' extension with ENE-WSW  $\sigma_3$

202 trajectories characterizes the second phase (Simón, 1982, 1983, 1989; Cortés, 1999; Capote *et*  
203 *al.*, 2002; Arlegui *et al.*, 2005, 2006; Liesa, 2011; Ezquerro, 2017; Liesa *et al.*, 2019).  
204 ~~Regional uplift during the Late Pliocene-Quaternary resulted in: (i) constraining~~  
205 ~~sedimentation to underfilled residual basins, with a modest sedimentary infill (normally less~~  
206 ~~than 100 m thick), and (ii) driving most of the area to exorheic conditions.~~

207 Geometric construction of normal fault profiles of the Teruel ~~fault-half-graben~~ system  
208 ~~locates-allows locating~~ the sole detachment at a depth of 14-17 km b.s.l., ~~and estimating an~~  
209 ~~average E-W stretching factor  $\beta = 1.1$  since its onset (11.2 Ma ago)~~ (Ezquerro *et al.*, 2020);  
210 ~~i.e., in an intermediate location within the ~30 km thick crust of the central Iberian Chain,~~  
211 ~~although it diminishes up to ~14 km in the central part of the Valencia Trough (e.g. Roca and~~  
212 ~~Guimerà, 1992). Ezquerro *et al.* (2020) estimate an average E-W stretching factor  $\beta=1.1$  since~~  
213 ~~the formation of the Teruel basin (11.2 Ma ago), accommodated by mMajor faults that have~~  
214 ~~verticalaccumulated~~ slip ~~between-of~~ a few hundred metres ~~and-to ca.~~ 1 km ~~(computing both~~  
215 ~~fault throw s.s. and associated bending)~~. The ~~total-verticalresulting~~ slip rate, ~~(considering fault~~  
216 ~~throw and associated bending) shows a similar value (around 0.09 mm/a in average,) is very~~  
217 ~~similar~~ for distinct transects across the ~~Teruel-half-grabenstructure~~, but ~~shows~~ a clear increase  
218 between both extensional phases: ~~(from 0.05-0.07 mm/a to 0.12-0.16 mm/a )-has been~~  
219 ~~reported~~ (Ezquerro *et al.*, 2020). ~~Such~~ slip rate increase has been attributed to: (i) onshore,  
220 westwards propagation of extensional deformation from the inner parts of the Valencia  
221 Trough, enhanced by crustal doming that would have affected the eastern Iberian Chain; (ii)  
222 ~~change-of-the-regional-stress-field, which evolved toonset of the~~ multidirectional extension  
223 ~~stress field~~ driven by ~~a~~ crustal doming mechanism; (iii) progressive fault linkage since the  
224 beginning of the Late Miocene (Ezquerro *et al.*, 2020); ~~which is documented from tectono-~~  
225 ~~stratigraphic information.~~

226 Mountains surrounding the Teruel and Jiloca basins show extensive erosion surfaces  
227 modelling Mesozoic-Palaeogene rocks and bevelling compressional structures. Two large  
228 planation surfaces, whose remnants appear at different heights either on the upthrown blocks  
229 or in the basin floors, have been traditionally defined (Gutiérrez and Peña, 1976; Peña *et al.*,  
230 1984; Sánchez-Fabre *et al.*, 2019): (i) *Intra-Miocene Erosion Surface (IES*, middle Miocene),  
231 generally recognized in the upper part of the main reliefs, and (ii) *Fundamental Erosion*  
232 *Surface (FES*, middle Pliocene), easily recognizable as a vast planation level at lower heights.  
233 They approximately correspond to the *Iberian Chain Surface* and the *Lower Pliocene Surface*  
234 by Pailhé (1984), and the S1 and S2 by Gutiérrez and Gracia (1997), respectively. Recent  
235 detailed studies (Simón-Porcar *et al.*, 2019; Ezquerro *et al.*, 2020) have demonstrated that the

236 *FES* splits into three different surfaces: an Upper Sublevel, the *FES s.s.* (the most widely  
237 developed), and a Lower Sublevel. In this work, these surfaces will be called as *FES1*, *FES2*  
238 and *FES3*, respectively. Planation surfaces have been physically correlated with different  
239 coeval sedimentary horizons (lacustrine-palustrine carbonates) within the sedimentary infill of  
240 the Teruel basin (Ezquerro, 2017), whose ages are well-constrained ~~on the basis of~~ ~~and~~ ~~on~~  
241 mammal sites ~~as well as~~ ~~on~~ and magnetostratigraphy ~~ie constraints~~. In this way, the *Intra-*  
242 *Miocene Erosion Surface* has been dated close to the Aragonian-Vallesian limit (~11.2 Ma;  
243 Alcalá *et al.*, 2000; Ezquerro, 2017), *FES1* and *FES2* to the Late Ruscinian (both merging  
244 around ~3.8 Ma), and *FES3* to the Early Villafranchian (~3,5 Ma) (Ezquerro *et al.*, 2020).

245 Qualitative and quantitative geomorphological features of the mountain fronts and the  
246 associated piedmonts of the eastern margin of the Jiloca graben are those typical of active  
247 normal faults. At the Conclud fault, Lafuente *et al.* (2011b) described conspicuous triangular  
248 facets and short, non-incised alluvial fans, and provided a significantly low value of the  
249 mountain-front sinuosity index defined by Bull and McFadden (1977) ( $S_{mf} = 1.24$ ). At the  
250 Sierra Palomera fault, García-Lacosta (2013) described trapezoidal facets and V-shaped  
251 gullies, and provided a similar value for the sinuosity index ( $S_{mf} = 1.27$ ). The fault scarps are  
252 connected with the depression bottom by gentle pediments mostly draining towards the Jiloca  
253 river, although endorheic conditions have locally remained until historical times, with  
254 development of a palustrine area at the basin centre (ancient Cañizar lake; Rubio and Simón,  
255 2007).

256 Historic and instrumental seismicity of the central-eastern Iberian Chain is low to  
257 moderate. In the Teruel region, the epicentres are concentrated at the Jiloca graben margins,  
258 the central-southern sector of the Teruel basin, and the Albarracín and Javalambre massifs.  
259 Apart from the Albarracín massif, epicentres can be reasonably associated to Neogene-  
260 Quaternary known faults. Measured magnitudes ( $M_b$ ) usually range from 1.5 to 3.5, with  
261 maximum  $M_b = 4.4$  in the Teruel Graben and  $M_b = 3.8$  in the Albarracín massif (~~data from~~  
262 ~~seismic database of Instituto Geográfico Nacional, IGN:~~  
263 ~~<https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>~~IGN, 2021).

264

### 265 **3. Methodology**

#### 266 **3.1. Structural and morphotectonic study**

267 The structural study is based on recognizing and mapping the main structures on aerial  
268 photographs at 1: 18,000 and 1: 33,000 scale, and satellite imagery, complemented with field

269 surveys involving outcrop-scale observations. Data of orientation of rupture surfaces and  
270 slickenlines have been collected in a number of sites within the Sierra Palomera fault damage  
271 zone, as well as within the trench described below. Stereoplots (equal-area, lower hemisphere)  
272 of those data sets have been elaborated using Stereonet 8 software (Allmendinger *et al.*, 2012;  
273 Cardozo and Allmendinger, 2013).

274 To characterize the geometry of recent vertical deformation, the three erosional planation  
275 surfaces (*FES1*, *FES2* and *FES3*) described above were used as markers. This required  
276 mapping of erosion surfaces and morphotectonic analysis based on aerial photographs (scales  
277 1: 18,000 and 1: 33,000) and orthorectified photographs (1: 5000), as well as on digital  
278 elevation models (DEM, pixel = 5 m) and the resulting hillshade images. A structural contour  
279 map of *FES2* was elaborated by interpolating the altitude of their remnants, which permits  
280 measuring ~~vertical displacement~~ throw across the main fault and hence calculating slip rate.  
281 Changes of throw ~~vertical displacement~~ along the fault zone were ~~inferred~~ calculated from 1-  
282 km-spaced transects orthogonal to the fault trace and analysed on a throw vs. distance (T-D)  
283 graph.

284 Once constrained the age of a planation surface (see Section 2), the main challenge to be  
285 addressed ~~when using it as a marker~~ is ensuring its degree of flatness, being aware of the  
286 degree of error involved in height ~~treatment~~ management. Continental planation surfaces can  
287 show gentle (short- to middle-wavelength) unevenness, or locally connect with residual, non-  
288 flattened reliefs through pediment slopes. Amplitude of their unevenness advises to use an  
289 adequate ~~spacing for~~ contour intervals for *FES2* in order to represent its present-day geometry  
290 with the suitable precision. Both the local difference in height between *FES2* and *FES3* and  
291 the local unevenness within each one usually lies within the range of 10-40 m. Therefore, we  
292 assume that: (i) ~~vertical~~ fault throws calculated from them implicitly include a maximum error  
293 bar of  $\pm 40$  m, and (ii) a 50-m-spaced contour map can be considered as reasonable for  
294 assessing recent movements (as previously proposed by Ezquerro *et al.*, 2020). Such level of  
295 uncertainty in the calculated fault throws results in errors for slip rates around 0.01 mm/a.

### 296 3.2. Subsoil exploration

297 Subsurface information was acquired by means of geophysical exploration. Two different  
298 techniques were utilised, which had rendered interesting results in other neighbouring sectors  
299 (*e.g.*, Pueyo *et al.*, 2016): magnetometry and electromagnetic (EM) multifrequency survey. A  
300 twofold approach was taken: first, a regional analysis by means of ten transects approximately  
301 orthogonal to the Sierra Palomera mountain front; second, a detailed analysis of a sector  
302 where the highest geophysical anomalies were identified and also where geomorphological

303 evidences hinted at the presence of a previously unknown antithetic fault. For the  
304 magnetometry survey, a GSM-19 equipment with built-in GPS was used to measure both  
305 Earth magnetic field intensity and vertical magnetic gradient (sensors separation of 0.5 m).  
306 Diurnal correction was performed from a second, stationary, magnetometer (PMG-01) that  
307 permitted to exclude natural earth magnetic field changes during the survey and to compare  
308 the results performed during different days. Then, the regional general trend was identified  
309 and subtracted to earth magnetic data to highlight anomalies in the form of residual values.  
310 The EM multifrequency survey was performed by a GEM-02 device for a range of  
311 frequencies between 65 and 0.5 kHz.

312 Subsoil information has been complemented with borehole data extensively compiled by  
313 Rubio (2004), whose synthetic results were presented by Rubio and Simón (2007). ~~Such~~  
314 ~~subsoil information,~~ Together with surface geology, it was used for constructing geological  
315 cross sections that have allowed characterizing the general geometry of macrostructure.  
316 Moreover, they were used for extending the contour map of FES2 to the centre of the Jiloca  
317 basin.

### 318 3.3. Trench analysis

319 A trench study focussed on the northwards prolongation of the La Peñuela fault,  
320 antithetic to the main Sierra Palomera fault, has been carried out following the classical  
321 methodology (see, *e.g.*, ~~McCalpin, 1996~~ McCalpin, 2009): excavating and shoring; cleansing  
322 and gridding the most suitable wall; identifying and marking sedimentary boundaries and  
323 deformation structures; drawing a detailed log and taking photographs of each grid cell;  
324 analysing the relationship between units and faults to identify individual events; and sampling  
325 materials for dating. Sedimentary units were defined on the basis of lithology, bed geometry,  
326 texture, colour and sedimentary structures.

327 Individual deformation events identified within the trench have been carefully verified by  
328 retrodeformational analysis, following the common practice in paleoseismological  
329 reconstruction (McCalpin, 2009). Several post-event sedimentary stages have also been  
330 included for a better understanding and representation of the evolutionary model. A number  
331 of identifiable faults were either formed, propagated or reactivated during successive  
332 deformation events. For each fault involved in each event, dip separation has been measured  
333 and equated to net slip (with precision of 5 cm). In addition, the resulting horizontal extension  
334 has been calculated taking into account the average dip of each fault. Further details are given  
335 in Section 7.4.

336 Dating of trench samples was achieved by the Luminiscence Dating Laboratory of



337 University of Georgia, USA, using the Optically Stimulated Luminescence (OSL) technique.  
338 Unfortunately, five of them were saturated samples that only provided minimum ages, which  
339 drastically decreased the consistency of the age model. Additional, preliminary OSL dating of  
340 shallow alluvial fan sediments had been achieved by Laboratorio de Datación y Radioquímica  
341 de la Universidad Autónoma de Madrid.

#### 342 **4. Structure and morphotectonics of the Sierra Palomera area**

343 The NNW-SSE trending Sierra Palomera extensional fault makes the eastern boundary of  
344 the Jiloca graben at its central sector (Figs. 1b, 2). In the footwall block, Jurassic marine  
345 carbonates are unconformably covered by Paleogene continental clastics ~~materials~~ (Figs. 2,  
346 3). In the ~~western,~~ hanging-wall block, *i.e.*, the central sector of the Jiloca basin, the  
347 sedimentary infill is made of: (i) Late Pliocene (Villafranchian) to Pleistocene alluvial and  
348 episodic palustrine deposits, all of them exposed at the ~~land~~ surface; (ii) an underlying  
349 carbonate unit, only observed in boreholes, that could represent an early lacustrine stage of  
350 Late Miocene-Early Pliocene age (Rubio and Simón, 2007). ~~Isopach maps elaborated from~~  
351 ~~b~~Borehole information ~~show how~~ indicates that the maximum thickness of the total infill  
352 approaches ~~one hundred metres, and its geometry is partially controlled by NW-SE to NNW-~~  
353 ~~SSE striking normal faults~~ 100 m (Rubio and Simón, 2007).

354

355 **[PREFERENTIALLY, FIG.2 SHOULD BE INSERTED HERE, AS A 1.5-COLUMN FIGURE]**

356 **[PREFERENTIALLY, FIG.3 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

357

358 The Jiloca basin runs slightly oblique to previous Paleogene, NW-SE trending folds (Fig.  
359 1b; ~~).~~ ~~Their hinges can be tentatively interpolated beneath the Neogene-Quaternary infilling~~  
360 ~~from geology of the basin margins, borehole data and hydrogeological criteria~~ (Rubio and  
361 Simón, 2007; Rubio *et al.*, 2007). In particular, the Sierra Palomera ~~extensional~~ fault follows  
362 the eastern limb, nearly vertical, of an eastwards verging anticline (Fig. 3), ~~suggesting that it~~  
363 ~~could result from negative inversion of a previous reverse fault linked to that fold~~. Its core is  
364 represented by ~~the Lower\_ and~~ Middle Triassic rocks that crop out in the neighbourhoods of  
365 Singra village, ~~making two gentle reliefs not completely buried by the basin filling. I and~~ its  
366 periclinal closure is partially preserved close to the southern tip of Sierra Palomera fault (Fig.  
367 2). ~~Such structural setting suggests that the main extensional fault resulted from negative~~  
368 ~~inversion, during Late Pliocene-Pleistocene times, of a previous reverse fault linked to that~~  
369 ~~anticline and developed during the Paleogene compression~~ (Rubio and Simón, 2007).

370 The Sierra Palomera fault trace is ca. 26 km long and trends N152°E in average. The  
371 main fault surface only crops out in a few, ~~very~~ small exposures (1 to 4 m<sup>2</sup> in area). A number  
372 of rupture surfaces observed within the damage zone show orientations consistent with the  
373 map trend: ~~they~~ strike between NW-SE and N-S, and dip between 54° and 87° W (mean  
374 orientation: N155°E, 70° W; Fig. 4). Slickenlines show pitch ranging from 75°N to 70°S,  
375 therefore indicating almost pure normal movement, with mean transport direction towards  
376 N230°E.

377

378 **[PREFERENTIALLY, FIG.4 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

379

380 Two wide right relay zones separate the Sierra Palomera fault from the Calamocha and  
381 Concud faults. The dominant trend of recent, extensional faults and fractures distributed  
382 within both relay zones is similar to that of the main fault or slightly deviates to approach the  
383 N-S direction. These relay zones dominated by along-strike fractures were described in detail  
384 by Peiro *et al.* (2019, 2020).

385 The Sierra Palomera fault is expressed in the landscape by a conspicuous, 20-km-long  
386 fault mountain front (Fig. 5a,b), which attains heights of 200 to 300 m above its toe, 450 to  
387 550 with respect to the bottom of the Jiloca ~~basin~~depression. The mountain front ~~It is quite~~  
388 ~~rectilinear, with~~shows a significantly low value of the sinuosity index ( $S_{mf} = 1.27$ ; García-  
389 Lacosta, 2013). A number of gullies (most of them exhibiting V-shaped transverse profiles)  
390 run across the fault scarp and delimit some well-preserved trapezoidal facets (Fig. 5c). Gullies  
391 feed short, high-slope alluvial fans (Fig. 5d) that are barely incised, only partially connected  
392 to the axial fluvial system, and exhibit signs of present-day functionality (*e.g.*, gravel  
393 aggradation affecting bush vegetation).

394

395 **[PREFERENTIALLY, FIG.5 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

396

397 The difference in height of the geomorphological markers *FES2* and *FES3* between the  
398 footwall and the hanging-wall blocks reasonably allows approaching the Sierra Palomera fault  
399 throw. The envelope of relief at the footwall block is largely represented by the *FES2*  
400 planation surface ~~cutting, which cuts Triassic, Jurassic and Paleogene~~pre-Neogene units, ~~and~~  
401 ~~which~~ attains a maximum height of 1430 m close to the edge (Fig. 6). The summit of Sierra  
402 Palomera (1533 m a.s.l.) and its surrounding area constitutes a residual relief that stands out  
403 from ~~the *FES2* erosion level~~, while remains of an upper erosion sublevel (*FES1*) extend at the

404 eastern foothills. A lower sublevel (*FES3*, usually lying 10-40 m below *FES2*) is also present:  
405 (i) eastwards of Sierra Palomera, over large areas of the northern Teruel basin; (ii) northwards  
406 and southwards, at the relay zones with the Calamocha and Conclud faults, respectively; and  
407 (iii) along a narrow band westwards of the Sierra Palomera divide.

408

409 **[PREFERENTIALLY, FIG.6 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

410

411 ~~Within the sedimentary infill of the Teruel basin, these planation surfaces can be~~  
412 ~~physically correlated with different coeval sedimentary horizons (lacustrine palustrine~~  
413 ~~carbonates) that were precisely characterized and dated by Ezquerro (2017) based on both~~  
414 ~~paleontological and magnetostratigraphic data. As stated above, the age of *FES1* and *FES2* is~~  
415 ~~constrained at about 3.8 Ma (Late Ruscianian, mammal zone MN15), while *FES3* is dated to~~  
416 ~~3.5 Ma (Early Villafranchian, MN16) (Ezquerro *et al.*, 2020).~~

417 The height of *FES2* and *FES3* ~~surfaces~~ within the Jiloca depression can only be inferred  
418 indirectly. Both have been mapped at the eastern margin of the Jiloca depression, W of Santa  
419 Eulalia town, where they descend to ca. 1100 and 1050 m, respectively (Fig. 6). Then they are  
420 supposed to be covered by the Plio-Pleistocene infill, while gentle residual reliefs at the  
421 Singra-Villafranca del Campo area (made of Triassic and Jurassic rocks belonging to the core  
422 of the Sierra Palomera anticline) stand out above the depression bottom. ~~Having in mind the~~  
423 ~~morpho-sedimentary setting at the nearby Teruel basin, †~~The subsoil data provided by Rubio  
424 and Simón (2007; Fig. 6) for the central Jiloca basin ~~can be used for~~ constraining the heights  
425 of those planation surfaces. ~~In this way,~~ the boundary between Plio-Pleistocene alluvial  
426 deposits and the underlying carbonate unit, lying at about 950 m a.s.l. in the Santa Eulalia  
427 area, could be correlated with either *FES2* or *FES3*. ~~This piece of data will allow reasonably~~  
428 ~~approaching the total tectonic offset at the Sierra Palomera fault zone since 3.8-3.5 Ma.~~

429 Within the Sierra Palomera block, *FES2* and its correlative Late Ruscianian carbonates ~~of~~  
430 ~~the Teruel basin systematically lose height towards east. Both~~ are in continuity with each  
431 other and show a quite homogeneous slope of about 1.5-2% along a distance of 20 km, in  
432 which the altitude of this morpho-sedimentary marker diminishes from 1400-1430 m (central  
433 sector of Sierra Palomera) to 1090-1120 m (Alfambra area) (Fig. 6). This morphotectonic  
434 setting defines a conspicuously tilted block whose edge has undergone a tectonic uplift of  
435 about 300 m relative to the bottom of the Teruel depression, as can be visualized from  
436 structural contours in Figure 6.

437 The latter value closely approaches the topographic amplitude of the Sierra Palomera  
438 scarp itself, and ~~also is comparable to~~ the ~~maximum~~ fault throw inferred from offset of the  
439 *FES2* marker. Such fault throw, and its variation along the Sierra Palomera fault, have been  
440 analysed on a series of 1-km-spaced transects across the fault trace on the contour map of  
441 Figure 6, assuming that *FES2* within the Jiloca basin coincides with the base of the Plio-  
442 Pleistocene infill. The result is shown in the throw vs. distance (T-D) graph of Figure 7, where  
443 two distinct curves depict values of (i) fault throw *s.s.*, and (ii) total tectonic ~~offset-throw~~ of  
444 *FES2* between the Sierra Palomera summits and the Jiloca depression bottom (including the  
445 bending component). The T-D curves show an overall bell-shape, ~~while exhibiting although~~  
446 slight~~ly~~ bimodal~~ity~~ in detail. The maximum values, 330 m and 480 m, respectively, are found  
447 at the central sector. Considering the age of the *FES2* morpho-sedimentary marker (3.8 Ma),  
448 and assuming an average dip of 70° for the fault plane and a pure normal movement, a  
449 maximum net slip rate of 0.09 mm/a can be inferred (0.13 mm/a for the total rate between  
450 Sierra Palomera and the Jiloca bottom).

451

452 [PREFERENTIALLY, FIG.7 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]

453

454 ~~Although-Despite~~ the initial appearance of the Sierra Palomera fault is that of a single  
455 major rupture that accommodates the entire ~~vertical~~-throw, there ~~are indications~~ is evidence  
456 of a parallel, synthetic fault (Las Vallejadas fault) located west of the main escarpment at its  
457 southern sector (Fig. 2). Both delimit an intermediate step within the mountain front, in which  
458 *FES2* lies at an altitude of 1140-1220 m, furthermore offset (ca. 10 m) by a minor antithetic  
459 rupture (La Peñuela fault). Recent activation of both subsidiary faults is revealed by local  
460 deformation of Villafranchian alluvial deposits: (i) back tilting (up to 25°E), due to rollover  
461 kinematics, observed at the foot of the morphological escarpment of Las Vallejadas fault (Fig.  
462 2); (ii) accommodation monocline (dip up to 22°E) in the case of La Peñuela fault (Fig. 8; see  
463 location in Fig. 2).

464

465 [PREFERENTIALLY, FIG.8 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]

466

467

## 468 5. Geophysical exploration of the overall Sierra Palomera piedmont

469 Data of magnetic intensity field and vertical magnetic gradient were extensively collected  
470 along ten transects, roughly orthogonal to the Sierra Palomera fault trace along its hanging-

471 wall block and ranging from 2.0 to 5.2 km in length (Fig. 9a). Spacing between successive  
472 measurement points was about 0.8 m. The two northernmost transects (profiles 01 and 02)  
473 and the southernmost one (profile 10) show a narrow distribution of residuals due to their  
474 lesser contrast with respect to the general, regional trend (Fig. 9b). The central transects (03 to  
475 09) have spikes and lows that depart considerably from the general trend, and therefore, when  
476 data of the ten transects are considered as a whole, they define the range of the distribution  
477 (more specifically, profile 03 has the lowest and the highest values of residual magnetic  
478 intensity). Nonetheless, transects 01, 02 and 10 show a similar (albeit reduced in magnitude)  
479 outline to the rest.

480  
481 **[PREFERENTIALLY, FIG.9 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**  
482

483 The variation pattern of residuals in magnetometric magnetic and EM profiles (also  
484 corroborated by EM profiles) allows follow a common pattern of variation of residuals,  
485 portraying three domains (A, B and C) that are broadly parallel the Sierra Palomera fault (Fig.  
486 9b). In the northern section of the studied area, the boundary between domains A and B is  
487 largely evident, due to the sudden change and amplitude of the anomaly. Moreover, these  
488 profiles show a more direct correlation between them than the southern ones, where the  
489 contact progresses through a magnetic dipole (Fig 9a, b). These three domains are  
490 characterised by:

491 a) Closer~~st~~ to the Sierra Palomera fault, domain A is an area where residual values of  
492 magnetic intensity are close to zero and barely change, except for a subtle decrease to the  
493 west.

494 b) Westwards, a sharp change of attitude marks the onset of domain B, a zone of  
495 anomalies expressed as variations of residuals up to 20-30 nT over decametric distances. Such  
496 anomalies reflect the presence of small magnetic dipoles and, a slightly higher mean value of  
497 Earth magnetic field. Values for, apparent conductivity while are still homogeneous values for  
498 apparent conductivity.

499 c) Finally, domain C is separated from domain B by a sharp decrease in magnetic  
500 intensity (it goes down about 100 nT) with lower relative values of Earth magnetic field, and  
501 presence of a lower density of magnetic dipoles (including those of higher wavelength),  
502 Apparent conductivity and magnetic susceptibility and are higher apparent conductivity and  
503 magnetic suseptibility.

504 In map view, Figure 9a shows the location of transects, on which the residual values of  
505 field intensity (nT) are plotted as a colour palette. The spatial correlation of the described

506 ~~domains on successive transects is depicted. While the boundary between A and B domains is~~  
507 ~~largely evident, the northern profiles show a more direct correlation than the southern ones,~~  
508 ~~where the contact progresses through a magnetic dipole.~~

509 The reported geophysical results (Earth magnetic field, together with apparent  
510 conductivity, and susceptibility) suggest the presence of a body of relatively higher magnetic  
511 susceptibility underlying domain A, which gets shallower under domain B, and gets again  
512 deeper under domain C. Boundaries between those domains are sharp and clear. This setting  
513 can be interpreted as an uplifted block (made of Paleozoic and Triassic materials belonging to  
514 the core of the Sierra Palomera anticline) bounded by faults nearly parallel to the Sierra  
515 Palomera fault trace.

## 516

### 517 **6. ~~Detailed study at~~ La Sima alluvial fan: linear topographic anomaly and its** 518 **geomagnetic expression**

519 In the absence of any visible surficial rupture across Quaternary sediments of the Sierra  
520 Palomera piedmont, ~~the need to excavate and survey a trench arose~~ evidence of recent tectonic  
521 activity should be obtained from trenching. After careful field survey in search of a suitable  
522 location for such trench, no locality could be selected on the Sierra Palomera fault trace itself,  
523 Owing to non-favourable topographic, lithologic and access conditions at the Sierra  
524 Palomera fault trace itself, our search was then focused on the surface of two ~~of the recent~~  
525 alluvial fans sourced at the mountain front, at La Cecilia and La Sima areas (see location in  
526 Figs. 2 and 5d). Both exhibit well-preserved alluvial fan morphology at its proximal sectors,  
527 with evidence of present-day aggradation at the apex. Shallow sand and silty sedimentary  
528 horizons in those alluvial fans have provided ages of  $28.9 \pm 2.0$  ka BP (La Cecilia) and  $19.2 \pm$   
529  $1.1$  ka BP (La Sima) (see Table 1; location in Fig. 2).

530

531 **[PREFERENTIALLY, TABLE 1 SHOULD BE INSERTED HERE AS A 2-COLUMN FIGURE]**

532

533 In the middle sector of La Sima alluvial fan, a sharp NNW-SSE trending lineament is  
534 clearly visible on aerial photographs and DEM images, beyond which the fan surface is more  
535 deeply incised by the local drainage network (Fig. 10a). That lineament involves a  
536 morphological anomaly, a break in the fan slope, which becomes null or even negative up to  
537 take locally the appearance of a gentle, degraded uphill-facing scarplet (Fig. 10c). ~~In view of~~  
538 ~~These features, it came to mind~~ suggest the hypothesis occurrence of an antithetic fault that

539 would have ~~raised-sunk~~ the ~~middle-proximal~~ sector of the fan with respect to the ~~proximal~~  
540 ~~middle~~ one by about 2.56 m. This ~~e-described~~ lineament coincides with the boundary between  
541 domains A and B defined from geophysical results (Fig. 9b). ~~Moreover, it and~~ is virtually  
542 prolonged towards SSE up to connect with the antithetic La Peñuela fault (Fig. 2).

543  
544 **[PREFERENTIALLY, FIG.10 SHOULD BE INSERTED HERE AS A 1.5-COLUMN FIGURE]**

545  
546 In order to test the hypothesis of an antithetic fault cutting the La Sima alluvial fan, the  
547 subsoil in the neighbourhoods of the morphological lineament was intensively explored by  
548 means of a magnetic and electromagnetic survey. ~~Seeing at the geophysical domains~~  
549 ~~described in Section 5, the~~The coincidence of the lineament ~~coincides~~ with the A/B boundary,  
550 ~~which~~ is clearly expressed in the detailed map of residual magnetic anomalies shown in  
551 Figure 10b. The area east of the sharp linear, NNW-SSE trending limit, clearly visible on this  
552 map, shows low residual values with wide (hectometre-scale) wavelength variations. To the  
553 west of this limit, an increase of more than 30 nT is observed, as well as a decrease of more  
554 than 50 mS/m in the total conductivity; moreover, the texture of the residual map changes  
555 noticeably, showing sharper magnetic dipoles of decametric wavelength.

556 The amplitude and morphology of the linear anomaly is not consistent with the  
557 susceptibility values of surficial sediments, and suggest the contrast, at shallow levels,  
558 between a high-susceptibility rock body to the west (domain B, as defined in section 5) and  
559 the domain A to the east. In addition, Figure 10b shows other NW-SE trending linear  
560 anomalies in domain B, which involve a lower contrast of magnetic field values. Both the  
561 main anomaly and the secondary ones show high gradient and sharpness of the observed  
562 dipoles, suggesting near-surface, high dipping discontinuities or rock boundaries compatible  
563 with recent faults.

## 564 565 **7. Trench study at La Sima alluvial fan**

566 Once verified that geophysical and topographic analysis of La Sima lineament reinforced  
567 our preliminary hypothesis about the northwards prolongation of the antithetic La Peñuela  
568 fault, we selected an easily accessible site for trench study. A 40 m long, 1.4 m wide trench  
569 was dug along a N067°E direction, roughly orthogonal to the linear anomaly that separates  
570 domains A and B. A segment of 19 m on its southern wall, with depth ranging from 3.0 to 3.5  
571 m, was logged and analysed in detail (Fig. 11a,b).

572

573

[PREFERENTIALLY, FIG.11 SHOULD BE INSERTED HERE IN VERTICAL IF POSSIBLE]

574

### 575 *7.1. Sedimentary units*

576 The materials exposed at La Sima trench essentially correspond to relatively well-bedded  
577 Pleistocene alluvial sediments (Fig. 11a). Sedimentary features indicate alternating energetic  
578 flows, sometimes flash floods, recorded by gravel channel and bar deposits, and waning  
579 discharges that settled fines over the gravel deposits. All the succession includes clear signs of  
580 calcrete development and periods of time with negligible sedimentation. Bioturbation signs  
581 and carbonate precipitation are related to pedogenesis, ~~and~~-suggesting wetting and drying  
582 episodes of the sedimentary surface. The sedimentary succession has been subdivided into  
583 twelve lithological units (Fig. 11~~b~~<sup>a</sup>):

584 Unit 1 (up to 50 cm in thickness): Massive reddish mudstone with isolated, mm- to cm-sized  
585 angular limestone clasts (more abundant at the base), with bioturbation traces and  
586 smooth carbonate nodules.

587 Unit 2 (25 to 55 cm): Orange massive sandy mudstone with floating angular-subangular grey  
588 limestone granules and pebbles, and some irregular cm-thick gravel bed. Grey  
589 mudstones laminae towards the top.

590 Unit 3 (55 to 75 cm): Tabular laminated, indurated and brecciated, carbonate crust with some  
591 cm-thick interbedded silts with carbonate clasts. Carbonate fragments are smaller in  
592 the upper part; laminated fragments are less abundant towards W.

593 Unit 4 (20 to 35 cm): Reddish massive silty sand and mudstone in a tabular level with vertical  
594 root traces filled by fine sands. Some carbonate nodules, plant remains and scattered  
595 grey, angular limestone and caliche clasts up to 10 cm in size can be recognized.

596 Unit 5 (15 to >50 cm): Clast-supported gravel with silty to sandy matrix in a tabular, locally  
597 channelized sedimentary body with crude horizontal stratification. Gravel is made of  
598 angular-subrounded limestone clasts (up to 8 cm) and smaller caliche clasts.

599 Unit 6 (25-55 cm): Orange to brownish massive silt and mudstone with greyish limestone  
600 angular clasts and floating whitish caliche rounded nodules (up to 2 cm). Clast content  
601 increases locally. Root traces, plant remains and organic matter patches can be  
602 recognized in the western sector.

603 Unit 7 (30 to >150 cm): Heterogeneous unit mainly made of grain-supported gravel, locally  
604 cemented, with angular-subrounded limestone clasts (up to 15 cm in size) and caliche



605 nodules. It includes red mudstone discontinuous intercalations, up to 20 cm in  
606 thickness, with floating cm-sized angular clasts ~~(labelled as 7a in Fig. 11a)~~. The  
607 overall geometry of the unit is tabular in the footwall block and channelized in the  
608 hanging-wall block. A level of calcrete gravel, >50 cm in thickness, appears at the top  
609 of this unit within the footwall block.

610 Unit 8 (10-60 cm): Reddish silt with floating limestone angular granules and pebbles (up to 8  
611 cm) with evidence of bioturbation.

612 Unit 9 (45-120 cm): Grey gravel in a channeled body with limestone angular clasts (up to 12-  
613 14 cm in size) and rounded caliche ~~rounded~~ clasts. Crude finning upwards cycles can  
614 be recognized. Pedogenic features increase towards the top, where brecciated  
615 limestones locally appear.

616 Unit 10 (55 to 70 cm): Reddish massive silts with floating subangular limestone clasts (up to  
617 7 cm), whitish carbonate nodules and an interbedded discontinuous clast-supported  
618 gravel level ~~(10b)~~ with subangular clasts up to 10 cm in size.

619 Unit 11: Wedge-shaped body of orange and whitish massive, highly cemented silt, with  
620 carbonate floating subangular limestone clasts (up to 10 cm) and caliche clasts  
621 arranged with the A-axis subvertical.

622 Unit 12 (20 to 50 cm): Surface regolith made of silt with angular to subangular clasts,  
623 reworked by agricultural labours.

## 624 **7.2. OSL dating**

625 ~~Dating of a total of s~~Seven samples (S1 to S7) of alluvial sediments within the trench (see  
626 Fig. 11ba for location) have been dated, ~~has allowed approaching their age distribution,~~  
627 although, unfortunately, the results show a high level of uncertainty (see Table 1). Other three  
628 collected samples did not contain enough sand grains for providing a representative dose  
629 distribution and therefore OSL dates were not reliable in this case. These samples are not  
630 located in Fig. 11ba.

631 Samples S2, S3, S4, S6 and S7 have presented signal saturation, *i.e.*, their natural  
632 luminescence signal lies beyond the saturation of the OSL response with dose, making it  
633 impossible to provide adequate results. According to laboratory results, their ages should be  
634 older than 193 to 378 ka, although such figures should not be taken *sensu stricto*. Only one of  
635 the alluvial sedimentary units is directly dated: S1 provides an age  $97.4 \pm 10.2$  ka for the top of  
636 unit 9. Unit 11 (sample S5), which will be next interpreted as a fissure infill, is dated to  
637  $49.2 \pm 5.4$  ka. As a result, the chronology of unit 10, overlapping unit 9 and being cut by the

638 fissure, can be broadly constrained between both numerical ages.

639 Without the support of further anchors, building an age model for the overall alluvial  
640 succession exposed in the trench is not feasible. In any case, the ensemble of OSL dating  
641 results and geomorphological observations in the study area suggest that: (i) most of that  
642 alluvial succession belongs to the Middle Pleistocene; (ii) a rapid decrease of sedimentation  
643 rate occurs by the Middle-Late Pleistocene transition; and (iii) sedimentation persisting in  
644 proximal and middle sectors of the alluvial fans during Late Pleistocene to present-day times  
645 only represents a small contribution to the surficial aggradation and landscape modelling.

### 646 7.3. Deformation structures

647 ~~In a first approach,~~ ~~†~~The trench log shows a main extensional fault zone at the central  
648 sector, dipping eastward and hence antithetic with respect to the Sierra Palomera fault (Fig.  
649 11ab), and full consistent with the uphill-facing scarplet described in section 6. These features  
650 allow identifying such antithetic fault zone with the map-scale La Peñuela fault (Fig. 2). The  
651 footwall block of that fault zone shows a gentle monocline, while other normal (both  
652 synthetic and antithetic) faults, cutting most of the sedimentary succession, are distributed  
653 along the entire section. The orientations of all these structures are overall consistent, as  
654 depicted in stereoplots of ~~Figure:~~ 11b,c,d,e,f.

655 The central fault zone is made of three significant structural elements:

656 1(i) Main ~~rupture~~fault, expressed by  $\theta_1$  and  $\theta_2$  ~~fault~~-individual rupture surfaces.

657 2(ii) Splay faults  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ , associated to the tip of the main rupture and  
658 propagated through unit 7. Both the main, westwards dipping rupture surfaces and the nearly  
659 vertical splay faults consistently strike NNW-SSE (Fig. 11cb). Such structural arrangement  
660 suggests that, at certain stage of its development, the main rupture  $\theta_1$ - $\theta_2$  was covered by the  
661 upper part of unit 7, and then reactivated in the form of splay faults related to refraction at the  
662 extensional tip (horse-tail structure, in the sense of Granier, 1985). That is the key, purely  
663 instrumental criterium for separating lower and upper unit 7 in Figure 12; therefore, such  
664 separation is not based on a visible lithological boundary (we have defined a single unit 7  
665 indeed).

666 3(iii) Open fissure bounded by fault  $\theta_3$  ~~and~~  $\eta$  and another irregular surface, and filled  
667 with unit 11. The interpretation is based on its wedge shape, the massive internal structure of  
668 the infill, and the occurrence of clasts with nearly vertical A-axes. According to this  
669 interpretation, both bounding surfaces  $\theta_3$  ~~(smooth)~~ and  $\eta$  ~~(more irregular)~~ would have  
670 represented both walls of a single, also NNW-SSE striking fault, then disengaged from each

671 other when the fissure opened up and ~~in the case of  $\eta$~~ , partially crumbled before infilling  
672 took place.

673 The footwall block is deformed by the monocline and cut by a number of NNW-SSE  
674 striking normal faults (Fig. 11ed), all of them synthetic with the Sierra Palomera fault and  
675 exhibiting dip separations in the range of 10 to 20 cm (Fig. 11ba). Faults  $\rho$ ,  $\pi_1$  and  $\pi_2$  cut the  
676 horizontal limb of the monocline, and have apparently kept their original, high dip. The rest of  
677 faults ( $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) appear at the hinge and the abrupt limb of the monocline. They  
678 show a progressive decrease in dip towards the east as the bedding dip increases, and some  
679 individual faults ( $\mu$ ,  $\lambda_1$ ,  $\lambda_2$ ) exhibit conspicuously arched traces, so that the angle between  
680 faults and bedding remains broadly constant (mostly within the range of 55-65°). Such  
681 geometrical setting strongly suggests that they were folded by the monocline. Concerning the  
682 relationships between faults and sedimentary units,  $\rho$  and  $\pi_1$  uniformly offset (15-20 cm) the  
683 base of units 2 to 6, while they suddenly vanish and does not affect the base of unit 7. Also  
684 fault  $\sigma$  shows similar relationships, although in this case it does not propagated through the  
685 lower units, probably detached within low-viscosity materials of unit 4. As a consequence,  $\rho$ ,  
686  $\pi_1$  and  $\sigma$  produce a noticeable thickening of unit 6 in their respective hanging-wall blocks.  
687 Faults  $\pi_2$ ,  $\tau$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) also offset rather uniformly the sedimentary boundaries, and at  
688 least two of them ( $\pi_2$  and  $\mu$ ) propagated across unit 7.

689 The hanging-wall block shows two ensembles of intersecting faults that cut ~~younger~~ units  
690 that are younger than the ones from the footwall block (Fig. 11ba). Individual faults show  
691 distinct ~~offsets—slip~~ for different sedimentary markers, which indicates diachronic  
692 development. The  $\varepsilon_0$ - $\varepsilon_1$  couple offsets more than 1.42 m the base of unit 7, while it produces a  
693 rather uniform dip separation of 8-10 cm in the bases of units 8, 9 and 10. We should  
694 therefore interpret that  $\varepsilon_0$ - $\varepsilon_1$  underwent most of its present-date displacement (>1.3 m) before  
695 sedimentation of unit 8, and was then reactivated after the lower part (at least) of unit 10 was  
696 deposited. Splaying from  $\varepsilon_1$ , fault  $\varepsilon_2$  cuts units 7 and 8, and is covered by unit 9, while  $\varepsilon_3$  cuts  
697 the base of unit 9, thus making the three faults a footwall rupture sequence. The antithetic  $\varepsilon_4$   
698 propagated ~~up thorough unit 9 and to~~ the lowermost unit 10. At the easternmost trench sector  
699 we find a similar pattern in the NNW-SSE striking faults  $\alpha$  and  $\beta$ . Fault  $\beta$  offsets more than  
700 0.7 m the base of unit 7, while (together with its splay faults  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ ) produces a smaller  
701 separation (0.4 m) in the bases of units 8 and 9. We interpret that  $\beta$  underwent displacement  $\approx$   
702 0.3 m before sedimentation of unit 8, and was then reactivated after deposition of unit 9. Fault

703  $\alpha$  propagated through unit 7, previous to sedimentation of unit 8, and did not undergo further  
704 reactivation.

705 ~~We should emphasize the strict consistence of~~The orientations of the described structures  
706 have a strict consistence. All faults systematically strike NNW-SSE (Fig. 11fe), and so does  
707 the limb of the monocline (Fig. 11de). There is no doubt that the latter is (i) genetically linked  
708 to faults, and (ii) responsible for the decrease in dip of faults  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Bedding and  
709 fault surfaces are rotated around a common, well-defined horizontal axis ca. N160°E (Fig.  
710 11de). Strikes of minor fractures measured along the trench are also clustered around NNW-  
711 SSE, although a small number among them are oriented NNE-SSW (in blue in Fig. 11ed). A  
712 brief discussion about the dynamic framework (stress fields) in which such fault and fracture  
713 pattern developed will be made in Section 8.57.6.

#### 714 **7.4. Retrodeformational analysis and ~~E~~evolutionary model: deformation events**

715 ~~According~~ Based on the former structural description, in particular ~~to~~ on the  
716 relationships between structures ~~themselves~~ and ~~with~~ the sedimentary units, a careful  
717 retrodeformational analysis has been achieved, with a double purpose: (i) building an  
718 evolutionary model, i.e. a systematic succession of deformation events, and (ii) testing its  
719 kinematic consistence ~~we propose the evolutionary model explained below, tested by means~~  
720 ~~of careful retrodeformation analysis~~ (Fig. 12).

721 ~~The evolution has been conventionally divided into a succession of “deformation events”,~~  
722 ~~following the common practice in paleoseismological reconstruction. Several post-event~~  
723 ~~sedimentary stages have been also included for better understanding.~~ A number of identifiable  
724 faults were either formed, propagated or reactivated during each deformation event (Fig. 12  
725 and Table 2). Dip separation directly measured on the trench log is taken as practically  
726 representing the net slip on each fault, since: (i) bedding is roughly horizontal, (ii) the trench,  
727 oriented N067°E, is nearly orthogonal to the prevailing strike of faults, and (iii) the only  
728 kinematical indicator observed during trench survey (slickenlines with pitch 82°S on fault  $\mu$ ;  
729 Fig. 11d), as well as those collected at the Sierra Palomera fault zone itself (see Fig. 4b),  
730 suggest nearly pure normal slip for the overall extensional fault system.

731 Net slip for every individual fault (with positive sign for synthetic faults and negative  
732 sign for antithetic ones), together with the resulting horizontal extension (considering the  
733 average fault dip), are depicted in Table 2. Such measurements exclude offset accommodated  
734 by the bending monocline. The latter has been only considered for computing the total  
735 accumulated deformation, since it is not possible to accurately calculate which fraction of

736 bending occurred during each event. The total slip per event, taken as the algebraic sum of  
737 slip values on individual faults, is also shown. The total horizontal extension per event  
738 considers the aggregate of extension values on individual faults, but also includes an estimate  
739 of the contribution of bending, in order to jointly accommodate the horizontal extension  
740 visually expressed in the successive cross sections of Fig. 12.

741  
742 **[PREFERENTIALLY, FIG.12 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

743  
744 **[PREFERENTIALLY, TABLE 2 SHOULD BE INSERTED HERE AS A 2-COLUMN FIGURE]**

745  
746 ~~A number of identifiable faults were either formed, propagated or reactivated during each~~  
747 ~~deformation event (Fig. 12 and Table 2). Dip separation directly measured on the trench log is~~  
748 ~~taken as the first approach to the net slip on each fault, since: (i) bedding is roughly~~  
749 ~~horizontal, (ii) the trench, oriented N067°E, is nearly orthogonal to the prevailing strike of~~  
750 ~~faults, and (iii) the only kinematical indicator observed during trench survey (slickenlines~~  
751 ~~with pitch 82°S on fault  $\mu$ ), as well as those collected at the Sierra Palomera fault zone itself~~  
752 ~~(see Fig. 4b), suggest nearly pure normal movement for the overall extensional fault system.~~  
753 ~~A precision of 5 cm has been adopted for net slip measurements; those that are synthetic to~~  
754 ~~the Sierra Palomera fault (downthrown block to the west) are compiled as positive in Table 2,~~  
755 ~~while those antithetic are compiled as negative.~~

756 Below we summarize the main features of each of the seven deformation events (T to Z)  
757 ~~distinguished defined at~~ the La Sima trench (Fig. 12; see measurements in Table 2):

758 **Event T:** Slip on faults  $\rho$ ,  $\pi_1$ ,  $\tau$  and  $\sigma$  after deposition of unit 6 and previous to unit 7.  
759 Accumulated net slip: +45 cm.

760 **Event U:** Slip on faults  $\pi_2$ ,  ~~$\tau$~~ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$ ,  $\lambda_2$  and  $\varepsilon_1$ , subsequent or coeval with deposition of the  
761 lower part of unit 7. Accumulated net slip: +~~10540~~ cm.

762 **Event V:** Slip on fault  $\theta_2$ , subsequent to deposition of lower unit 7, then covered by upper  
763 unit 7. Development of the monocline begins; according to our progressive  
764 deformation model depicted in Fig. 12, in which the main rupture had always  
765 propagated through units 1 to 6, this monocline should be interpreted as a drag fold.  
766 Net slip: -~~105~~ cm.

767 **Event W:** Reactivation of the main, central fault through the rupture surfaces  $\theta_1$ - $\theta_2$ , which  
768 propagates across upper unit 7 splitting into  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ . Progress of the  
769 monocline produces rotation of faults  $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Slip on faults  $\varepsilon_0$ - $\varepsilon_1$ ,  $\alpha$  and  
770  $\beta$ , all of them subsequent to top of unit 7 and previous to unit 8. Accumulated net slip:  
771  $+1\cancel{2500} - \cancel{6105} = +\cancel{60} = 5$  cm.

772 **Event X:** Propagation of the main fault zones,  $\theta$  and  $\varepsilon$ , through new rupture surfaces:  $\theta_2$ - $\theta_3$   
773 and  $\varepsilon_2$ , respectively. Both are younger than unit 8 and older than unit 9. Accumulated  
774 net slip:  $+\cancel{05} - \cancel{5095} = -\cancel{4590}$  cm.

775 **Event Y:** Activation of fault  $\varepsilon_3$ , and propagation of  $\beta$  splitting into  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ . Both  
776 processes are subsequent to deposition of unit 9 and probably previous to unit 10,  
777 therefore close to (or slightly younger than) the numerical age provided by sample S1  
778 ( $97.4 \pm 10.2$  ka). Accumulated net slip:  $-\cancel{3540}$  cm.

779 **Event Z:** Formation of fault  $\varepsilon_4$  and propagation of  $\varepsilon_1$  cutting the lower part of unit 10. Slip on  
780  $\theta_2$  that induces extensional movement on passively activates the  $\theta_3$  surface with  
781 extensional component, giving rise to an open fissure (from fault  $\eta$ ) that tears apart  
782 units 7 to 10 and is subsequently filled with unit 11. This event should be dated just  
783 prior to the numerical age provided by sample S5 ( $49.2 \pm 5.4$  ka). Accumulated net  
784 slip:  $+\cancel{10} - \cancel{12035} = -\cancel{11025}$  cm.

785

## 786 **8. The Sierra Palomera fault: synthesis ~~Overall interpretation~~ and discussion**

### 787 **8.1. *Geometry and kinematics of macrostructures***

788 Structural information from field survey has allowed characterizing geometry and  
789 kinematics of the Sierra Palomera fault itself (Figs. 4, 6, 13). The attitude of the main fault  
790 surface is N155°E, 70° W in average, while most ruptures visible along and close to it are  
791 systematically parallel. The fault shows pure normal movement, with mean transport direction  
792 towards N230°E. In addition, the use of two geomorphological markers (mid-Pliocene *FES2*  
793 and *FES3* planation surfaces; Fig 13b) has permitted measuring the fault throw s.s. (330 m)  
794 and the total tectonic throw (480 m, including bending) at the Sierra Palomera fault, resulting  
795 in slip rates of 0.09 and 0.13 mm/a, respectively.

796

797 **[PREFERENTIALLY, FIG.13 SHOULD BE INSERTED HERE, AS A 2-COLUMN FIGURE]**

798

799 ~~We have seen how g~~Geophysical results reported in Section 5, defining three adjacent,  
800 NNW-SSE trending elongated domains (A, B, C) suggest the existence of an uplifted block  
801 bounded by faults nearly parallel to the Sierra Palomera fault trace. At the southern sector of  
802 the study area, local coincidence of the A/B and B/C domain boundaries with La Peñuela and  
803 Las Vallejadas faults, respectively, strongly supports such interpretation. The antithetic  
804 rupture exposed in La Sima trench, revealed in the landscape by a gentle uphill-facing scarplet  
805 across the La Sima alluvial fan (section 6), unequivocally represents that map-scale antithetic  
806 La Peñuela fault and corroborates the extensional character of such structure.

807 In this way, the results of subsoil exploration by geophysical methods and trench survey,  
808 together with structural and morphotectonic data, allow refining the structural model of the  
809 central Jiloca graben, beyond the apparently flat appearance of the Sierra Palomera pediment,  
810 ~~i.e., deformation style of the hanging wall block of the Sierra Palomera fault. These new~~  
811 ~~inferred faults separating domains A, B and C have been incorporated to the geological map~~  
812 ~~of Fig. 2.~~

813 ~~The Sierra Palomera fault probably resulted from negative inversion, during the Late~~  
814 ~~Pliocene-Quaternary extensional phase, of a previous contractive structure developed under~~  
815 ~~the Paleogene-Early Miocene compression. Such origin is suggested by its spatial coincidence~~  
816 ~~with the eastern, nearly vertical limb of an eastwards verging anticline. Evidence of the same~~  
817 ~~inversion setting has been described for the other master faults bounding the Jiloca graben,~~  
818 ~~namely the Concud fault (Lafuente *et al.*, 2011a) and the Calamocha fault (Liesa *et al.*, 2021).~~

819 ~~The attitude of the main fault surface is N155°E, 70° W in average, while most ruptures~~  
820 ~~visible along and close to it are systematically parallel to it. The fault shows pure normal~~  
821 ~~movement, with mean transport direction towards N230°E. These features are similar to those~~  
822 ~~of the Concud and Calamocha faults, the other structures that make the eastern boundary of~~  
823 ~~the Jiloca graben. In particular, the average transport direction of those faults is N220°E~~  
824 ~~(Lafuente *et al.*, 2014) and W to SW (Martín Bello *et al.*, 2014), respectively, thus jointly~~  
825 ~~making a geometrically and kinematically consistent major extensional fault system.~~

826 ~~Two wide right relay zones separate the Sierra Palomera fault from the Calamocha and~~  
827 ~~Concud faults. The dominant trend of recent, extensional faults and fractures distributed~~  
828 ~~within both relay zones is similar to that of the main fault or slightly deviates to approach the~~  
829 ~~N-S direction. Close to the southern tip, such fractures mainly affect Upper Miocene and~~  
830 ~~Villafranchian sediments, while close to the northern tip they cut Jurassic carbonates giving~~  
831 ~~rise to narrow N-S trending grabens filled with Pleistocene alluvial sediments (Capote *et al.*,~~  
832 ~~1981). These relay zones dominated by along-strike fractures were described in detail and~~

833 interpreted by Peiro *et al.* (2019, 2020) with the help of analogue modelling. Fracturing in this  
834 new type of fault relay is controlled by both the structural inherited grain and the remote  
835 stress field, and efficiently contribute to slip transfer and dynamical interaction between  
836 adjacent faults. It strongly contrasts with the classical models reported in the literature (*e.g.*,  
837 Peacock and Sanderson, 1994; Young *et al.*, 2001; Fossen and Rotevatn, 2016), in which  
838 transverse connecting faults controlled by the own relay kinematics prevail. According to  
839 Peiro *et al.* (2020), the overall fault system at the eastern boundary of the Jiloca basin is at an  
840 intermediate stage between complete independence and coalescence, and will probably evolve  
841 to an along strike propagation of the master faults through the distributed longitudinal fracture  
842 ensembles. The slightly bimodal throw vs. distance (T-D) curve depicted in Fig. 7 suggests  
843 that the Sierra Palomera fault itself resulted from coalescence of two distinct fault segments,  
844 although their overall bell shape indicates full linkage between them. Moreover, the  
845 persistence of an important bending component beyond both tips of the fault trace reveals that  
846 the total length of the Sierra Palomera fault is larger than that exposed at the surface, thus  
847 being propagated towards NNW and SSE as a blind fault.

848 Geophysical and morphotectonic data have allowed characterizing the overall structure of  
849 the hanging wall block beyond the apparently flat appearance of the Sierra Palomera  
850 pediment. We have explained (sections 5 and 6) how magnetic field linear anomalies parallel  
851 to the Sierra Palomera fault trace suggest a distribution of subsoil lithological domains  
852 consistent with a gentle horst and graben setting.

853 The most conspicuous linear anomaly coincides with a morphological lineament (a gentle  
854 uphill facing scarplet) across the middle sector of La Sima alluvial fan (section 6), and with  
855 the uphill facing fault scarp east of Las Vallejadas fault. The hypothesis that all of these  
856 elements represent an antithetic fault has been corroborated by the exposure of that antithetic  
857 rupture in La Sima trench. In summary, the available information reveals a more complex  
858 structure in the Sierra Palomera hanging wall block than the one assumed so far, including: (i)  
859 a synthetic fault, located at about 1.5 km basinwards, which at its southern sector emerges at  
860 surface (Las Vallejadas fault); (ii) a recent antithetic fault, at a distance of 0.7–1.0 km, which  
861 would have displaced the surface of the La Sima alluvial fan and would extend southwards up  
862 to La Peñuela fault.

863 In order to depict the refined structural model of the Sierra Palomera hanging wall block,  
864 The synthetic Las Vallejadas fault and the antithetic La Peñuela fault both faults have been  
865 incorporated to the geological map of Figure 2, as well as to a new version of the cross section  
866 (Fig. 13a). Furthermore, the latter depicts a reinterpretation of the geometry of the master



867 fault. It is known that the shape of the main fault surface strongly controls the style of  
868 accommodation folding and subsidiary faulting in the hanging-wall block of extensional  
869 faults. Rollover folds and antithetic faults develop above concave-upward fault bends,  
870 whereas drag folds and synthetic faults form above convex-upward fault bends, their  
871 propagation being facilitated by high curvature of such fault bends (McClay and Scott, 1991;  
872 Xiao and Suppe, 1992; Withjack *et al.*, 1995; Delogkos *et al.*, 2020). In our case, the  
873 occurrence of the antithetic and the synthetic inferred subsidiary faults strongly suggests the  
874 presence, at a depth of less than 1 km, of a relative flat in the main fault surface (*i.e.*, a double,  
875 convex-concave bend), probably located at the Middle-Upper Triassic lutite and evaporite  
876 units (Middle Muschelkalk and Keuper facies).

877 Concerning the along-strike propagation of the Sierra Palomera fault, the slightly bimodal  
878 throw vs. distance (T-D) curve depicted in Fig. 7 suggests that it could result from  
879 coalescence of two distinct fault segments (although the amplitude of the relative minimum  
880 between both maxima, close to the error bar adopted for throw estimations, casts doubt on the  
881 significance of this detail). In any case, the overall bell-shape of the T-D curve indicates full  
882 linkage along the fault zone. Moreover, the persistence of a bending component beyond both  
883 tips of the fault trace reveals that the total length of the Sierra Palomera fault is larger than  
884 that exposed at the surface, thus being propagated towards NNW and SSE as a blind fault.

885 According to Peiro *et al.* (2020), the overall fault system at the eastern boundary of the  
886 Jiloca basin is at a transient stage towards coalescence, and will probably evolve to an along-  
887 strike propagation of the master faults through distributed longitudinal fractures. The relay  
888 zones between Sierra Palomera, Calamocha and Conclud faults, dominated by longitudinal  
889 fractures, represent a type of fault relay controlled by both inherited structures and the remote  
890 stress field (Peiro *et al.*, 2019, 2020). It strongly contrasts with the classical models reported  
891 in the literature (*e.g.*, Peacock and Sanderson, 1994; Young *et al.*, 2001; Fossen and Rotevatn,  
892 2016), in which transverse connecting faults controlled by the own relay kinematics prevail.

893 Such fault system makes a geometrically and kinematically consistent, genetically related  
894 major extensional fault system. The N230°E mean transport direction at the Sierra Palomera  
895 fault is similar to those of Conclud (N220°E; Lafuente *et al.*, 2014) and Calamocha (W to SW;  
896 Martín-Bello *et al.*, 2014). Moreover, all them probably resulted from negative inversion,  
897 during the Late Pliocene-Quaternary times, of previous contractive structures developed under  
898 the Paleogene-Early Miocene compression (Rubio and Simón, 2007; Lafuente *et al.*, 2011a;  
899 Liesa *et al.*, 2021).

900

901 ~~[PREFERENTIALLY, FIG-13 SHOULD BE INSERTED HERE, AS A 2 COLUMN FIGURE]~~

902  
903 8.2. Morphotectonic approach to assessing recent fault activity within the context of  
904 eastern Spain Planation surfaces as structural markers: inferred offsets and slip rates

905 ~~In the absence of stratigraphic markers recognized in both fault blocks, the~~ In contrast to  
906 ~~the other master faults bounding the Jiloca graben, namely the Calamocha and Conעד faults,~~  
907 ~~no dated stratigraphic marker is available at the Sierra Palomera fault in order to precisely~~  
908 ~~calculate its total offset and slip rate. In such context, the use of planation surfaces (in our~~  
909 ~~case, the mid Pliocene FES2 and FES3 surfaces; Fig 13b) is necessary for characterizing the~~  
910 ~~macrostructure and measuring fault throws. As explained in Section 4, fault throw s.s. and the~~  
911 ~~total tectonic offset of FES2 throw at the Sierra Palomera graben margin attain maximum~~  
912 ~~values of (up to 330 m and 480 m, respectively) have been reasonably estimated from offset of~~  
913 Late Neogene planation surfaces. Nevertheless, uncertainties linked to such geomorphological  
914 markers should be highlighted, resulting in slip rates of 0.09 and 0.13 mm/a.

915 ~~We should draw attention to the fact that~~ Our main geomorphological marker, FES2, is  
916 poorly represented within the Jiloca bottom, i.e., the hanging-all block of the Sierra Palomera  
917 fault, which makes difficult to calculate the actual throw. We interpret that the boundary  
918 between Plio-Pleistocene alluvial deposits and the underlying carbonate unit probably  
919 represents the first approach to the position of FES2 (Fig. 13b), although it also could be  
920 correlated with FES3. According to the results provided by Ezquerro et al. (2020), such  
921 uncertainty introduces a potential error of either 10-40 m in the height of the marker  
922 (equivalent to the thickness of Villafranchian palustrine carbonates  $\approx$  M8 megasequence of  
923 Ezquerro, 2017), or 0.3 Ma in its age. If the top of the buried carbonate unit would be Early  
924 Villafranchian in age (3.5 Ma, therefore correlative of FES3): (i) the fault throw s.s. and the  
925 total tectonic offset-throw calculated in section 4 (330 m and 480 m, respectively) should be  
926 applied to a 3.5 Ma time span, therefore resulting in slightly higher slip rates (0.10 vs. 0.09  
927 mm/a, 0.15 vs. 0.13 mm/a, respectively); (ii) FES2 would lie 10-40 m lower within the  
928 downthrown block, and hence the fault throw s.s. and the maximum total tectonic offset-throw  
929 could increase up to 370 m and 520 m, respectively, giving rise to slip rates of 0.10 and 0.15  
930 mm/a for the last 3.8 Ma. In any case, such height uncertainty is of the same order as the  
931 unevenness of the planation surfaces themselves, and results in a very small error in slip rate  
932 (0.01-0.02 mm/a).

933 ~~The consistency of this interpretation is further reinforced if a broader morphotectonic~~  
934 ~~perspective is adopted, considering the whole morphotectonic setting of footwall and~~

~~hanging wall blocks of the Sierra Palomera fault and neighbouring structures is considered.~~

We have explained how the morpho-sedimentary *FES2* marker defines a tilted Sierra Palomera-Alfambra block whose edge is tectonically uplifted ca. 300 m relative to the bottom of the Teruel basin. A similar morphostructural outline can be drawn for the Sierra de Albarracín-Jiloca block, in which ~~the *FES2* shows a~~ altitude progressively decreases eastwards ~~decrease in altitude~~, from 1400-1500 m to <1100 m. Therefore, the inference that the fault separating such tilted blocks has a throw in the range of 300-400 m seems well-founded. On the other hand, the notion of recent ~~vertical displacement~~ throw on the Sierra Palomera fault being larger than those on Calamocha and Conclud faults (210 and 260 m, respectively; Martín-Bello *et al.*, 2014; Ezquerro *et al.*, 2020) fits a common structural feature of segmented extensional fault zones, in which maximum throws are found in central segments (self-similar pattern as that of individual faults; Cowie and Roberts, 2001). Gracia *et al.* (2003) aimed to minimize the role of tectonic ~~slip on the Sierra Palomera fault~~ subsidence in benefit of erosional lowering in the development of the central Jiloca depression, ~~and hence to underestimate the throw of the Sierra Palomera fault (see further discussion by Rubio and Simón, 2007; Rubio et al., 2007; Gracia et al., 2008). Nevertheless, such~~ but that controversy is currently out of place.

~~It is also pertinent to~~ We should compare the displacement and slip rates on the Sierra Palomera fault with those in the neighbouring Teruel graben. During the last 3.8 Ma (Late Pliocene-Quaternary extensional phase), fault zones making the eastern margin of the Teruel basin underwent total ~~vertical displacement~~ throw (including bending component) in the range of 440 to 620 m, and hence long-term vertical slip rates of 0.12 to 0.16 mm/a (Ezquerro *et al.*, 2020). Assuming an average dip of 70° for the fault plane and a pure normal movement, the resulting total net slip rates for this period are 0.13 to 0.17 mm/a, similar to that calculated for the Sierra Palomera fault (0.15 mm/a) and higher than those for the Conclud (0.07-0.08 mm/a; Lafuente *et al.*, 2011a), Calamocha (0.06-0.09 mm/a; Martín-Bello *et al.*, 2014), and Teruel (0.075 mm/a; Simón *et al.*, 2017) faults.

### ***8.3. Geomorphic indices of the mountain front: assessing fault activity***

~~It is also pertinent to consider~~ g Geomorphic indices constitute an auxiliary tool s for assessing fault activity, ~~as enhanced by,~~ (e.g., Bull and McFadden, (1977); McCalpin, (1996;2009);, Silva et al., (2003);, or Burbank and Anderson, (2012). With this respect, it is interesting to, and compare the values ~~proposed~~ obtained for the Sierra Palomera mountain front with those of other faults in the same geodynamic framework.

At Sierra Palomera, García-Lacosta (2013) calculated ~~values of two significant~~

969 ~~geomorphic indices defined by Bull and McFadden (1977), i.e., the~~ mountain-front sinuosity  
970 ( $S_{mf} = 1.27$ ), and valley width/height ratio ( $V_f = 0.22$ ). ~~The value of  $S_{mf}$  is 1.27. The average~~  
971 ~~width/height ratio calculated for 10 gullies crossing the fault is  $V_f = 0.22$  (measured 250 m~~  
972 ~~upstream from the fault trace).~~ These values, together with ~~other mentioned~~ qualitative  
973 attributes ~~of the mountain front (as~~ trapezoidal facets, V-shaped gullies, ~~and,~~ small alluvial  
974 fans not connected to the regional fluvial system), indicate ‘rapid’ fault slip according to the  
975 classification by McCalpin (2009~~1996~~), and ‘active’ (according to Silva *et al.*, 2003) (Fig.  
976 14). The range of slip rates that those authors estimate for such categories in their respective  
977 classifications (0.08 to 0.5 mm/a) encloses the value calculated for the Sierra Palomera ~~our~~  
978 fault from offset of the *FES2* marker (0.09-0.13 mm/a).

979  
980 **[PREFERENTIALLY, FIG.14 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

981  
982 The sinuosity index  $S_{mf}$  at the Sierra Palomera mountain front is very similar to those  
983 published for that at the Conclud fault ( $S_{mf} = 1.24$ ; Lafuente *et al.*, 2011b), ~~and to those~~  
984 ~~calculated by Perea (2006) for twenty fault-generated mountain fronts at the~~ Maestrat grabens  
985 in, eastern Iberian Chain ( $S_{mf} = 1.04-1.60$ ; mean = 1.27; Perea, 2006), ~~or.~~ ~~They also resemble~~  
986 ~~those obtained at well known active faults of the Betic Chains (SE Spain), such as the~~  
987 Carboneras, Lorca-Alhama ~~or~~ and Baza faults in the Betic Chains, ~~(in which  $S_{mf}$  usually~~  
988 rangings from 1.05 to 1.4; (Silva *et al.*, 2003; García-Tortosa *et al.*, 2008).

989 ~~The average value of the  $V_f$  index computed at a distance of 250 m upstream from~~ the  
990 Sierra Palomera fault ~~trace ( $V_f = 0.22$ )~~ does not differ ~~very much~~ from that of the Conclud fault  
991 ( $V_f = 0.30$ ; Lafuente *et al.*, 2011b), while higher and more variable values have been reported  
992 in the Maestrat grabens (Silva *et al.*, 2003;  $V_f = 0.12-1.5$ ; Perea, 2006), ~~and Betic Chains: Baza~~  
993 ~~fault ( $V_f = 0.28-0.86$ ; ;~~ García-Tortosa *et al.*, 2008); ~~Carboneras and Lorea Alhama faults~~  
994 ~~(0.38 to 0.59; Silva *et al.*, 2003).~~

995 Plotting  $S_{mf}$  vs.  $V_f$  values on the diagram proposed by Silva *et al.* (2003) allows ~~us~~  
996 assessing the relative position of the Sierra Palomera fault among extensional fault-generated  
997 mountain fronts of eastern Spain (Fig. 14). The relatively low values of both  $S_{mf}$  and  $V_f$  indices  
998 found at the Sierra Palomera mountain front (1.27 and 0.22, respectively) represent a  
999 morphotectonic signal similar to that of the Conclud fault, and also consistent with the  
1000 tendency of extensional faults studied by Silva *et al.* (2003) in the Valencia area and Betic  
1001 Chains, ~~which draw the tendency curve plotted in Fig. 14. The position of our geomorphic~~

1002 ~~indices on that diagram: (i) demonstrates that the Sierra Palomera fault fits the same tendency,~~  
1003 ~~and (ii) corroborates that it lies within Class 1 (active).~~

#### 1004 **8.34. Pleistocene fault activity and *its* paleoseismological relevance**

1005 ~~Although m~~Morphotectonic data indicate that the Sierra Palomera fault has a significant  
1006 degree of activity, but no outcrop observation on the main trace has unequivocally evidenced  
1007 ~~its~~ Quaternary activity/displacement on it. Therefore, it is very relevant the finding, in La Sima  
1008 trench, of Pleistocene faults that accommodate extensional deformation associated to the  
1009 hanging-wall rollover, since they indirectly confirm, for the first time, Pleistocene activity of  
1010 the ~~main~~ Sierra Palomera fault.

1011 As explained in section 6.4, seven deformation events (T to Z) have been recognized after  
1012 detailed trench analysis, which could be conventionally considered as paleoseismic events  
1013 according to usual criteria in Paleoseismology. Individual faults activated in each event have  
1014 been recognized, and; their displacements have slip on them has been quantified (individual  
1015 net slip in the range of 5 to 1125 cm; ~~mean = 28 cm;~~ Table 2). Finally, t, and the overall  
1016 faulting history has been carefully reconstructed by means of retrodeformational analysis  
1017 (Fig. 12). Nevertheless, we should critically admit that the meaning of these results in relation  
1018 to paleoseismicity of the Sierra Palomera fault is very imprecise, since:

1019 (i) Instead of crossing the main fault, the trench only represents a short transect within the  
1020 hanging-wall block, at a distance of 1.0 km from the ~~Sierra Palomera~~ fault trace.

1021 (ii) During each event, faults widely distributed along the surveyed transect underwent  
1022 both synthetic slip with Sierra Palomera fault (downthrown block to the west; positive values  
1023 in Table 2) and antithetic slip (negative). The algebraic sum of those values does not  
1024 necessarily ~~have~~ no any meaning in relation to the real slip on the main fault.

1025 (iii) The poor quality of OSL results precludes us from having an age model of the  
1026 exposed sedimentary succession; therefore, the age constraints of the individual events are  
1027 very limited. Only the last two events, Y and Z, could be dated to ca.  $97 \pm 10$  ka and  $49 \pm 5$  ka,  
1028 respectively.

1029 Concerning the net slip accumulated by faults (see Table 2), ~~three among: (i) the first two~~  
1030 four events (T, ~~and~~ U and W) involve significant synthetic slip ( $+45$ ,  $+105$  and  $+60$ ~~40~~ cm,  
1031 respectively), while ; (ii) ~~for V and W, synthetic and antithetic movements almost~~  
1032 ~~counterbalanced each other; (iii) the last three events ones~~ (X, Y, Z) involve significant  
1033 antithetic slip ( $-4590$ ,  $-3540$  and  $-11025$  cm, respectively). The ~~cumulative~~ global aggregate  
1034 fault slip for the ensemble of deformation events; is virtually null (+10 cm). Nevertheless, a  
1035 total accumulated =110 cm, considering an average fault dip of 65°, represents an antithetic

1036 ~~throw of ca. 100 cm. We should add the vertical offset accommodated as continuous~~  
1037 ~~deformation in the bending monocline (amplitude: ca. 120 cm), not included when computing~~  
1038 ~~fault slip s.s. The total tectonic, antithetic throw throw at the transect should be therefore~~  
1039 ~~estimated at of 2120 cm (net slip ~ 230 cm). This value reasonably approaches the total throw~~  
1040 ~~(190 cm) that can be directly measured on the log from offset of the top of unit 6, the~~  
1041 ~~(youngest sedimentary marker previous to the recorded faulting episodes (compare the first~~  
1042 ~~and the last picture in Fig. 12)). Consequently, that resulting throw should be entirely~~  
1043 ~~attributed to the bending monocline (i.e., accommodated in the form of continuous~~  
1044 ~~deformation, not computed within fault slip measurements depicted in Table 2). That value~~  
1045 ~~reasonably approaches the apparent vertical offset ofIt is also consistent with the apparent~~  
1046 ~~height of the gentle uphill-facing scarplet that breaks the natural slope of La Sima alluvial fan~~  
1047 ~~(ca. 2.5260 em; Fig. 10c). In summary, the morphological expression (up-facing scarplet) of~~  
1048 the fault zone exposed in the trench fits well the antithetic sign of the accumulated  
1049 displacementsslip during the most recentyoungest faulting episodes.

1050 Thesee youngest, antithetic faulting events (X, Y and Z) have associated net slip values (-  
1051 3540 to -11025 cm) that should be accommodated on faults several km long (in the range of  
1052 104 to 4023 km, according to the empirical relationships proposed by Wells and Coppersmith,  
1053 1994). This inference plays in favour of: (i) the interpretation of the antithetic fault exposed at  
1054 La Sima trench as a large structure, comparable in length to the Sierra Palomera fault itself, as  
1055 the macrostructural and geophysical data suggested (see sections 5, 6 and 87.1); (ii) the notion  
1056 that faulting events recorded at the trench, in particular those dated to ca. 97±10 ka and 49±5  
1057 ka, very probablyshould respond to coseismic slip-events on the main fault.

1058 Could the timing of those younger events be taken as a reference for approaching seismic  
1059 recurrence periods and slip rates of the Sierra Palomera fault during Pleistocene times? ~~This is~~  
1060 ~~a very difficult question to answer from the available information.~~The tempting hypothesis  
1061 that the two aforementioned ages correspond to the last two major paleoearthquakes would  
1062 suggest a single interseismic period of around 48 ka. According to ~~the empirical relationship~~  
1063 ~~by Villamor and Berryman (1999), such a recurrence period is~~this would be reliable for faults  
1064 ~~moving at an~~showing average slip rate around 0.1 mm/a; ~~therefore, it fits well the long-term~~  
1065 ~~slip rate estimated for, as~~ the Sierra Palomera fault ~~does~~(in the range of 0.09 to 0.15 mm/a).

1066 Nevertheless, ~~we do not consider this as the most reliable scenario.~~The space and time  
1067 window examined in our trench is too narrow for providing a representative  
1068 paleoseismological record. Subsidiary faults similar to those exposed at La Sima could have  
1069 form at other sites within the hanging-wall block in response to other slip-events on the Sierra

1070 Palomera main fault. Furthermore, each ~~slip~~ event on this main fault did not necessarily  
1071 reactivate the antithetical fault exposed at La Sima trench. Accordingly, the actual slip rate on  
1072 the ~~main~~ Sierra Palomera fault during Late Pleistocene times could be significantly higher  
1073 than the long-term one, ~~as evinced in other active faults of the region. Slip rate increased~~  
1074 ~~during Late Pleistocene times with respect to its average value since Late Pliocene times in~~  
1075 ~~the most documented structures south of Sierra Palomera: the Concud fault (0.29 vs. 0.07-~~  
1076 ~~0.08 mm/a) and Teruel fault (0.19 vs. 0.07 mm/a) (Lafuente *et al.*, 2014; Simón *et al.*, 2016;~~  
1077 ~~2017). The same tendency has been revealed for other large faults of the neighbouring Teruel~~  
1078 ~~basin (Ezquerro *et al.*, 2020; see Section 2) and Calatayud basin (Peiro and Simón, 2021). We~~  
1079 ~~therefore consider that the Sierra Palomera fault, larger than the Concud and Teruel faults,~~  
1080 ~~very probably underwent a slip rate higher than 0.09-0.15 mm/a, and an average recurrence~~  
1081 ~~period shorter than 48 ka, since Late Pleistocene time. — (0.09-0.15 mm/a since mid-Pliocene~~  
1082 ~~times; see sections 8.1 and 8.2), following the same tendency found in other active structures~~  
1083 ~~of the region, such as the Concud fault (Lafuente *et al.*, 2014; Simón *et al.*, 2016), Teruel fault~~  
1084 ~~(Simón *et al.*, 2017), Teruel basin (Ezquerro *et al.*, 2020; see Section 2) and Calatayud basin~~  
1085 ~~(Peiro and Simón, 2021).~~

1086 ~~With this respect, the estimation of short-term slip rate that can be made for the antithetic~~  
1087 ~~La Peñuela fault from offset of Unit 9 in the studied trench is irrelevant. The top of that unit is~~  
1088 ~~dated to  $97.4 \pm 10.2$  ka, and has been displaced by the last two deformation events defined (Y~~  
1089 ~~and Z), totalizing a cumulative antithetic net slip of 165 cm. This results in a slip rate of~~  
1090 ~~0.015-0.019 mm/a, which only reflects the local deformation rate on a subsidiary fault for a~~  
1091 ~~very narrow, non-representative time window.~~

#### 1092 ***8.54. Internal deformation of the hanging-wall fault block: a close look from trench*** 1093 ***analysis***

1094 Although the succession of deformation events identified at La Sima trench have a very  
1095 limited paleoseismic meaning, it allows understanding progressive stretching within the  
1096 hanging-wall block of the Sierra Palomera fault. In particular, sequential activation of  
1097 synthetic and antithetic individual faults has been carefully reconstructed by means of  
1098 retrodeformational analysis (Fig. 12) and can be precisely compared with faulting patterns  
1099 linked to rollover deformation at both smaller and larger scales (observed in published  
1100 analogue models and field or seismic-profile examples, respectively) of rollover deformation.

1101 Usually, the hanging-wall rollover geometry is not entirely achieved through ductile  
1102 continuous deformation. Examples from analogue models (*e.g.*, Withjack and Schlische,  
1103 2006), outcrops and high-resolution seismic profiles (*e.g.*, Song and Cawood, 2001; Delogkos

1104 *et al.*, 2020) indicate that a portion of ~~the hanging-wall~~ deformation is accommodated by  
1105 smaller-scale faults. Antithetic faults directly materialize the antithetic simple shear ~~band~~ that  
1106 nucleates at the transition ~~zone~~ from the main ramp to the basal detachment (Withjack *et al.*,  
1107 1995). ~~Therefore, they occur above, and,~~ frequently abutting, the connection line between the  
1108 steep and flat segments of the main fault surface (Bruce, 1973; Song and Cawood, 2001;  
1109 Withjack and Schlische, 2006). In addition, together with subsidiary synthetic faults, they can  
1110 accommodate layer-parallel extension along the rollover. ~~Such extension mainly operates at~~  
1111 ~~the hinge zone of the rollover~~, giving rise to crestral collapse grabens ~~that are well documented~~  
1112 ~~from~~ both analogue models (*e.g.*, McClay, 1990; McClay and Scott, 1991; Buchanan and  
1113 McClay, 1991; Soto *et al.*, 2007) and field examples (*e.g.*, Imber *et al.*, 2003; Back and  
1114 Morley, 2016; Fazli Khani *et al.*, 2017).

1115 The locus of active hanging-wall antithetic faulting, as well as that of crestral graben  
1116 formation, have the appearance of having migrated landwards during development of  
1117 extensional systems: ~~e.~~ Each individual antithetic fault ~~(or fault fan) forms near the fault bend,~~  
1118 moves passively ~~within the hanging-wall block~~ beyond the fault bend, and becomes inactive,  
1119 while a new fault ~~zone~~ propagating from the same ~~fault~~ bend replaces it. Thus, secondary  
1120 faults tend to be progressively older basinwards (Christiansen, 1983; McClay, 1990; Withjack  
1121 *et al.*, 1995; Withjack and Schlische, 2006). ~~That tendency can be enhanced by repeated~~  
1122 ~~footwall collapse (footwall faulting sequence) at the main structure (Imber et al., 2003).~~

1123 In any case, periods of activity of the hanging-wall growth faults can overlap such overall  
1124 time polarity of hanging-wall growth faults does not exclude significant overlap in their  
1125 periods of activity (Imber *et al.*, 2003), ~~as well as variations in the relative occurrence of~~  
1126 ~~synthetic and antithetic faults~~. The great majority of analogue models of rollovers show a  
1127 faulting sequence that begins with an antithetic fault, then alternating synthetic and antithetic  
1128 ones eventually joining and reciprocally offsetting at depth (McClay, 1990; McClay *et al.*,  
1129 1991; T. Román-Berdiel, personal communication). The same pattern has been reported in  
1130 actual examples (e.g., Fazli Khani and Back, 2015, fig. 10). Nevertheless, sandbox  
1131 experiments have also been ~~reported~~ described in which alternating activation of synthetic and  
1132 antithetic faults is initiated with a synthetic one (*e.g.*, Buchanan and McClay, 1991).

1133 The fault sequence interpreted at La Sima trench share some of the former evolutionary  
1134 patterns typical of rollover deformation, such as the: (i) relevance and persistence of a  
1135 subsidiary antithetic fault, the; (ii) activation of ~~additional~~, younger antithetic ruptures closer  
1136 to the main fault, and; (iii) overall alternating onset of synthetic and antithetic ruptures. ~~On the~~  
1137 ~~other hand~~ However, we have also found a non-typical feature: the oldest recorded meso-scale



1138 faults are synthetic with the Sierra Palomera fault, despite having formed in the same area  
1139 where the persistent antithetic fault will later appear. The first ~~two~~ deformational events (T to  
1140 ~~W and U~~) mainly involve accumulation of significant synthetic net slip (+~~200~~~~155~~ cm), while  
1141 ~~in the following two (V and W) synthetic and antithetic movements almost counterbalanced~~  
1142 ~~each other, and~~ the last three ones (X, Y, Z) involve substantial antithetic net slip (~~-190~~~~255~~  
1143 cm). Briefly, progressive deformation in the hanging-wall block is shifted from dominantly  
1144 synthetic faulting to dominantly antithetic faulting. Such particular deformation  
1145 pattern “irregularity” suggests the existence of other controls on the hanging-wall deformation  
1146 in addition to the rollover kinematics itself, as discussed in the next section.

1147 ~~On the other hand~~ Finally, the accumulated net slip has an associated component of  
1148 horizontal extension that enables ~~another~~ a further quantitative kinematical approach (see  
1149 Table 2). The total extension recorded at La Sima trench is  $\approx$ 3~~10~~~~85~~ cm, which represents  
1150 about ~~19~~~~20~~% of the ~~total~~ restored length of the logged transect (local  $\beta$  factor = 1.~~19~~~~2~~).  
1151 Horizontal extension accommodated by faults totalizes ca. 210 cm (125 cm by synthetic ones  
1152 and 86 cm by antithetic ones). Development of the bending monocline involves additional  
1153 extension of about 100 cm. ~~The antithetic faults accommodate much more extension (200 cm)~~  
1154 ~~than the synthetic ones (115 cm).~~ Considering that the bending monocline represents  
1155 ~~additional antithetic offset, it also involves additional horizontal extension, which can be~~  
1156 ~~estimated at 70 cm assuming a fault dip of 65°.~~ Two main events (W, equally represented by  
1157 ~~synthetic and antithetic faults, and Z, mostly antithetic) accumulate about one half of the total~~  
1158 ~~extension (85 cm, ca. 4.5%, each one).~~

1159 Overall considered, our results represent a high-resolution, sub-seismic-scale picture of  
1160 hanging-wall deformation that complements natural case studies based on seismic profiles and  
1161 ‘fills the gap’ with the scale of laboratory analogue models. It documents both (i) earlier  
1162 stages of a process of hanging-wall deformation (those mostly governed by synthetic faulting)  
1163 that usually are not recognized from seismic reflection data, and (ii) later stages governed by  
1164 antithetic faulting that better correlate with seismic-reflection-based models.

1165

#### 1166 **8.56. Kinematic and dynamic controls on deformation of the hanging-wall block:** 1167 **relevance of the tectonic $S_{stress}$ regime and tectonic framework**

1168 It is not easy to discriminate whether faults propagated through the hanging-wall block  
1169 are kinematically or dynamically controlled, i.e., they essentially accommodate extensional  
1170 deformation associated to the rollover monocline, or they are directly linked to regional stress.

1171 Geometry and kinematics of faults ~~exposed in the surveyed at both map and trench scales, as~~  
1172 ~~well as of those inferred at a macrostructural scale from surface mapping and geophysical~~  
1173 ~~exploration,~~ overall fits the expected deformation within the hanging-wall block of the Sierra  
1174 Palomera fault. But, ~~at the same time, it is~~ they are also consistent with the regional  
1175 extensional stress field, whose  $\sigma_3$  trajectories trend ENE-WSW (Simón, 1982, 1989; Arlegui  
1176 *et al.*, 2005, 2006; Liesa *et al.*, 2019), orthogonal to the overall trend of the Jiloca graben, and  
1177 only slightly oblique to the Sierra Palomera fault trace itself. Stress inversion from the most  
1178 representative, non-rotated conjugate faults measured within the trench, according to  
1179 Anderson (1951)'s ~~model~~, provides local stress axes matching those regional trajectories (Fig.  
1180 15).

1182 **[PREFERENTIALLY, FIG.15 SHOULD BE INSERTED HERE, AS A 1-COLUMN FIGURE]**

1184 ~~It is not easy to discriminate whether the faults propagated through the hanging-wall~~  
1185 ~~block are kinematically or dynamically controlled, i.e., they essentially accommodate~~  
1186 ~~extensional deformation associated to the rollover monocline, or they are directly linked to~~  
1187 ~~regional stress conditions.~~ The extension direction expectable for the first kinematical  
1188 scenario could be constrained between N065°E (orthogonal to the average strike of the Sierra  
1189 Palomera fault; an inherited feature indeed) and N050°E (transport direction). The extension  
1190 trend expectable for the second dynamical scenario would approach N075°E (seeing at the  
1191 average trend of the Jiloca graben), or would range from N055°E to N080°E (seeing at  
1192 paleostress results reported by Arlegui *et al.*, 2005, and Liesa *et al.*, 2019). The similarity  
1193 between both inferences prevents us from discriminating among those hypothetical controls  
1194 based solely on the orientation of structures (stereoplots of Fig. 11 show how the strongly  
1195 clustered directions of normal faults in La Sima trench fit equally well the two scenarios).  
1196 Nevertheless, some details of the faulting succession suggest that both controls probably  
1197 coexist. The kinematical control has been attested and discussed in sections 8.1 and 8.5. The  
1198 dynamical one could explain the early occurrence of early synthetic meso-scale faults (an  
1199 unusual feature in kinematically-driven models) at La Sima site.

1200 Additionally, there also seems to be a certain degree of control by a recent ESE-WNW  
1201 extension direction. ~~B~~the imprint of the regional stress field is revealed by certain fracture  
1202 features directly linked to characteristic heterogeneities of the extensional Plio-Quaternary  
1203 stress field in the eastern Iberian Chain. First, ~~under the biaxial or multidirectional extension~~  
1204 regime characterizing such stress field, a strong tendency for the  $\sigma_2$  and  $\sigma_3$  axes to switch

1205 typically results in secondary faults striking at right angles to the master faults. (Simón *et al.*,  
1206 1988; Simón, 1989; Arlegui *et al.* 2005, 2006). Second, both E-W to ESE-WNW, and ENE-  
1207 WSW extension directions (characterizing the Late Miocene-Early Pliocene and the Plio-  
1208 Quaternary rift episodes, respectively) are recorded during the entire extensional period  
1209 indeed (Liesa *et al.*, 2019). This suggests stress partitioning (in the sense of Simón *et al.*,  
1210 2008) of the composite extensional field that results from combination of intraplate NNW-  
1211 SSE compression (Africa-Iberia convergence) and WNW-ESE extension (rifting of the  
1212 Valencia trough) (Simón, 1989; Herraiz *et al.*, 2000; Capote *et al.*, 2002). Among fractures  
1213 observed at La Sima trench that do not show any sign of displacement, only reveal the second  
1214 type of stress heterogeneity. There is no orthogonal fault or fracture, and hence no evidence of  
1215 permutation of  $\sigma_2$  and  $\sigma_3$  axes. Nevertheless, a minority NNE-SSW trending set can be  
1216 distinguished among fractures that do not show any sign of displacement (Fig. 11f), which  
1217 records the WNW-ESE extensional component of the regional, locally and episodically  
1218 partitioned stress field.

## 1220 9. Conclusions

1221 ~~1) The NNW-SSE trending, 26 km long Sierra Palomera extensional fault probably~~  
1222 ~~resulted from negative inversion of a previous contractive structure developed under the~~  
1223 ~~Paleogene-Early Miocene compression of the Iberian Chain.~~

1224 2) The NNW-SSE trending, 26 km long Sierra Palomera extensional fault has been active  
1225 during Late Pliocene-Quaternary times. It has undergone nearly pure normal movement with  
1226 mean transport direction towards N230°E, consistent with the ENE-WSW extension  
1227 trajectories of the recent to present-day regional stress field.

1228 ~~3) Magnetic and electromagnetic profiles, together with local geological and~~  
1229 ~~geomorphological evidence, suggest that the~~ The hanging-wall block of the Sierra Palomera fault  
1230 is cut by two subsidiary parallel ruptures: (i) the synthetic Las Vallejadas fault, located at  
1231 about 1.5 km basinwards, and (ii) the antithetic La Peñuela fault, at a distance of 0.7-1.0 km,  
1232 which apparently offsets ca. 2.5 m the surface of the La Sima alluvial fan giving rise to a  
1233 gentle uphill-facing scarplet.

1234 ~~4) In the absence of recent stratigraphic markers visible in the both fault blocks, the FES2~~  
1235 ~~planation surface (3.8 Ma) has constituted a useful marker for estimating the extensional net~~  
1236 ~~slip on the main fault. The corresponding contour map~~ has allowed calculating a maximum  
1237 value of 330 ± 40 m for the fault throw *s.s.*, and ca. 480 ± 40 m for the total tectonic offset

1238 ~~throw~~ at the ~~half~~-graben margin (including the bending component). ~~Assuming an average dip~~  
1239 ~~of 70° for the fault plane and a pure normal movement, resulting in~~ a net slip rate of  $0.09 \pm$   
1240 ~~0.01~~ mm/a ~~is inferred~~ ( $0.13 \pm 0.01$  mm/a including bending). ~~Based on the natural unevenness~~  
1241 ~~of the FES2 marker, the error bar for the calculated throws and net slip values is  $\pm 40$  m,~~  
1242 ~~which results in errors for slip rates around 0.01 mm/a.~~

1243 5) ~~The Sierra Palomera fault is expressed in the landscape by a conspicuous fault~~  
1244 ~~mountain front. Qualitative geomorphological features (trapezoidal facets; V-shaped gullies;~~  
1245 ~~small, steep alluvial fans not fully connected to the axial drainage), as well as values of~~  
1246 ~~geomorphic indices, are consistent with a significant degree of recent fault activity.~~

1247 6) ~~Trench study has~~ Results from La Sima trench have demonstrated the existence of the  
1248 ~~above-mentioned~~ antithetic subsidiary La Peñuela fault, accompanied by a number of minor  
1249 synthetic and antithetic ones, and its activity during Middle-Late Pleistocene times. Their  
1250 detailed kinematical analysis has allowed building an evolutionary model made of seven  
1251 deformation events ~~recorded in Middle Late Pleistocene alluvial deposits~~. Net slip on  
1252 individual faults ranges from 5 to 1125 cm (~~mean = 28 cm~~). The cumulative global antithetic  
1253 throw at the antithetic-exposed fault zone, including fault slip s.s. and bending, is estimated at  
1254 2120 cm, which reasonably approaches the apparent offset of the natural slope of La Sima  
1255 alluvial fan, at the uphill-facing scarp (260 cm).

1256 The significance of the paleoseismic results is certainly limited. The surveyed trench  
1257 within the hanging-wall block does not cross the main fault itself. In addition<sup>7)</sup>  
1258 Unfortunately, it was not feasible to achieve a consistent age model for the entire sedimentary  
1259 sequence, ~~since the majority of samples dated by Optically Stimulated Luminescence (OSL)~~  
1260 ~~presented signal saturation.  $\emptyset$ ; only the last two deformation events have been dated to ca.~~  
1261 ~~97 $\pm$ 10 ka and 49 $\pm$ 5 ka, respectively. In addition, the surveyed trench only represents a short~~  
1262 ~~transect within the hanging-wall block, not across the main fault itself, so that its paleoseismic~~  
1263 ~~significance is limited.~~ Nevertheless, it is worth highlighting the fact that, for the first time,  
1264 Pleistocene activity of the Sierra Palomera fault has been unequivocally (although indirectly)  
1265 proved for the first time, although indirectly from hanging-wall deformation.~~from outcrop~~  
1266 ~~observation.~~

1267 8) ~~Despite its poor paleoseismic meaning,~~ The succession of faulting events identified at  
1268 La Sima trench study allows unravelling the progressive extensional deformation mechanisms  
1269 within the hanging-wall block of the Sierra Palomera fault. The total horizontal extension  
1270 recorded at La Sima trench is  $\approx 3$ 1085 cm (local  $\beta$  factor = 1.192). The evolutionary  
1271 model faulting succession ~~built from retrodeformation analysis~~ indicates that synthetic slip

1272 prevailing in early deformation events was ~~gradually substituted by~~shifted to antithetic slip,  
1273 ~~the latter being clearly predominant~~ during the younger ones. Geometry and sequential  
1274 development of meso-scale faults suggest the concurrence of: (1) a kinematic control, *i.e.*,  
1275 antithetic simple shear linked to rollover kinematics (mostly resulting in the main antithetic  
1276 fault zone), eventually accompanied by layer-parallel extension orthogonal to the rollover  
1277 axis, and (2) a dynamic control, *i.e.*, response to the ~~regional remote extensional~~stress field,  
1278 characterized by ENE-WSW (occasionally ESE-WSW) extension trajectories.

1279

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1293

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1580

1581 **FIGURE CAPTIONS:**

1582 **Figure 1:**

1583 (a) Location of the Iberian Chain within the Iberian Peninsula. (b) Geological sketch of the Iberian  
1584 Chain, with location of the main Neogene-Quaternary extensional basins. (c) Simplified geological  
1585 map of the Jiloca graben, with location of Figures 2, 6 and 9.

1586 **Figure 2:**

1587 Geological map of the Sierra Palomera area (on DEM image from Instituto Geográfico Nacional)  
1588 showing the main structures associated to the Sierra Palomera fault. Location of Figures 3, 4, 8, 10a,  
1589 11 is indicated, as well as that of OSL samples in La Cecilia and La Sima alluvial fans (see Table 1).

1590 **Figure 3:**

1591 Cross section of the Jiloca Graben at its central sector, initially reconstructed from surface geology and  
1592 shallow borehole data (modified from Rubio and Simón, 2007). See location in Figure 2.

1593 **Figure 4:**

1594 (a) Field view of one of the rupture surfaces within the damage zone of the Sierra Palomera fault; it  
1595 cuts Lower Jurassic limestones and shows associated fault breccia. (b) Stereoplot (equal area, lower  
1596 hemisphere) showing orientations of fault planes and slickenlines collected in that zone.

1597 **Figure 5:**

1598 The Sierra Palomera mountain front. (a) Field panoramic view. (b) Hillshade oblique image rendered  
1599 from Digital Elevation Model (5 m grid) of Instituto Geográfico Nacional (IGN). (c) Detail of a  
1600 trapezoidal facet within the fault scarp. (d) Hillshade oblique image (5-m-grid DEM, IGN) showing a  
1601 close view to the alluvial fans sourced at the mountain front; La Cecilia and La Sima alluvial fans are  
1602 identified.

1603 **Figure 6:**

1604 Morphotectonic map of the Sierra Palomera area.

1605 **Figure 7:**

1606 Throw vs. distance (T-D) graph along the Sierra Palomera fault. Lower curve: fault throw s.s. recorded  
1607 by the FES2 marker. Upper curve: total tectonic ~~offset-throw~~ of FES2 including the bending  
1608 component.

1609 **Figure 8:**

1610 Villafranchian alluvial deposits (V) ~~deformed-tilted~~ by an accommodation monocline above in the  
1611 footwall block of La Peñuela fault. Jurassic limestones (J) of the footwall block crops out at the  
1612 bottom of the gully. See location in Figure 2.

1613 **Figure 9:**



1614 Results of the ~~geomagnetic–magnetometric~~ survey covering the Sierra Palomera piedmont. (a)  
1615 Location of ~~magnetic~~ profiles 01 to 10 (which is the same as for the electromagnetic survey), with the  
1616 residual values of field intensity (nT) plotted as a colour palette. Black thin lines depict the Sierra  
1617 Palomera fault trace. Grey thick lines depict the spatial correlation of trending changes on the  
1618 successive transects, and therefore of the described domains (A, B and C). (b) ~~Magnetic-Residual earth~~  
1619 magnetic field profiles plotted with a normalized horizontal length, in which domains A, B and C  
1620 roughly parallel to the Sierra Palomera fault are defined (data are in nT; see text for details).

1621 **Figure 10:**

1622 (a) Hillshade relief map of the barranco de la Sima alluvial fan rendered from digital elevation model  
1623 (DEM, 5 m grid) of the Instituto Geográfico Nacional. See location in Figure 2. (b) Residual magnetic  
1624 field anomalies at the central sector of the alluvial fan, at the contact between domains A and B. (c)  
1625 Detailed topographic profile showing a slope anomaly in the longitudinal profile of the alluvial fan  
1626 surface, from which an apparent antithetic throw of ca. 2,56 m can be inferred.

1627 **Figure 11:**

1628 (a) Uninterpreted photomosaic of La Sima trench, see location in Figure 2. (b) Detailed log ~~of La Sima~~  
1629 ~~trench. See location in Figure 2.~~ 1 to 12: Quaternary units described in the text. Greek characters:  
1630 faults referred in the text. The location and age of samples dated by OSL is indicated. Stereoplots  
1631 (equal area, lower hemisphere) show orientations of faults and fractures measured within the trench:  
1632 (cb) Central fault zone. (de) Footwall block, including monocline. (de) Synthetic stereoplot of fault  
1633 planes, including a main set parallel to the prevailing structural trend (NNW-SSE, black great circles)  
1634 and a subsidiary set oriented NNE-SSW (blue great circles); fault planes rotated at the; those rotated at  
1635 the central monocline have been restored to their original orientation. (ef) Synthetic stereoplot of  
1636 fractures without displacement.

1637

1638 **Figure 12:**

1639 Evolutionary model of sedimentation and deformation recorded at the La Sima trench from  
1640 retrodeformational analysis. Each sketch represents a stage subsequent to the paleoseismic event (and,  
1641 in some cases, to deposition of sedimentary units) labelled above. Unexposed sectors below the trench  
1642 have been locally reconstructed in the sketches in order to complete the evolutionary model. Bold  
1643 traces indicate which faults are active during each event. Total horizontal extension and throw  
1644 calculated in Table 2 are shown.

1645 **Figure 13:**

1646 (a) Refined cross section of the Jiloca graben at its central sector, in which the new inferred, subsidiary  
1647 faults have been incorporated. (b) Upper fringe of the same cross section (vertical scale x2) showing  
1648 offset of planation surfaces *FES2* and *FES3*.

1649 **Figure 14:**

1650 Plot of  $S_{mf}$  (mountain-front sinuosity index) vs.  $V_f$  (valley width/height ratio, measured 250 m  
1651 upstream from the fault trace), showing the relative position of the Sierra Palomera Fault among  
1652 extensional fault-generated mountain fronts of eastern Spain. For comparison, the  $S_{mf}$ - $V_f$  plots for the  
1653 neighbouring Conclud fault (Lafuente et al, 2011b), faults bounding the Maestrat grabens (eastern  
1654 Iberian Chain; Perea, 2006), and Valencia region and Betic chains (Silva *et al.*, 2003) are also  
1655 included. Class 1, 2, 3: activity classes (active, moderate and inactive, respectively); the curve  
1656 represents the tendency for normal faults in SE Spain according to Silva *et al.* (2003).

1657 **Figure 15:**

1658 Interpretation of paleostress axes from orientation of non-rotated, conjugate fault planes measured  
1659 within La Sima trench. Stress inversion based on model by Anderson (1951).

1660 **Table 1:**

1661 Parameters and results of OSL dating of samples collected at the La Sima trench (S1 to S7;  
1662 Luminescence Dating Laboratory of University of Georgia, USA), and La Cecilia and La Sima alluvial  
1663 fans (Laboratorio de Datación y Radioquímica de la Universidad Autónoma de Madrid, Spain).

1664 **Table 2:**

1665 Synthesis of deformation events inferred at La Sima trench: faults activated during each event; net  
1666 slip values calculated from the trench log and the retrodeformational analysis (positive: synthetic with  
1667 the Sierra Palomera fault; negative: antithetic; Figs. 11, 12), and associated values of horizontal  
1668 extension. Further explanation in text.

[Click here to view linked References](#)

1 ***Hanging-wall deformation at the active Sierra Palomera extensional fault***  
2 ***(Jiloca basin, Spain) from structural, morphotectonic, geophysical and trench***  
3 ***study***

4

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18

19 **Abstract**

20 The NNW-SSE trending Sierra Palomera fault is characterized as an active, nearly pure  
21 extensional fault with mean transport direction towards N230°E, consistent with the ENE-  
22 WSW extension trajectories of the recent to present-day regional stress field. Its  
23 macrostructure is described from surface geology and magnetometric and electromagnetic  
24 surveys, which have allowed identifying two subsidiary, nearly parallel normal faults  
25 (antithetic and synthetic, respectively). The structural contour map of an extensive planation  
26 surface, dated to 3.8 Ma, provides a maximum fault throw *s.s.* of 330 m for the main fault  
27 (480 m including bending), and a net slip rate of 0.09 mm/a (0.13 mm/a including bending).  
28 Trench study focussed on the subsidiary antithetic fault shows evidence of its activity during  
29 Middle-Late Pleistocene times, offsetting ca. 2.5 m the slope of a well-preserved alluvial fan.  
30 Detailed analysis and retrodeformation of the antithetic fault and other minor ruptures in the  
31 trench has allowed defining seven deformation events. The lack of a consistent age model for

32 the involved sedimentary sequence makes them almost meaningless in terms of paleoseismic  
33 history. However, geometry and sequential development of meso-scale faults (intermediate  
34 between seismic-scale and analogue models) allows unravelling the extensional deformation  
35 history within the hanging-wall block of the Sierra Palomera fault. Progressive rupture  
36 patterns reveal shifting from dominantly synthetic to dominantly antithetic faulting,  
37 suggesting both kinematical control linked to rollover growth, and dynamical control by the  
38 regional stress field.

39 **Keywords:** Active fault, antithetic fault, rollover, magnetometry, Pleistocene, Iberian Chain.

## 40 **1. Introduction**

41 Our understanding of geometry and kinematics of extensional fault systems has been  
42 significantly improved thanks to analytical and scaled analogue models, particularly  
43 concerning deformation of the hanging-wall block of listric faults. Such models provide  
44 interesting inferences about controls that the shape of the main fault surface exerts on the  
45 development of hanging-wall folds and fractures. Fault surfaces with irregular geometry  
46 induce antithetic simple shear along a deformation band that nucleates at shallowing fault  
47 bends, while synthetic shear is induced at steepening fault bends (McClay and Scott, 1991;  
48 Xiao and Suppe, 1992; Withjack *et al.*, 1995; Delogkos *et al.*, 2020). Depending on the  
49 mechanical behaviour of materials, such overall simple shear mechanism results in either  
50 fault-related folding (rollover and drag folds, respectively) or faulting (antithetic and  
51 synthetic, respectively). Analogue models provide insights into both differential behaviours,  
52 *e.g.*, by comparing experimental materials as clay and sand (*e.g.*, Withjack *et al.*, 1995).  
53 Nevertheless, as discussed by Xiao and Suppe (1992), models give limited information about  
54 the actual small-scale mechanisms that accommodate deformation. Therefore, contribution of  
55 data directly supplied by field examples is necessary for full understanding of kinematics of  
56 extensional systems.

57 The Sierra Palomera fault, at the central sector of the Jiloca basin, is one of the most  
58 conspicuous recent, hypothetically active extensional faults in the central Iberian Chain  
59 (Spain; Fig. 1), but less known than other neighbouring structures. The Calamocha and  
60 Conclud faults, which bound the northern and southern sectors of the Jiloca basin (Fig. 1c),  
61 offset early Pliocene lacustrine deposits of the Calatayud and Teruel basins, respectively. This  
62 allows calculating their total throws at about 210 m for the Calamocha fault (Martín-Bello *et al.*,  
63 2014), and 260 m for the Conclud fault (Ezquerro *et al.*, 2020). On the contrary, no recent  
64 stratigraphic marker is available for the Sierra Palomera fault. The tectonic nature of the basin  
65 boundary itself, and particularly the relative role of erosive lowering and fault displacement in

66 the creation of the mountain scarp, has been the object of controversy indeed. After Cortés  
67 and Casas (2000), its topography is essentially a result of erosive incision in response to  
68 orogenic uplift during the Paleogene. Gracia *et al.* (2003) reinterpret the Jiloca depression as a  
69 polje developed during the Late Pliocene-Quaternary. Rubio and Simón (2007) and Rubio *et*  
70 *al.* (2007) provide new sedimentary, geomorphological and hydrogeological evidence on the  
71 tectonic origin of the Jiloca depression, concluding that the Sierra Palomera fault has a  
72 maximum throw approaching 350-400 m.

73 Concerning the signs of Quaternary activity, these are again conspicuous in the northern  
74 and southern sectors of the Jiloca graben but not in the central one. The Conclud fault has been  
75 object of intense paleoseismological research, which has allowed reconstructing a succession  
76 of eleven events since ca. 74 ka BP, with average recurrence period of 7.1-8.0 ka, total  
77 accumulated net slip of about 20 m, and average slip rate of 0.29 mm/a (Lafuente, 2011;  
78 Lafuente *et al.*, 2011a,b, 2014; Simón *et al.*, 2016). Quaternary activity of the Calamocha  
79 fault is revealed by the mechanical contact between Neogene units of the Calatayud basin and  
80 Late Pleistocene alluvial deposits that infill the northernmost Jiloca basin (Martín-Bello *et al.*,  
81 2014). Other neighbouring faults (Munébrega, Teruel, Valdecebro) have also been object of  
82 trench studies in the last two decades (Gutiérrez *et al.*, 2009; Simón *et al.*, 2017, 2019). On  
83 the contrary, no exposure of the Sierra Palomera fault cutting Quaternary deposits has been  
84 reported, and no paleoseismological analysis has been carried out. This is mainly due to the  
85 fact that the Quaternary fluvial incision is virtually absent, and there is a lack of appropriate  
86 sites for digging trenches across the main fault.

87 In such a situation, the study of the Sierra Palomera fault should be focussed on obtaining  
88 indirect evidence of its recent activity from hanging-wall deformation. This can be achieved  
89 by (i) exploring the subsoil of the associated pediment by means of geophysical techniques,  
90 (ii) analysing the effects of fault activity on the relief through morphotectonic analysis, and  
91 (iii) recognizing deformation of Quaternary materials in trenches. Methodology of trench  
92 analysis, extensively used and standardized for paleoseismological studies (*e.g.*, McCalpin,  
93 2009), offers new insights for detailed analysis of progressive extensional deformation.  
94 Concerning scale, trenches have the advantage of delivering valuable information on faults at  
95 an intermediate scale between seismic profiles and laboratory analogue models. Concerning  
96 timing, each identified event can be considered as an incremental or ‘infinitesimal’  
97 deformation episode, and hence the reconstructed paleoseismic succession provides a detailed  
98 and realistic view of extension kinematics (although ineludibly constrained to a given space  
99 and time window).

100 The present work has been carried out in that perspective. Our specific objectives are: (1)  
101 improving our overall knowledge on the structure and evolution of the Sierra Palomera fault  
102 and the Jiloca basin; (2) reporting evidence on the activity of the Sierra Palomera fault during  
103 the Quaternary, and (3) characterizing the patterns of progressive extensional deformation  
104 within its hanging-wall block.

105

## 106 **2. Geological setting**

107 The Iberian Chain is a NW-SE trending, 450 km long intraplate mountain range located  
108 in the eastern Iberian Peninsula (Fig. 1a). This chain developed in Paleogene to Early  
109 Miocene times due to positive inversion of the extensional Mesozoic Iberian basin, under the  
110 convergence between the Africa and Eurasia plates (Álvaro *et al.*, 1979; Guimerà and Álvaro,  
111 1990; Capote *et al.*, 2002; Liesa *et al.*, 2018). After a transition period during the Early  
112 Miocene, in which the longitudinal Calatayud basin developed under a transpressional regime  
113 (Colomer and Santanach, 1988; Simón *et al.*, 2021), a new extensional stage associated to  
114 rifting of the Valencia Trough took place.

115 Extensional deformation propagated onshore towards the central part of the Iberian Chain  
116 (Álvaro *et al.* 1979, Vegas *et al.*, 1979) in two stages, inducing both reactivation of the main  
117 inherited Mesozoic faults and formation of new normal faults, and generating a number of  
118 diversely oriented intracontinental grabens and half-grabens (Simón, 1982, 1989; Gutiérrez *et al.*  
119 *et al.*, 2008, 2012; Ezquerro, 2017; Liesa *et al.*, 2019). During the first stage (Late Miocene to  
120 Early Pliocene in age), the 90-km-long, NNE-SSW to N-S trending Teruel half-graben basin  
121 developed, filled with terrestrial sediments up to 500 m thick (Simón, 1982, 1983; Moissenet,  
122 1983; Anadón and Moissenet, 1996; Ezquerro, 2017; Ezquerro *et al.*, 2019, 2020). The  
123 second extensional stage that started by the mid-Pliocene has produced a more widespread  
124 deformation in the central Iberian Chain. A large number of inherited structures were  
125 reactivated, producing new NNW-SSE trending grabens and half-grabens that are inset or  
126 cross-cut the pre-existent Teruel and Calatayud basins (Simón, 1983, 1989; Gutiérrez *et al.*,  
127 2008, 2020; Liesa *et al.*, 2019). They include, among others (Fig. 1c), the 80-km-long Jiloca  
128 graben, which results from en-échelon, right releasing arrangement of the NW-SE striking  
129 Concud, Sierra Palomera and Calamocha faults (Simón, 1983; Rubio and Simón, 2007;  
130 Simón *et al.*, 2012, 2017; Peiro *et al.*, 2019, 2020). In the first extensional phase, the direction  
131 of maximum extension ( $\sigma_3$ ) was E-W to ESE-WNW (under a triaxial extensional regime),  
132 while ‘multidirectional’ extension with ENE-WSW  $\sigma_3$  trajectories characterizes the second

133 phase (Simón, 1982, 1983, 1989; Cortés, 1999; Capote *et al.*, 2002; Arlegui *et al.*, 2005,  
134 2006; Liesa, 2011; Ezquerro, 2017; Liesa *et al.*, 2019).

135 Geometric construction of normal fault profiles of the Teruel half-graben system allows  
136 locating the sole detachment at a depth of 14-17 km b.s.l., and estimating an average E-W  
137 stretching factor  $\beta = 1.1$  since its onset (11.2 Ma ago) (Ezquerro *et al.*, 2020). Major faults  
138 accumulated slip of a few hundred metres to ca. 1 km (computing both fault throw *s.s.* and  
139 associated bending). The resulting slip rate, around 0.09 mm/a in average, is very similar for  
140 distinct transects across the structure, but shows a clear increase between both extensional  
141 phases: from 0.05-0.07 mm/a to 0.12-0.16 mm/a (Ezquerro *et al.*, 2020). Such slip rate  
142 increase has been attributed to: (i) onshore, westwards propagation of extensional deformation  
143 from the inner parts of the Valencia Trough, enhanced by crustal doming that would have  
144 affected the eastern Iberian Chain; (ii) onset of the multidirectional extension stress field  
145 driven by crustal doming mechanism; (iii) progressive fault linkage since the beginning of the  
146 Late Miocene (Ezquerro *et al.*, 2020).

147 Mountains surrounding the Teruel and Jiloca basins show extensive erosion surfaces  
148 modelling Mesozoic-Palaeogene rocks and bevelling compressional structures. Two large  
149 planation surfaces, whose remnants appear at different heights either on the upthrown blocks  
150 or in the basin floors, have been traditionally defined (Gutiérrez and Peña, 1976; Peña *et al.*,  
151 1984; Sánchez-Fabre *et al.*, 2019): (i) *Intra-Miocene Erosion Surface (IES, middle Miocene)*,  
152 generally recognized in the upper part of the main reliefs, and (ii) *Fundamental Erosion*  
153 *Surface (FES, middle Pliocene)*, easily recognizable as a vast planation level at lower heights.  
154 They approximately correspond to the *Iberian Chain Surface* and the *Lower Pliocene Surface*  
155 by Pailhé (1984), and the S1 and S2 by Gutiérrez and Gracia (1997), respectively. Recent  
156 detailed studies (Simón-Porcar *et al.*, 2019; Ezquerro *et al.*, 2020) have demonstrated that the  
157 *FES* splits into three different surfaces: an Upper Sublevel, the *FES s.s.* (the most widely  
158 developed), and a Lower Sublevel. In this work, these surfaces will be called as *FES1*, *FES2*  
159 and *FES3*, respectively. Planation surfaces have been physically correlated with different  
160 coeval sedimentary horizons (lacustrine-palustrine carbonates) within the sedimentary infill of  
161 the Teruel basin (Ezquerro, 2017), whose ages are well-constrained on the basis of mammal  
162 sites and magnetostratigraphy. In this way, the *Intra-Miocene Erosion Surface* has been dated  
163 close to the Aragonian-Vallesian limit (~11.2 Ma; Alcalá *et al.*, 2000; Ezquerro, 2017), *FES1*  
164 and *FES2* to the Late Ruscinian (both merging around ~3.8 Ma), and *FES3* to the Early  
165 Villafranchian (~3,5 Ma) (Ezquerro *et al.*, 2020).

166 Qualitative and quantitative geomorphological features of the mountain fronts and the

167 associated piedmonts of the eastern margin of the Jiloca graben are those typical of active  
168 normal faults. At the Conclud fault, Lafuente *et al.* (2011b) described conspicuous triangular  
169 facets and short, non-incised alluvial fans, and provided a significantly low value of the  
170 mountain-front sinuosity index defined by Bull and McFadden (1977) ( $S_{mf} = 1.24$ ). At the  
171 Sierra Palomera fault, García-Lacosta (2013) described trapezoidal facets and V-shaped  
172 gullies, and provided a similar value for the sinuosity index ( $S_{mf} = 1.27$ ). The fault scarps are  
173 connected with the depression bottom by gentle pediments mostly draining towards the Jiloca  
174 river, although endorheic conditions have locally remained until historical times, with  
175 development of a palustrine area at the basin centre (ancient Cañizar lake; Rubio and Simón,  
176 2007).

177 Historic and instrumental seismicity of the central-eastern Iberian Chain is low to  
178 moderate. In the Teruel region, the epicentres are concentrated at the Jiloca graben margins,  
179 the central-southern sector of the Teruel basin, and the Albarracín and Javalambre massifs.  
180 Apart from the Albarracín massif, epicentres can be reasonably associated to Neogene-  
181 Quaternary known faults. Measured magnitudes ( $M_b$ ) usually range from 1.5 to 3.5, with  
182 maximum  $M_b = 4.4$  in the Teruel Graben and  $M_b = 3.8$  in the Albarracín massif (IGN, 2021).

183

### 184 **3. Methodology**

#### 185 ***3.1. Structural and morphotectonic study***

186 The structural study is based on recognizing and mapping the main structures on aerial  
187 photographs at 1: 18,000 and 1: 33,000 scale, and satellite imagery, complemented with field  
188 surveys involving outcrop-scale observations. Data of orientation of rupture surfaces and  
189 slickenlines have been collected in a number of sites within the Sierra Palomera fault damage  
190 zone, as well as within the trench described below. Stereoplots (equal-area, lower hemisphere)  
191 of those data sets have been elaborated using Stereonet 8 software (Allmendinger *et al.*, 2012;  
192 Cardozo and Allmendinger, 2013).

193 To characterize the geometry of recent vertical deformation, the three erosional planation  
194 surfaces (*FES1*, *FES2* and *FES3*) described above were used as markers. This required  
195 mapping of erosion surfaces and morphotectonic analysis based on aerial photographs (scales  
196 1: 18,000 and 1: 33,000) and orthorectified photographs (1: 5000), as well as on digital  
197 elevation models (DEM, pixel = 5 m) and the resulting hillshade images. A structural contour  
198 map of *FES2* was elaborated by interpolating the altitude of their remnants, which permits  
199 measuring throw across the main fault and hence calculating slip rate. Changes of throw along



200 the fault zone were calculated from 1-km-spaced transects orthogonal to the fault trace and  
201 analysed on a throw *vs.* distance (T-D) graph.

202 Once constrained the age of a planation surface (see Section 2), the main challenge to be  
203 addressed is ensuring its degree of flatness, being aware of the degree of error involved in  
204 height management. Continental planation surfaces can show gentle (short- to middle-  
205 wavelength) unevenness, or locally connect with residual, non-flattened reliefs through  
206 pediment slopes. Amplitude of the unevenness advises to use an adequate contour interval for  
207 *FES2* in order to represent its present-day geometry with the suitable precision. Both the local  
208 difference in height between *FES2* and *FES3* and the local unevenness within each one  
209 usually lies within the range of 10-40 m. Therefore, we assume that: (i) fault throws  
210 calculated from them implicitly include a maximum error bar of  $\pm 40$  m, and (ii) a 50-m-  
211 spaced contour map can be considered as reasonable for assessing recent movements (as  
212 previously proposed by Ezquerro *et al.*, 2020). Such level of uncertainty in the calculated fault  
213 throws results in errors for slip rates around 0.01 mm/a.

### 214 **3.2. Subsoil exploration**

215 Subsurface information was acquired by means of geophysical exploration. Two different  
216 techniques were utilised, which had rendered interesting results in other neighbouring sectors  
217 (*e.g.*, Pueyo *et al.*, 2016): magnetometry and electromagnetic (EM) multifrequency survey. A  
218 twofold approach was taken: first, a regional analysis by means of ten transects approximately  
219 orthogonal to the Sierra Palomera mountain front; second, a detailed analysis of a sector  
220 where the highest geophysical anomalies were identified and also where geomorphological  
221 evidences hinted at the presence of a previously unknown antithetic fault. For the  
222 magnetometry survey, a GSM-19 equipment with built-in GPS was used to measure both  
223 Earth magnetic field intensity and vertical magnetic gradient (sensors separation of 0.5 m).  
224 Diurnal correction was performed from a second, stationary, magnetometer (PMG-01) that  
225 permitted to exclude natural earth magnetic field changes during the survey and to compare  
226 the results performed during different days. Then, the regional general trend was identified  
227 and subtracted to earth magnetic data to highlight anomalies in the form of residual values.  
228 The EM multifrequency survey was performed by a GEM-02 device for a range of  
229 frequencies between 65 and 0.5 kHz.

230 Subsoil information has been complemented with borehole data extensively compiled by  
231 Rubio (2004), whose synthetic results were presented by Rubio and Simón (2007). Together  
232 with surface geology, it was used for constructing geological cross sections that have allowed  
233 characterizing the general geometry of macrostructure. Moreover, they were used for

234 extending the contour map of FES2 to the centre of the Jiloca basin.

### 235 **3.3. Trench analysis**

236 A trench study focussed on the northwards prolongation of the La Peñuela fault,  
237 antithetic to the main Sierra Palomera fault, has been carried out following the classical  
238 methodology (see, *e.g.*, McCalpin, 2009): excavating and shoring; cleansing and gridding the  
239 most suitable wall; identifying and marking sedimentary boundaries and deformation  
240 structures; drawing a detailed log and taking photographs of each grid cell; analysing the  
241 relationship between units and faults to identify individual events; and sampling materials for  
242 dating. Sedimentary units were defined on the basis of lithology, bed geometry, texture,  
243 colour and sedimentary structures.

244 Individual deformation events identified within the trench have been carefully verified by  
245 retrodeformational analysis, following the common practice in paleoseismological  
246 reconstruction (McCalpin, 2009). Several post-event sedimentary stages have also been  
247 included for a better understanding and representation of the evolutionary model. A number  
248 of identifiable faults were either formed, propagated or reactivated during successive  
249 deformation events. For each fault involved in each event, dip separation has been measured  
250 and equated to net slip (with precision of 5 cm). In addition, the resulting horizontal extension  
251 has been calculated taking into account the average dip of each fault. Further details are given  
252 in Section 7.4.

253 Dating of trench samples was achieved by the Luminiscence Dating Laboratory of  
254 University of Georgia, USA, using the Optically Stimulated Luminiscence (OSL) technique.  
255 Unfortunately, five of them were saturated samples that only provided minimum ages, which  
256 drastically decreased the consistency of the age model. Additional, preliminary OSL dating of  
257 shallow alluvial fan sediments had been achieved by Laboratorio de Datación y Radioquímica  
258 de la Universidad Autónoma de Madrid.

## 259 **4. Structure and morphotectonics of the Sierra Palomera area**

260 The NNW-SSE trending Sierra Palomera extensional fault makes the eastern boundary of  
261 the Jiloca graben at its central sector (Figs. 1b, 2). In the footwall block, Jurassic marine  
262 carbonates are unconformably covered by Paleogene continental clastics (Figs. 2, 3). In the  
263 hanging-wall block, *i.e.*, the central sector of the Jiloca basin, the sedimentary infill is made  
264 of: (i) Late Pliocene (Villafranchian) to Pleistocene alluvial and episodic palustrine deposits,  
265 all of them exposed at the surface; (ii) an underlying carbonate unit, only observed in  
266 boreholes, that could represent an early lacustrine stage of Late Miocene-Early Pliocene age

267 (Rubio and Simón, 2007). Borehole information indicates that the maximum thickness of the  
268 total infill approaches 100 m (Rubio and Simón, 2007).

269 The Jiloca basin runs slightly oblique to previous Paleogene, NW-SE trending folds (Fig.  
270 1b; Rubio and Simón, 2007; Rubio *et al.*, 2007). In particular, the Sierra Palomera fault  
271 follows the eastern limb, nearly vertical, of an eastwards verging anticline (Fig. 3). Its core is  
272 represented by Lower-Middle Triassic rocks that crop out in the neighbourhoods of Singra  
273 village, and its periclinal closure is partially preserved close to the southern tip of Sierra  
274 Palomera fault (Fig. 2). Such structural setting suggests that the main extensional fault  
275 resulted from negative inversion, during Late Pliocene-Pleistocene times, of a previous  
276 reverse fault linked to that anticline and developed during the Paleogene compression (Rubio  
277 and Simón, 2007).

278 The Sierra Palomera fault trace is ca. 26 km long and trends N152°E in average. The  
279 main fault surface only crops out in a few small exposures (1 to 4 m<sup>2</sup> in area). A number of  
280 rupture surfaces observed within the damage zone show orientations consistent with the map  
281 trend: strike between NW-SE and N-S, and dip between 54° and 87° W (mean orientation:  
282 N155°E, 70° W; Fig. 4). Slickenlines show pitch ranging from 75°N to 70°S, therefore  
283 indicating almost pure normal movement, with mean transport direction towards N230°E.

284 Two wide right relay zones separate the Sierra Palomera fault from the Calamocha and  
285 Concul faults. The dominant trend of recent, extensional faults and fractures distributed  
286 within both relay zones is similar to that of the main fault or slightly deviates to approach the  
287 N-S direction. These relay zones dominated by along-strike fractures were described in detail  
288 by Peiro *et al.* (2019, 2020).

289 The Sierra Palomera fault is expressed in the landscape by a conspicuous, 20-km-long  
290 fault mountain front (Fig. 5a,b), which attains heights of 200 to 300 m above its toe, 450 to  
291 550 with respect to the bottom of the Jiloca depression. The mountain front shows a  
292 significantly low value of the sinuosity index ( $S_{mf} = 1.27$ ; García-Lacosta, 2013). A number of  
293 gullies (most of them exhibiting V-shaped transverse profiles) run across the fault scarp and  
294 delimit some well-preserved trapezoidal facets (Fig. 5c). Gullies feed short, high-slope  
295 alluvial fans (Fig. 5d) that are barely incised, only partially connected to the axial fluvial  
296 system, and exhibit signs of present-day functionality (*e.g.*, gravel aggradation affecting bush  
297 vegetation).

298 The difference in height of the geomorphological markers *FES2* and *FES3* between the  
299 footwall and the hanging-wall blocks reasonably allows approaching the Sierra Palomera fault  
300 throw. The envelope of relief at the footwall block is largely represented by the *FES2*

301 planation surface cutting pre-Neogene units, which attains a maximum height of 1430 m close  
302 to the edge (Fig. 6). The summit of Sierra Palomera (1533 m a.s.l.) and its surrounding area  
303 constitutes a residual relief that stands out from *FES2*, while remains of an upper erosion  
304 sublevel (*FES1*) extend at the eastern foothills. A lower sublevel (*FES3*, usually lying 10-40  
305 m below *FES2*) is also present: (i) eastwards of Sierra Palomera, over large areas of the  
306 northern Teruel basin; (ii) northwards and southwards, at the relay zones with the Calamocha  
307 and Conclud faults, respectively; and (iii) along a narrow band westwards of the Sierra  
308 Palomera divide.

309 The height of *FES2* and *FES3* within the Jiloca depression can only be inferred indirectly.  
310 Both have been mapped at the eastern margin of the Jiloca depression, W of Santa Eulalia  
311 town, where they descend to ca. 1100 and 1050 m, respectively (Fig. 6). Then they are  
312 supposed to be covered by the Plio-Pleistocene infill, while gentle residual reliefs at the  
313 Singra-Villafranca del Campo area (made of Triassic and Jurassic rocks belonging to the core  
314 of the Sierra Palomera anticline) stand out above the depression bottom. The subsoil data  
315 provided by Rubio and Simón (2007; Fig. 6) for the central Jiloca basin constrain the heights  
316 of those planation surfaces. The boundary between Plio-Pleistocene alluvial deposits and the  
317 underlying carbonate unit, lying at about 950 m a.s.l. in the Santa Eulalia area, could be  
318 correlated with either *FES2* or *FES3*.

319 Within the Sierra Palomera block, *FES2* and its correlative Late Ruscinian carbonates are  
320 in continuity with each other and show a quite homogeneous slope of about 1.5-2% along a  
321 distance of 20 km, in which the altitude of this morphosedimentary marker diminishes from  
322 1400-1430 m (central sector of Sierra Palomera) to 1090-1120 m (Alfambra area) (Fig. 6).  
323 This morphotectonic setting defines a conspicuously tilted block whose edge has undergone a  
324 tectonic uplift of about 300 m relative to the bottom of the Teruel depression, as can be  
325 visualized from structural contours in Figure 6.

326 The latter value closely approaches the topographic amplitude of the Sierra Palomera  
327 scarp itself, and is comparable to the fault throw inferred from offset of the *FES2* marker.  
328 Such fault throw, and its variation along the Sierra Palomera fault, have been analysed on a  
329 series of 1-km-spaced transects across the fault trace on the contour map of Figure 6,  
330 assuming that *FES2* within the Jiloca basin coincides with the base of the Plio-Pleistocene  
331 infill. The result is shown in the throw vs. distance (T-D) graph of Figure 7, where two  
332 distinct curves depict values of (i) fault throw *s.s.*, and (ii) total tectonic throw of *FES2*  
333 between the Sierra Palomera summits and the Jiloca depression bottom (including the bending  
334 component). The T-D curves show an overall bell-shape, although slightly bimodal in detail.

335 The maximum values, 330 m and 480 m, respectively, are found at the central sector.  
336 Considering the age of the *FES2* morphosedimentary marker (3.8 Ma), and assuming an  
337 average dip of 70° for the fault plane and a pure normal movement, a maximum net slip rate  
338 of 0.09 mm/a can be inferred (0.13 mm/a for the total rate between Sierra Palomera and the  
339 Jiloca bottom).

340 Despite the initial appearance of the Sierra Palomera fault is that of a single major rupture  
341 that accommodates the entire throw, there is evidence of a parallel, synthetic fault (Las  
342 Vallejadas fault) located west of the main escarpment at its southern sector (Fig. 2). Both  
343 delimit an intermediate step within the mountain front, in which *FES2* lies at an altitude of  
344 1140-1220 m, furthermore offset (ca. 10 m) by a minor antithetic rupture (La Peñuela fault).  
345 Recent activation of both subsidiary faults is revealed by local deformation of Villafranchian  
346 alluvial deposits: (i) back tilting (up to 25°E), due to rollover kinematics, observed at the foot  
347 of the morphological escarpment of Las Vallejadas fault (Fig. 2); (ii) accommodation  
348 monocline (dip up to 22°E) in the case of La Peñuela fault (Fig. 8; see location in Fig. 2).

349

## 350 **5. Geophysical exploration of the overall Sierra Palomera piedmont**

351 Data of magnetic intensity field and vertical magnetic gradient were extensively collected  
352 along ten transects, roughly orthogonal to the Sierra Palomera fault trace along its hanging-  
353 wall block and ranging from 2.0 to 5.2 km in length (Fig. 9a). Spacing between successive  
354 measurement points was about 0.8 m. The two northernmost transects (profiles 01 and 02)  
355 and the southernmost one (profile 10) show a narrow distribution of residuals due to their  
356 lesser contrast with respect to the general, regional trend (Fig. 9b). The central transects (03 to  
357 09) have spikes and lows that depart considerably from the general trend, and therefore, when  
358 data of the ten transects are considered as a whole, they define the range of the distribution  
359 (more specifically, profile 03 has the lowest and the highest values of residual magnetic  
360 intensity). Nonetheless, transects 01, 02 and 10 show a similar (albeit reduced in magnitude)  
361 outline to the rest.

362 The variation pattern of residuals in magnetometric profiles (also corroborated by EM  
363 profiles) allows portraying three domains (A, B and C) that are broadly parallel the Sierra  
364 Palomera fault (Fig. 9b). In the northern section of the studied area, the boundary between  
365 domains A and B is largely evident, due to the sudden change and amplitude of the anomaly.  
366 Moreover, these profiles show a more direct correlation between them than the southern ones,  
367 where the contact progresses through a magnetic dipole (Fig 9a, b). These three domains are  
368 characterised by:

369 a) Closer to the Sierra Palomera fault, domain A is an area where residual values of  
370 magnetic intensity are close to zero and barely change, except for a subtle decrease to the  
371 west.

372 b) Westwards, a sharp change of attitude marks the onset of domain B, a zone of  
373 anomalies expressed as variations of residuals up to 20-30 nT over decametric distances. Such  
374 anomalies reflect the presence of small magnetic dipoles and a slightly higher mean value of  
375 Earth magnetic field. Values for apparent conductivity are still homogeneous.

376 c) Finally, domain C is separated from domain B by a sharp decrease in magnetic  
377 intensity (it goes down about 100 nT) with lower relative values of Earth magnetic field and  
378 presence of a lower density of magnetic dipoles (including those of higher wavelength).  
379 Apparent conductivity and magnetic susceptibility are higher.

380 The reported geophysical results (Earth magnetic field, together with apparent  
381 conductivity and susceptibility) suggest the presence of a body of relatively higher magnetic  
382 susceptibility underlying domain A, which gets shallower under domain B, and gets again  
383 deeper under domain C. Boundaries between those domains are sharp and clear. This setting  
384 can be interpreted as an uplifted block (made of Paleozoic and Triassic materials belonging to  
385 the core of the Sierra Palomera anticline) bounded by faults nearly parallel to the Sierra  
386 Palomera fault trace.

387

## 388 **6. La Sima alluvial fan: linear topographic anomaly and its geomagnetic expression**

389 In the absence of any visible surficial rupture across Quaternary sediments of the Sierra  
390 Palomera piedmont, evidence of recent tectonic activity should be obtained from trenching.  
391 Owing to non-favourable topographic, lithologic and access conditions at the Sierra Palomera  
392 fault trace itself, our search was focused on the surface of two alluvial fans sourced at the  
393 mountain front, at La Cecilia and La Sima areas (see location in Figs. 2 and 5d). Both exhibit  
394 well-preserved alluvial fan morphology at its proximal sectors, with evidence of present-day  
395 aggradation at the apex. Shallow sand and silty sedimentary horizons in those alluvial fans  
396 have provided ages of  $28.9 \pm 2.0$  ka BP (La Cecilia) and  $19.2 \pm 1.1$  ka BP (La Sima) (see  
397 Table 1; location in Fig. 2).

398 In the middle sector of La Sima alluvial fan, a sharp NNW-SSE trending lineament is  
399 clearly visible on aerial photographs and DEM images, beyond which the fan surface is more  
400 deeply incised by the local drainage network (Fig. 10a). That lineament involves a  
401 morphological anomaly, a break in the fan slope, which becomes null or even negative up to  
402 take locally the appearance of a gentle, degraded uphill-facing scarplet (Fig. 10c). These

403 features suggest the occurrence of an antithetic fault that would have sunk the proximal sector  
404 of the fan with respect to the middle one by about 2.5 m. This lineament coincides with the  
405 boundary between domains A and B defined from geophysical results (Fig. 9b), and is  
406 virtually prolonged towards SSE up to connect with the antithetic La Peñuela fault (Fig. 2).

407 In order to test the hypothesis of an antithetic fault cutting the La Sima alluvial fan, the  
408 subsoil in the neighbourhoods of the morphological lineament was intensively explored by  
409 means of a magnetic and electromagnetic survey. The coincidence of the lineament with the  
410 A/B boundary is clearly expressed in the detailed map of residual magnetic anomalies shown  
411 in Figure 10b. The area east of the sharp linear NNW-SSE trending limit, clearly visible on  
412 this map, shows low residual values with wide (hectometre-scale) wavelength variations. To  
413 the west of this limit, an increase of more than 30 nT is observed, as well as a decrease of  
414 more than 50 mS/m in the total conductivity; moreover, the texture of the residual map  
415 changes noticeably, showing sharper magnetic dipoles of decametric wavelength.

416 The amplitude and morphology of the linear anomaly is not consistent with the  
417 susceptibility values of surficial sediments, and suggest the contrast, at shallow levels,  
418 between a high-susceptibility rock body to the west (domain B, as defined in section 5) and  
419 the domain A to the east. In addition, Figure 10b shows other NW-SE trending linear  
420 anomalies in domain B, which involve a lower contrast of magnetic field values. Both the  
421 main anomaly and the secondary ones show high gradient and sharpness of the observed  
422 dipoles, suggesting near-surface, high dipping discontinuities or rock boundaries compatible  
423 with recent faults.

424

## 425 **7. Trench study at La Sima alluvial fan**

426 Once verified that geophysical and topographic analysis of La Sima lineament reinforced  
427 our preliminary hypothesis about the northwards prolongation of the antithetic La Peñuela  
428 fault, we selected an easily accessible site for trench study. A 40 m long, 1.4 m wide trench  
429 was dug along a N067°E direction, roughly orthogonal to the linear anomaly that separates  
430 domains A and B. A segment of 19 m on its southern wall, with depth ranging from 3.0 to 3.5  
431 m, was logged and analysed in detail (Fig. 11a,b).

### 432 ***7.1. Sedimentary units***

433 The materials exposed at La Sima trench essentially correspond to relatively well-bedded  
434 Pleistocene alluvial sediments (Fig. 11a). Sedimentary features indicate alternating energetic  
435 flows, sometimes flash floods, recorded by gravel channel and bar deposits, and waning

436 discharges that settled fines over the gravel deposits. All the succession includes clear signs of  
437 calcrete development and periods of time with negligible sedimentation. Bioturbation signs  
438 and carbonate precipitation are related to pedogenesis, suggesting wetting and drying episodes  
439 of the sedimentary surface. The sedimentary succession has been subdivided into twelve  
440 lithological units (Fig. 11b):

441 Unit 1 (up to 50 cm in thickness): Massive reddish mudstone with isolated, mm- to cm-sized  
442 angular limestone clasts (more abundant at the base), with bioturbation traces and  
443 smooth carbonate nodules.

444 Unit 2 (25 to 55 cm): Orange massive sandy mudstone with floating angular-subangular grey  
445 limestone granules and pebbles, and some irregular cm-thick gravel bed. Grey  
446 mudstones laminae towards the top.

447 Unit 3 (55 to 75 cm): Tabular laminated, indurated and brecciated, carbonate crust with some  
448 cm-thick interbedded silts with carbonate clasts. Carbonate fragments are smaller in  
449 the upper part; laminated fragments are less abundant towards W.

450 Unit 4 (20 to 35 cm): Reddish massive silty sand and mudstone in a tabular level with vertical  
451 root traces filled by fine sands. Some carbonate nodules, plant remains and scattered  
452 grey, angular limestone and caliche clasts up to 10 cm in size can be recognized.

453 Unit 5 (15 to >50 cm): Clast-supported gravel with silty to sandy matrix in a tabular, locally  
454 channelized sedimentary body with crude horizontal stratification. Gravel is made of  
455 angular-subrounded limestone clasts (up to 8 cm) and smaller caliche clasts.

456 Unit 6 (25-55 cm): Orange to brownish massive silt and mudstone with greyish limestone  
457 angular clasts and floating whitish caliche rounded nodules (up to 2 cm). Clast content  
458 increases locally. Root traces, plant remains and organic matter patches can be  
459 recognized in the western sector.

460 Unit 7 (30 to >150 cm): Heterogeneous unit mainly made of grain-supported gravel, locally  
461 cemented, with angular-subrounded limestone clasts (up to 15 cm in size) and caliche  
462 nodules. It includes red mudstone discontinuous intercalations, up to 20 cm in  
463 thickness, with floating cm-sized angular clasts. The overall geometry of the unit is  
464 tabular in the footwall block and channelized in the hanging-wall block. A level of  
465 calcrete gravel, >50 cm in thickness, appears at the top of this unit within the footwall  
466 block.

467 Unit 8 (10-60 cm): Reddish silt with floating limestone angular granules and pebbles (up to 8  
468 cm) with evidence of bioturbation.



469 Unit 9 (45-120 cm): Grey gravel in a channeled body with limestone angular clasts (up to 12-  
470 14 cm in size) and rounded caliche clasts. Crude fining upwards cycles can be  
471 recognized. Pedogenic features increase towards the top, where brecciated limestones  
472 locally appear.

473 Unit 10 (55 to 70 cm): Reddish massive silts with floating subangular limestone clasts (up to  
474 7 cm), whitish carbonate nodules and an interbedded discontinuous clast-supported  
475 gravel level with subangular clasts up to 10 cm in size.

476 Unit 11: Wedge-shaped body of orange and whitish massive, highly cemented silt, with  
477 carbonate floating subangular limestone clasts (up to 10 cm) and caliche clasts  
478 arranged with the A-axis subvertical.

479 Unit 12 (20 to 50 cm): Surface regolith made of silt with angular to subangular clasts,  
480 reworked by agricultural labours.

## 481 **7.2. OSL dating**

482 Seven samples (S1 to S7) of alluvial sediments within the trench (see Fig. 11b for  
483 location) have been dated, although unfortunately the results show a high level of uncertainty  
484 (see Table 1). Other three collected samples did not contain enough sand grains for providing  
485 a representative dose distribution and therefore OSL dates were not reliable in this case. These  
486 samples are not located in Fig. 11b.

487 Samples S2, S3, S4, S6 and S7 have presented signal saturation, *i.e.*, their natural  
488 luminescence signal lies beyond the saturation of the OSL response with dose, making it  
489 impossible to provide adequate results. According to laboratory results, their ages should be  
490 older than 193 to 378 ka, although such figures should not be taken *sensu stricto*. Only one of  
491 the alluvial sedimentary units is directly dated: S1 provides an age  $97.4 \pm 10.2$  ka for the top of  
492 unit 9. Unit 11 (sample S5), which will be next interpreted as a fissure infill, is dated to  
493  $49.2 \pm 5.4$  ka. As a result, the chronology of unit 10, overlapping unit 9 and being cut by the  
494 fissure, can be broadly constrained between both numerical ages.

495 Without the support of further anchors, building an age model for the overall alluvial  
496 succession exposed in the trench is not feasible. In any case, the ensemble of OSL dating  
497 results and geomorphological observations in the study area suggest that: (i) most of that  
498 alluvial succession belongs to the Middle Pleistocene; (ii) a rapid decrease of sedimentation  
499 rate occurs by the Middle-Late Pleistocene transition; and (iii) sedimentation persisting in  
500 proximal and middle sectors of the alluvial fans during Late Pleistocene to present-day times  
501 only represents a small contribution to the surficial aggradation and landscape modelling.

502           **7.3. Deformation structures**

503           The trench log shows a main extensional fault zone at the central sector, dipping  
504 eastward and hence antithetic with respect to the Sierra Palomera fault (Fig. 11b), and full  
505 consistent with the uphill-facing scarplet described in section 6. These features allow  
506 identifying such antithetic fault zone with the map-scale La Peñuela fault (Fig. 2). The  
507 footwall block of that fault zone shows a gentle monocline, while other normal (both  
508 synthetic and antithetic) faults, cutting most of the sedimentary succession, are distributed  
509 along the entire section. The orientations of all these structures are overall consistent, as  
510 depicted in stereoplots of Figure 11c,d,e,f.

511           The central fault zone is made of three significant structural elements:

512           1) Main fault, expressed by  $\theta_1$  and  $\theta_2$  individual rupture surfaces.

513           2) Splay faults  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ , associated to the tip of the main rupture and propagated  
514 through unit 7. Both the main, westwards dipping rupture surfaces and the nearly vertical  
515 splay faults consistently strike NNW-SSE (Fig. 11c). Such structural arrangement suggests  
516 that, at certain stage of its development, the main rupture  $\theta_1$ - $\theta_2$  was covered by the upper part  
517 of unit 7, and then reactivated in the form of splay faults related to refraction at the  
518 extensional tip (horse-tail structure, in the sense of Granier, 1985). That is the key, purely  
519 instrumental criterium for separating lower and upper unit 7 in Figure 12; therefore, such  
520 separation is not based on a visible lithological boundary (we have defined a single unit 7  
521 indeed).

522           3) Open fissure bounded by fault  $\theta_3$  and another irregular surface, and filled with unit 11.  
523 The interpretation is based on its wedge shape, the massive internal structure of the infill, and  
524 the occurrence of clasts with nearly vertical A-axes. According to this interpretation, both  
525 bounding surfaces would have represented both walls of a single, also NNW-SSE striking  
526 fault, then disengaged from each other when the fissure opened up and partially crumbled  
527 before infilling took place.

528           The footwall block is deformed by the monocline and cut by a number of NNW-SSE  
529 striking normal faults (Fig. 11d), all of them synthetic with the Sierra Palomera fault and  
530 exhibiting dip separations in the range of 10 to 20 cm (Fig. 11b). Faults  $\rho$ ,  $\pi_1$  and  $\pi_2$  cut the  
531 horizontal limb of the monocline, and have apparently kept their original, high dip. The rest of  
532 faults ( $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) appear at the hinge and the abrupt limb of the monocline. They  
533 show a progressive decrease in dip towards the east as the bedding dip increases, and some  
534 individual faults ( $\mu$ ,  $\lambda_1$ ,  $\lambda_2$ ) exhibit conspicuously arched traces, so that the angle between  
535 faults and bedding remains broadly constant (mostly within the range of 55-65°). Such

536 geometrical setting strongly suggests that they were folded by the monocline. Concerning the  
537 relationships between faults and sedimentary units,  $\rho$  and  $\pi_1$  uniformly offset (15-20 cm) the  
538 base of units 2 to 6, while they suddenly vanish and does not affect the base of unit 7. Also  
539 fault  $\sigma$  shows similar relationships, although in this case it does not propagated through the  
540 lower units, probably detached within low-viscosity materials of unit 4. As a consequence,  $\rho$ ,  
541  $\pi_1$  and  $\sigma$  produce a noticeable thickening of unit 6 in their respective hanging-wall blocks.  
542 Faults  $\pi_2$ ,  $\tau$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ ) also offset rather uniformly the sedimentary boundaries, and at  
543 least two of them ( $\pi_2$  and  $\mu$ ) propagated across unit 7.

544 The hanging-wall block shows two ensembles of intersecting faults that cut units that are  
545 younger than the ones from the footwall block (Fig. 11b). Individual faults show distinct slip  
546 for different sedimentary markers, which indicates diachronic development. The  $\varepsilon_0$ - $\varepsilon_1$  couple  
547 offsets more than 1.2 m the base of unit 7, while it produces a rather uniform dip separation of  
548 8-10 cm in the bases of units 8, 9 and 10. We should therefore interpret that  $\varepsilon_0$ - $\varepsilon_1$  underwent  
549 most of its present-date displacement ( $>1.3$  m) before sedimentation of unit 8, and was then  
550 reactivated after the lower part (at least) of unit 10 was deposited. Splaying from  $\varepsilon_1$ , fault  $\varepsilon_2$   
551 cuts units 7 and 8, and is covered by unit 9, while  $\varepsilon_3$  cuts the base of unit 9, thus making the  
552 three faults a footwall rupture sequence. The antithetic  $\varepsilon_4$  propagated thorough unit 9 and the  
553 lowermost unit 10. At the easternmost trench sector we find a similar pattern in the NNW-  
554 SSE striking faults  $\alpha$  and  $\beta$ . Fault  $\beta$  offsets more than 0.7 m the base of unit 7, while (together  
555 with its splay faults  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ ) produces a smaller separation (0.4 m) in the bases of units 8  
556 and 9. We interpret that  $\beta$  underwent displacement  $\approx 0.3$  m before sedimentation of unit 8,  
557 and was then reactivated after deposition of unit 9. Fault  $\alpha$  propagated through unit 7,  
558 previous to sedimentation of unit 8, and did not undergo further reactivation.

559 The orientations of the described structures have a strict consistence. All faults  
560 systematically strike NNW-SSE (Fig. 11f), and so does the limb of the monocline (Fig. 11d).  
561 There is no doubt that the latter is (i) genetically linked to faults, and (ii) responsible for the  
562 decrease in dip of faults  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Bedding and fault surfaces are rotated around a  
563 common, well-defined horizontal axis ca. N160°E (Fig. 11d). Strikes of minor fractures  
564 measured along the trench are also clustered around NNW-SSE, although a small number  
565 among them are oriented NNE-SSW (in blue in Fig. 11e). A brief discussion about the  
566 dynamic framework (stress fields) in which such fault and fracture pattern developed will be  
567 made in Section 8.5.

568 ***7.4. Retrodeformational analysis and evolutionary model: deformation events***

569 Based on the former structural description, in particular on the relationships between  
570 structures and the sedimentary units, a careful retrodeformational analysis has been achieved,  
571 with a double purpose: (i) building an evolutionary model, i.e. a systematic succession of  
572 deformation events, and (ii) testing its kinematic consistence (Fig. 12).

573 A number of identifiable faults were either formed, propagated or reactivated during each  
574 deformation event (Fig. 12 and Table 2). Dip separation directly measured on the trench log is  
575 taken as practically representing the net slip on each fault, since: (i) bedding is roughly  
576 horizontal, (ii) the trench, oriented N067°E, is nearly orthogonal to the prevailing strike of  
577 faults, and (iii) the only kinematical indicator observed during trench survey (slickenlines  
578 with pitch 82°S on fault  $\mu$ ; Fig. 11d), as well as those collected at the Sierra Palomera fault  
579 zone itself (see Fig. 4b), suggest nearly pure normal slip for the overall extensional fault  
580 system.

581 Net slip for every individual fault (with positive sign for synthetic faults and negative  
582 sign for antithetic ones), together with the resulting horizontal extension (considering the  
583 average fault dip), are depicted in Table 2. Such measurements exclude offset accommodated  
584 by the bending monocline. The latter has been only considered for computing the total  
585 accumulated deformation, since it is not possible to accurately calculate which fraction of  
586 bending occurred during each event. The total slip per event, taken as the algebraic sum of  
587 slip values on individual faults, is also shown. The total horizontal extension per event  
588 considers the aggregate of extension values on individual faults, but also includes an estimate  
589 of the contribution of bending, in order to jointly accommodate the horizontal extension  
590 visually expressed in the successive cross sections of Fig. 12.

591 Below we summarize the main features of each of the seven deformation events (T to Z)  
592 defined at the La Sima trench (Fig. 12; see measurements in Table 2):

593 **Event T:** Slip on faults  $\rho$ ,  $\pi_1$ ,  $\tau$  and  $\sigma$  after deposition of unit 6 and previous to unit 7.

594 Accumulated net slip: +45 cm.

595 **Event U:** Slip on faults  $\pi_2$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$ ,  $\lambda_2$  and  $\varepsilon_1$ , subsequent or coeval with deposition of the  
596 lower part of unit 7. Accumulated net slip: +105 cm.

597 **Event V:** Slip on fault  $\theta_2$ , subsequent to deposition of lower unit 7, then covered by upper  
598 unit 7. Development of the monocline begins; according to our progressive  
599 deformation model depicted in Fig. 12, in which the main rupture had always  
600 propagated through units 1 to 6, this monocline should be interpreted as a drag fold.

601 Net slip: -10 cm.

602 **Event W:** Reactivation of the main, central fault through the rupture surfaces  $\theta_1$ - $\theta_2$ , which  
603 propagates across upper unit 7 splitting into  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$  and  $\kappa_4$ . Progress of the  
604 monocline produces rotation of faults  $\tau$ ,  $\sigma$ ,  $\mu$ ,  $\chi$ ,  $\lambda_1$  and  $\lambda_2$ . Slip on faults  $\varepsilon_0$ - $\varepsilon_1$ ,  $\alpha$  and  
605  $\beta$ , all of them subsequent to top of unit 7 and previous to unit 8. Accumulated net slip:  
606  $+125 - 65 = +60$  cm.

607 **Event X:** Propagation of the main fault zones,  $\theta$  and  $\varepsilon$ , through new rupture surfaces:  $\theta_2$ - $\theta_3$   
608 and  $\varepsilon_2$ , respectively. Both are younger than unit 8 and older than unit 9. Accumulated  
609 net slip:  $+5 - 50 = -45$  cm.

610 **Event Y:** Activation of fault  $\varepsilon_3$ , and propagation of  $\beta$  splitting into  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$ . Both  
611 processes are subsequent to deposition of unit 9 and probably previous to unit 10,  
612 therefore close to (or slightly younger than) the numerical age provided by sample S1  
613 ( $97.4 \pm 10.2$  ka). Accumulated net slip:  $-35$  cm.

614 **Event Z:** Formation of fault  $\varepsilon_4$  and propagation of  $\varepsilon_1$  cutting the lower part of unit 10. Slip on  
615  $\theta_2$  that induces extensional movement on the  $\theta_3$  surface, giving rise to an open fissure  
616 that tears apart units 7 to 10 and is subsequently filled with unit 11. This event should  
617 be dated just prior to the numerical age provided by sample S5 ( $49.2 \pm 5.4$  ka).  
618 Accumulated net slip:  $+10 - 120 = -110$  cm.

619

## 620 **8. The Sierra Palomera fault: synthesis and discussion**

### 621 ***8.1. Geometry and kinematics of macrostructures***

622 Structural information from field survey has allowed characterizing geometry and  
623 kinematics of the Sierra Palomera fault itself (Figs. 4, 6, 13). The attitude of the main fault  
624 surface is N155°E, 70° W in average, while most ruptures visible along and close to it are  
625 systematically parallel. The fault shows pure normal movement, with mean transport direction  
626 towards N230°E. In addition, the use of two geomorphological markers (mid-Pliocene *FES2*  
627 and *FES3* planation surfaces; Fig 13b) has permitted measuring the fault throw *s.s.* (330 m)  
628 and the total tectonic throw (480 m, including bending) at the Sierra Palomera fault, resulting  
629 in slip rates of 0.09 and 0.13 mm/a, respectively.

630 Geophysical results reported in Section 5, defining three adjacent, NNW-SSE trending  
631 elongated domains (A, B, C) suggest the existence of an uplifted block bounded by faults  
632 nearly parallel to the Sierra Palomera fault trace. At the southern sector of the study area,  
633 local coincidence of the A/B and B/C domain boundaries with La Peñuela and Las Vallejadas

634 faults, respectively, strongly supports such interpretation. The antithetic rupture exposed in La  
635 Sima trench, revealed in the landscape by a gentle uphill-facing scarplet across the La Sima  
636 alluvial fan (section 6), unequivocally represents that map-scale antithetic La Peñuela fault  
637 and corroborates the extensional character of such structure.

638 In this way, the results of subsoil exploration by geophysical methods and trench survey,  
639 together with structural and morphotectonic data, allow refining the structural model of the  
640 central Jiloca graben, beyond the apparently flat appearance of the Sierra Palomera pediment.  
641 The synthetic Las Vallejadas fault and the antithetic La Peñuela fault have been incorporated  
642 to the geological map of Figure 2, as well as to a new version of the cross section (Fig. 13a).  
643 Furthermore, the latter depicts a reinterpretation of the geometry of the master fault. It is  
644 known that the shape of the main fault surface strongly controls the style of accommodation  
645 folding and subsidiary faulting in the hanging-wall block of extensional faults. Rollover folds  
646 and antithetic faults develop above concave-upward fault bends, whereas drag folds and  
647 synthetic faults form above convex-upward fault bends, their propagation being facilitated by  
648 high curvature of such fault bends (McClay and Scott, 1991; Xiao and Suppe, 1992; Withjack  
649 *et al.*, 1995; Delogkos *et al.*, 2020). In our case, the occurrence of the antithetic and the  
650 synthetic inferred subsidiary faults strongly suggests the presence, at a depth of less than 1  
651 km, of a relative flat in the main fault surface (*i.e.*, a double, convex-concave bend), probably  
652 located at the Middle-Upper Triassic lutite and evaporite units (Middle Muschelkalk and  
653 Keuper facies).

654 Concerning the along-strike propagation of the Sierra Palomera fault, the slightly bimodal  
655 throw *vs.* distance (T-D) curve depicted in Fig. 7 suggests that it could result from  
656 coalescence of two distinct fault segments (although the amplitude of the relative minimum  
657 between both maxima, close to the error bar adopted for throw estimations, casts doubt on the  
658 significance of this detail). In any case, the overall bell-shape of the T-D curve indicates full  
659 linkage along the fault zone. Moreover, the persistence of a bending component beyond both  
660 tips of the fault trace reveals that the total length of the Sierra Palomera fault is larger than  
661 that exposed at the surface, thus being propagated towards NNW and SSE as a blind fault.

662 According to Peiro *et al.* (2020), the overall fault system at the eastern boundary of the  
663 Jiloca basin is at a transient stage towards coalescence, and will probably evolve to an along-  
664 strike propagation of the master faults through distributed longitudinal fractures. The relay  
665 zones between Sierra Palomera, Calamocha and Conclud faults, dominated by longitudinal  
666 fractures, represent a type of fault relay controlled by both inherited structures and the remote  
667 stress field (Peiro *et al.*, 2019, 2020). It strongly contrasts with the classical models reported

668 in the literature (*e.g.*, Peacock and Sanderson, 1994; Young *et al.*, 2001; Fossen and Rotevatn,  
669 2016), in which transverse connecting faults controlled by the own relay kinematics prevail.

670 Such fault system makes a geometrically and kinematically consistent, genetically related  
671 major extensional fault system. The N230°E mean transport direction at the Sierra Palomera  
672 fault is similar to those of Conclud (N220°E; Lafuente *et al.*, 2014) and Calamocha (W to SW;  
673 Martín-Bello *et al.*, 2014). Moreover, all them probably resulted from negative inversion,  
674 during the Late Pliocene-Quaternary times, of previous contractive structures developed under  
675 the Paleogene-Early Miocene compression (Rubio and Simón, 2007; Lafuente *et al.*, 2011a;  
676 Liesa *et al.*, 2021).

677

## 678 ***8.2. Morphotectonic approach to assessing recent fault activity within the context of*** 679 ***eastern Spain***

680 In the absence of stratigraphic markers recognized in both fault blocks, the fault throw  
681 *s.s.* and the total tectonic throw at the Sierra Palomera graben margin (up to 330 m and 480 m,  
682 respectively) have been reasonably estimated from offset of Late Neogene planation surfaces.  
683 Nevertheless, uncertainties linked to such geomorphological markers should be highlighted.

684 Our main geomorphological marker, *FES2*, is poorly represented within the Jiloca  
685 bottom, *i.e.*, the hanging-all block of the Sierra Palomera fault, which makes difficult to  
686 calculate the actual throw. We interpret that the boundary between Plio-Pleistocene alluvial  
687 deposits and the underlying carbonate unit probably represents the position of *FES2* (Fig.  
688 13b), although it also could be correlated with *FES3*. According to the results provided by  
689 Ezquerro *et al.* (2020), such uncertainty introduces a potential error of either 10-40 m in the  
690 height of the marker (equivalent to the thickness of Villafranchian palustrine carbonates  $\approx$  M8  
691 megasequence of Ezquerro, 2017), or 0.3 Ma in its age. If the top of the buried carbonate unit  
692 would be Early Villafranchian in age (3.5 Ma, therefore correlative of *FES3*): (i) the fault  
693 throw *s.s.* and the total tectonic throw calculated in section 4 (330 m and 480 m, respectively)  
694 should be applied to a 3.5 Ma time span, therefore resulting in slightly higher slip rates (0.10  
695 *vs.* 0.09 mm/a, 0.15 *vs.* 0.13 mm/a, respectively); (ii) *FES2* would lie 10-40 m lower within  
696 the downthrown block, and hence the fault throw *s.s.* and the maximum total tectonic throw  
697 could increase up to 370 m and 520 m, respectively, giving rise to slip rates of 0.10 and 0.15  
698 mm/a for the last 3.8 Ma. In any case, such height uncertainty is of the same order as the  
699 unevenness of the planation surfaces themselves, and results in a very small error in slip rate  
700 (0.01 mm/a).

701 The consistency of this interpretation is further reinforced if the whole morphotectonic  
702 setting is considered. We have explained how the morphosedimentary *FES2* marker defines a  
703 tilted Sierra Palomera-Alfambra block whose edge is tectonically uplifted ca. 300 m relative  
704 to the bottom of the Teruel basin. A similar morphostructural outline can be drawn for the  
705 Sierra de Albarracín-Jiloca block, in which the *FES2* altitude progressively decreases  
706 eastwards, from 1400-1500 m to <1100 m. Therefore, the inference that the fault separating  
707 such tilted blocks has a throw in the range of 300-400 m seems well-founded. On the other  
708 hand, the notion of recent throw on the Sierra Palomera fault being larger than those on  
709 Calamocha and Conclud faults (210 and 260 m, respectively; Martín-Bello *et al.*, 2014;  
710 Ezquerro *et al.*, 2020) fits a common structural feature of segmented extensional fault zones,  
711 in which maximum throws are found in central segments (self-similar pattern as that of  
712 individual faults; Cowie and Roberts, 2001). Gracia *et al.* (2003) aimed to minimize the role  
713 of tectonic slip on the Sierra Palomera fault in benefit of erosional lowering in the  
714 development of the central Jiloca depression, but that controversy is currently out of place.

715 We should compare the displacement and slip rates on the Sierra Palomera fault with  
716 those in the neighbouring Teruel graben. During the last 3.8 Ma (Late Pliocene-Quaternary  
717 extensional phase), fault zones making the eastern margin of the Teruel basin underwent total  
718 throw (including bending component) in the range of 440 to 620 m, and hence long-term  
719 vertical slip rates of 0.12 to 0.16 mm/a (Ezquerro *et al.*, 2020). Assuming an average dip of  
720 70° for the fault plane and a pure normal movement, the resulting total net slip rates for this  
721 period are 0.13 to 0.17 mm/a, similar to that calculated for the Sierra Palomera fault (0.15  
722 mm/a) and higher than those for the Conclud (0.07-0.08 mm/a; Lafuente *et al.*, 2011a),  
723 Calamocha (0.06-0.09 mm/a; Martín-Bello *et al.*, 2014), and Teruel (0.075 mm/a; Simón *et*  
724 *al.*, 2017) faults.

725 It is also pertinent to consider geomorphic indices as auxiliary tools for assessing fault  
726 activity (*e.g.*, Bull and McFadden, 1977; McCalpin, 2009; Silva *et al.*, 2003; Burbank and  
727 Anderson, 2012), and compare the values obtained for the Sierra Palomera mountain front  
728 with those of other faults in the same geodynamic framework. At Sierra Palomera, García-  
729 Lacosta (2013) calculated the mountain-front sinuosity ( $S_{mf} = 1.27$ ), and valley width/height  
730 ratio ( $V_f = 0.22$ ). These values, together with qualitative attributes as trapezoidal facets, V-  
731 shaped gullies, and small alluvial fans not connected to the regional fluvial system, indicate  
732 ‘rapid’ fault slip according to the classification by McCalpin (2009), and ‘active’ (according  
733 to Silva *et al.*, 2003) (Fig. 14). The range of slip rates that those authors estimate for such  
734 categories in their respective classifications (0.08 to 0.5 mm/a) encloses the value calculated



735 for the Sierra Palomera fault from offset of the *FES2* marker (0.09-0.13 mm/a).

736 The sinuosity index  $S_{mf}$  at the Sierra Palomera mountain front is very similar to those  
737 published for the Conclud fault ( $S_{mf}=1.24$ ; Lafuente *et al.*, 2011b), Maestrat grabens in eastern  
738 Iberian Chain ( $S_{mf} = 1.04-1.60$ ; mean = 1.27; Perea, 2006), or Carboneras, Lorca-Alhama and  
739 Baza faults in the Betic Chains ( $S_{mf}$  usually ranging from 1.05 to 1.4; Silva *et al.*, 2003;  
740 García-Tortosa *et al.*, 2008). The  $V_f$  index computed for the Sierra Palomera fault does not  
741 differ from that of the Conclud fault ( $V_f = 0.30$ ; Lafuente *et al.*, 2011b), while higher and more  
742 variable values have been reported in the Maestrat grabens (Silva *et al.*, 2003; Perea, 2006;  
743 García-Tortosa *et al.*, 2008).

744 Plotting  $S_{mf}$  vs.  $V_f$  values on the diagram proposed by Silva *et al.* (2003) allows assessing  
745 the relative position of the Sierra Palomera fault among extensional fault-generated mountain  
746 fronts of eastern Spain (Fig. 14). The relatively low values of both  $S_{mf}$  and  $V_f$  indices found at  
747 the Sierra Palomera mountain front (1.27 and 0.22, respectively) represent a morphotectonic  
748 signal similar to that of the Conclud fault, and also consistent with the tendency of extensional  
749 faults studied by Silva *et al.* (2003) in the Valencia area and Betic Chains.

### 750 **8.3. Pleistocene fault activity and its paleoseismological relevance**

751 Morphotectonic data indicate that the Sierra Palomera fault has a significant degree of  
752 activity, but no outcrop observation on the main trace has unequivocally evidenced  
753 Quaternary displacement on it. Therefore, it is very relevant the finding, in La Sima trench, of  
754 Pleistocene faults that accommodate extensional deformation associated to the hanging-wall  
755 rollover, since they indirectly confirm, for the first time, Pleistocene activity of the Sierra  
756 Palomera fault.

757 As explained in section 6.4, seven deformation events (T to Z) have been recognized after  
758 detailed trench analysis, which could be conventionally considered as paleoseismic events  
759 according to usual criteria in Paleoseismology. Individual faults activated in each event have  
760 been recognized, and slip on them has been quantified (individual net slip in the range of 5 to  
761 115 cm; Table 2). Finally, the overall faulting history has been carefully reconstructed by  
762 means of retrodeformational analysis (Fig. 12). Nevertheless, we should critically admit that  
763 the meaning of these results in relation to paleoseismicity of the Sierra Palomera fault is very  
764 imprecise, since:

765 (i) Instead of crossing the main fault, the trench only represents a short transect within the  
766 hanging-wall block, at a distance of 1.0 km from the fault trace.

767 (ii) During each event, faults widely distributed along the surveyed transect underwent  
768 both synthetic slip with Sierra Palomera fault (downthrown block to the west; positive values

769 in Table 2) and antithetic slip (negative). The algebraic sum of those values does not  
770 necessarily have any meaning in relation to the real slip on the main fault.

771 (iii) The poor quality of OSL results precludes us from having an age model of the  
772 exposed sedimentary succession; therefore, the age constraints of the individual events are  
773 very limited. Only the last two events, Y and Z, could be dated to ca.  $97\pm 10$  ka and  $49\pm 5$  ka,  
774 respectively.

775 Concerning the net slip accumulated by faults (see Table 2), three among the first four  
776 events (T, U and W) involve significant synthetic slip (+45, +105 and +60 cm, respectively),  
777 while the last three ones (X, Y, Z) involve significant antithetic slip (-45, -35 and -110 cm,  
778 respectively). The global aggregate fault slip for the ensemble of deformation events is  
779 virtually null (+10 cm). Nevertheless, a total accumulated antithetic throw of 210 cm can be  
780 directly measured on the log from offset of the top of unit 6, the youngest sedimentary marker  
781 previous to the recorded faulting episodes (compare the first and the last picture in Fig. 12).  
782 Consequently, that resulting throw should be entirely attributed to the bending monocline  
783 (i.e., accommodated in the form of continuous deformation, not computed within fault slip  
784 measurements depicted in Table 2). That value reasonably approaches the apparent vertical  
785 offset of the natural slope of La Sima alluvial fan (ca. 2.5 m; Fig. 10c). In summary, the  
786 morphological expression (up-facing scarplet) of the fault zone exposed in the trench fits well  
787 the antithetic sign of the accumulated slip during the youngest faulting episodes.

788 These youngest, antithetic faulting events (X, Y and Z) have associated net slip values (-  
789 35 to -110 cm) that should be accommodated on faults several km long (in the range of 10 to  
790 40 km, according to the empirical relationships proposed by Wells and Coppersmith, 1994).  
791 This inference plays in favour of: (i) the interpretation of the antithetic fault exposed at La  
792 Sima trench as a large structure, comparable in length to the Sierra Palomera fault itself, as  
793 the macrostructural and geophysical data suggested (see sections 5, 6 and 8.1); (ii) the notion  
794 that faulting events recorded at the trench, in particular those dated to ca.  $97\pm 10$  ka and  $49\pm 5$   
795 ka, should respond to coseismic events on the main fault.

796 Could the timing of those younger events be taken as a reference for approaching seismic  
797 recurrence periods and slip rates of the Sierra Palomera fault during Pleistocene times? The  
798 tempting hypothesis that the two aforementioned ages correspond to the last two major  
799 paleoearthquakes would suggest a single interseismic period of around 48 ka. According to  
800 Villamor and Berryman (1999), this would be reliable for faults showing average slip rate  
801 around 0.1 mm/a, as the Sierra Palomera fault does. Nevertheless, the space and time window  
802 examined in our trench is too narrow for providing a representative paleoseismological

803 record. Subsidiary faults similar to those exposed at La Sima could have form at other sites  
804 within the hanging-wall block in response to other events on the main fault. Furthermore,  
805 each event on this main fault did not necessarily reactivate the antithetic fault exposed at La  
806 Sima trench. Accordingly, the actual slip rate on the Sierra Palomera fault during Late  
807 Pleistocene times could be significantly higher than the long-term one (0.09-0.15 mm/a since  
808 mid-Pliocene times; see sections 8.1 and 8.2), following the same tendency found in other  
809 active structures of the region, such as the Conclud fault (Lafuente *et al.*, 2014; Simón *et al.*,  
810 2016), Teruel fault (Simón *et al.*, 2017), Teruel basin (Ezquerro *et al.*, 2020; see Section 2)  
811 and Calatayud basin (Peiro and Simón, 2021).

#### 812 ***8.4. Internal deformation of the hanging-wall fault block: a close look from trench*** 813 ***analysis***

814 Although the succession of deformation events identified at La Sima trench have a very  
815 limited paleoseismic meaning, it allows understanding progressive stretching within the  
816 hanging-wall block of the Sierra Palomera fault. In particular, sequential activation of  
817 synthetic and antithetic individual faults has been carefully reconstructed by means of  
818 retrodeformational analysis (Fig. 12) and can be precisely compared with faulting patterns  
819 linked to rollover deformation at both smaller and larger scales (analogue models and field or  
820 seismic-profile examples, respectively).

821 Usually, the hanging-wall rollover geometry is not entirely achieved through ductile  
822 deformation. Examples from analogue models (*e.g.*, Withjack and Schlische, 2006), outcrops  
823 and high-resolution seismic profiles (*e.g.*, Song and Cawood, 2001; Delogkos *et al.*, 2020)  
824 indicate that a portion of deformation is accommodated by smaller-scale faults. Antithetic  
825 faults directly materialize the antithetic simple shear that nucleates at the transition from the  
826 main ramp to the basal detachment (Withjack *et al.*, 1995), frequently abutting the connection  
827 line between the steep and flat segments of the main fault surface (Bruce, 1973; Song and  
828 Cawood, 2001; Withjack and Schlische, 2006). In addition, together with subsidiary synthetic  
829 faults, they can accommodate layer-parallel extension along the rollover, giving rise to crestral  
830 collapse grabens in both analogue models (*e.g.*, McClay, 1990; McClay and Scott, 1991;  
831 Buchanan and McClay, 1991; Soto *et al.*, 2007) and field examples (*e.g.*, Imber *et al.*, 2003;  
832 Back and Morley, 2016; Fazli Khani *et al.*, 2017). The locus of active hanging-wall antithetic  
833 faulting, as well as that of crestral graben formation, have the appearance of having migrated  
834 landwards during development of extensional systems: each individual antithetic fault moves  
835 passively beyond the fault bend and becomes inactive, while a new fault propagating from the  
836 same bend replaces it. Thus, secondary faults tend to be progressively older basinwards

837 (Christiansen, 1983; McClay, 1990; Withjack *et al.*, 1995; Withjack and Schlische, 2006). In  
838 any case, periods of activity of the hanging-wall growth faults can overlap (Imber *et al.*,  
839 2003). The great majority of analogue models of rollovers show a faulting sequence that  
840 begins with an antithetic fault, then alternating synthetic and antithetic ones eventually joining  
841 and reciprocally offsetting at depth (McClay, 1990; McClay *et al.*, 1991; T. Román-Berdiel,  
842 personal communication). The same pattern has been reported in actual examples (e.g., Fazli  
843 Khani and Back, 2015, fig. 10). Nevertheless, sandbox experiments have also been described  
844 in which alternating activation of synthetic and antithetic faults is initiated with a synthetic  
845 one (*e.g.*, Buchanan and McClay, 1991).

846 The fault sequence interpreted at La Sima trench share some of the former evolutionary  
847 patterns typical of rollover deformation, such as the relevance and persistence of a subsidiary  
848 antithetic fault, the activation of younger antithetic ruptures closer to the main fault, and  
849 overall alternating onset of synthetic and antithetic ruptures. However, we have also found a  
850 non-typical feature: the oldest recorded meso-scale faults are synthetic with the Sierra  
851 Palomera fault, despite having formed in the same area where the persistent antithetic fault  
852 will later appear. The first deformational events (T to W) mainly involve accumulation of  
853 significant synthetic net slip (+200 cm), while the last three ones (X, Y, Z) involve substantial  
854 antithetic net slip (−190 cm). Briefly, progressive deformation in the hanging-wall block is  
855 shifted from dominantly synthetic faulting to dominantly antithetic faulting. Such particular  
856 deformation pattern suggests the existence of other controls on the hanging-wall deformation  
857 in addition to the rollover kinematics itself, as discussed in the next section.

858 Finally, the accumulated net slip has an associated component of horizontal extension  
859 that enables a further quantitative kinematical approach (see Table 2). The total extension  
860 recorded at La Sima trench is  $\approx 310$  cm, which represents about 19% of the restored length of  
861 the logged transect (local  $\beta$  factor = 1.19). Horizontal extension accommodated by faults  
862 totalizes ca. 210 cm (125 cm by synthetic ones and 86 cm by antithetic ones). Development of  
863 the bending monocline involves additional extension of about 100 cm.

864 Overall considered, our results represent a high-resolution, sub-seismic-scale picture of  
865 hanging-wall deformation that complements natural case studies based on seismic profiles and  
866 ‘fills the gap’ with the scale of laboratory analogue models. It documents both (i) earlier  
867 stages of a process of hanging-wall deformation (those mostly governed by synthetic faulting)  
868 that usually are not recognized from seismic reflection data, and (ii) later stages governed by  
869 antithetic faulting that better correlate with seismic-reflection-based models.

870

871 **8.5. Kinematic and dynamic controls on deformation of the hanging-wall block:**  
872 **relevance of the tectonic stress framework**

873 It is not easy to discriminate whether faults propagated through the hanging-wall block  
874 are kinematically or dynamically controlled, *i.e.*, they essentially accommodate extensional  
875 deformation associated to the rollover monocline, or they are directly linked to regional stress.  
876 Geometry and kinematics of faults surveyed at both map and trench scales overall fits the  
877 expected deformation within the hanging-wall block of the Sierra Palomera fault. But they are  
878 also consistent with the regional extensional stress field, whose  $\sigma_3$  trajectories trend ENE-  
879 WSW (Simón, 1982, 1989; Arlegui *et al.*, 2005, 2006; Liesa *et al.*, 2019), orthogonal to the  
880 overall trend of the Jiloca graben, and only slightly oblique to the Sierra Palomera fault trace  
881 itself. Stress inversion from the most representative, non-rotated conjugate faults measured  
882 within the trench, according to Anderson (1951), provides local stress axes matching those  
883 regional trajectories (Fig. 15).

884 The extension direction expectable for the kinematical scenario could be constrained  
885 between N065°E (orthogonal to the average strike of the Sierra Palomera fault; an inherited  
886 feature indeed) and N050°E (transport direction). The extension trend expectable for the  
887 dynamical scenario would approach N075°E (seeing at the average trend of the Jiloca graben),  
888 or would range from N055°E to N080°E (seeing at paleostress results reported by Arlegui *et*  
889 *al.*, 2005, and Liesa *et al.*, 2019). The similarity between both inferences prevents us from  
890 discriminating among those hypothetical controls based solely on the orientation of structures  
891 (stereoplots of Fig. 11 show how the strongly clustered directions of normal faults in La Sima  
892 trench fit equally well the two scenarios). Nevertheless, some details of the faulting  
893 succession suggest that both controls probably coexist. The kinematical control has been  
894 attested and discussed in sections 8.1 and 8.5. The dynamical one could explain the  
895 occurrence of early synthetic meso-scale faults (an unusual feature in kinematically-driven  
896 models) at La Sima site.

897 Additionally, there also seems to be a certain degree of control by a recent ESE-WNW  
898 extension direction. Both E-W to ESE-WNW, and ENE-WSW extension directions  
899 (characterizing the Late Miocene-Early Pliocene and the Plio-Quaternary rift episodes,  
900 respectively) are recorded during the entire extensional period indeed (Liesa *et al.*, 2019).  
901 This suggests stress partitioning (in the sense of Simón *et al.*, 2008) of the composite  
902 extensional field that results from combination of intraplate NNW-SSE compression (Africa-  
903 Iberia convergence) and WNW-ESE extension (rifting of the Valencia trough) (Simón, 1989;  
904 Herraiz *et al.*, 2000; Capote *et al.*, 2002). Among fractures observed at La Sima trench that do

905 not show any sign of displacement, a minority NNE-SSW trending set can be distinguished  
906 (Fig. 11f), which records the WNW-ESE extensional component of the regional, locally and  
907 episodically partitioned stress field.

908

## 909 **9. Conclusions**

910 The NNW-SSE trending, 26 km long Sierra Palomera extensional fault has been active  
911 during Late Pliocene-Quaternary times. It has undergone nearly pure normal movement with  
912 mean transport direction towards N230°E, consistent with the ENE-WSW extension  
913 trajectories of the recent to present-day regional stress field.

914 The hanging-wall block of the Sierra Palomera fault is cut by two subsidiary parallel  
915 ruptures: (i) the synthetic Las Vallejadas fault, located at about 1.5 km basinwards, and (ii)  
916 the antithetic La Peñuela fault, at a distance of 0.7-1.0 km, which apparently offsets ca. 2.5 m  
917 the surface of the La Sima alluvial fan giving rise to a gentle uphill-facing scarplet.

918 In the absence of recent stratigraphic markers, the *FES2* planation surface (3.8 Ma) has  
919 allowed calculating a maximum value of  $330 \pm 40$  m for the fault throw *s.s.*, and ca.  $480 \pm 40$   
920 m for the total tectonic throw at the half-graben margin (including the bending component),  
921 resulting in a net slip rate of  $0.09 \pm 0.01$  mm/a ( $0.13 \pm 0.01$  mm/a including bending).

922 Results from La Sima trench have demonstrated the existence of the antithetic La Peñuela  
923 fault, accompanied by a number of minor synthetic and antithetic ones, and its activity during  
924 Middle-Late Pleistocene times. Their detailed kinematical analysis has allowed building an  
925 evolutionary model made of seven deformation events. Net slip on individual faults ranges  
926 from 5 to 115 cm. The cumulative antithetic throw at the exposed fault zone, including fault  
927 slip *s.s.* and bending, is estimated at 210 cm, which reasonably approaches the apparent offset  
928 of the natural slope of La Sima alluvial fan.

929 The significance of the paleoseismic results is certainly limited. The surveyed trench  
930 within the hanging-wall block does not cross the main fault itself. In addition, it was not  
931 feasible to achieve a consistent age model for the entire sedimentary sequence; only the last  
932 two deformation events have been dated to ca.  $97 \pm 10$  ka and  $49 \pm 5$  ka, respectively.  
933 Nevertheless, Pleistocene activity of the Sierra Palomera fault has been proved for the first  
934 time, although indirectly from hanging-wall deformation.

935 The succession of faulting events at La Sima trench study allows unravelling the  
936 progressive extensional deformation within the hanging-wall block of the Sierra Palomera  
937 fault. The total horizontal extension recorded at La Sima trench is  $\approx 310$  cm (local  $\beta$  factor =

938 1.19). The faulting succession indicates that synthetic slip prevailing in early deformation  
939 events was shifted to antithetic slip during the younger ones. Geometry and sequential  
940 development of meso-scale faults suggest the concurrence of: (1) a kinematic control, *i.e.*,  
941 antithetic simple shear linked to rollover kinematics (mostly resulting in the main antithetic  
942 fault zone), eventually accompanied by layer-parallel extension orthogonal to the rollover  
943 axis, and (2) a dynamic control, *i.e.*, response to the remote extensional stress field,  
944 characterized by ENE-WSW (occasionally ESE-WSW) extension trajectories.

945

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1222 relationships that could have appeared to influence the work reported in this paper.

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1224 **FIGURE CAPTIONS:**

1225 **Figure 1:**

1226 (a) Location of the Iberian Chain within the Iberian Peninsula. (b) Geological sketch of the Iberian  
1227 Chain, with location of the main Neogene-Quaternary extensional basins. (c) Simplified geological  
1228 map of the Jiloca graben, with location of Figures 2, 6 and 9.

1229 **Figure 2:**

1230 Geological map of the Sierra Palomera area (on DEM image from Instituto Geográfico Nacional)  
1231 showing the main structures associated to the Sierra Palomera fault. Location of Figures 3, 4, 8, 10a,  
1232 11 is indicated, as well as that of OSL samples in La Cecilia and La Sima alluvial fans (see Table 1).

1233 **Figure 3:**

1234 Cross section of the Jiloca Graben at its central sector, initially reconstructed from surface geology and  
1235 shallow borehole data (modified from Rubio and Simón, 2007). See location in Figure 2.

1236 **Figure 4:**

1237 (a) Field view of one of the rupture surfaces within the damage zone of the Sierra Palomera fault; it  
1238 cuts Lower Jurassic limestones and shows associated fault breccia. (b) Stereoplot (equal area, lower  
1239 hemisphere) showing orientations of fault planes and slickenlines collected in that zone.

1240 **Figure 5:**

1241 The Sierra Palomera mountain front. (a) Field panoramic view. (b) Hillshade oblique image rendered  
1242 from Digital Elevation Model (5 m grid) of Instituto Geográfico Nacional (IGN). (c) Detail of a  
1243 trapezoidal facet within the fault scarp. (d) Hillshade oblique image (5-m-grid DEM, IGN) showing a  
1244 close view to the alluvial fans sourced at the mountain front; La Cecilia and La Sima alluvial fans are  
1245 identified.

1246 **Figure 6:**

1247 Morphotectonic map of the Sierra Palomera area.

1248 **Figure 7:**

1249 Throw *vs.* distance (T-D) graph along the Sierra Palomera fault. Lower curve: fault throw *s.s.* recorded  
1250 by the *FES2* marker. Upper curve: total tectonic throw of *FES2* including the bending component.

1251 **Figure 8:**

1252 Villafranchian alluvial deposits (V) tilted by an accommodation monocline above La Peñuela fault.  
1253 Jurassic limestones (J) of the footwall block crops out at the bottom of the gully. See location in  
1254 Figure 2.

1255 **Figure 9:**

1256 Results of the magnetometric survey covering the Sierra Palomera piedmont. (a) Location of profiles  
1257 01 to 10 (which is the same as for the electromagnetic survey), with the residual values of field  
1258 intensity (nT) plotted as a colour palette. Black thin lines depict the Sierra Palomera fault trace. Grey  
1259 thick lines depict the spatial correlation of trending changes on the successive transects, and therefore  
1260 of the described domains (A, B and C). (b) Residual earth magnetic field profiles plotted with a  
1261 normalized horizontal length, in which domains A, B and C roughly parallel to the Sierra Palomera  
1262 fault are defined (data are in nT; see text for details).

1263 **Figure 10:**

1264 (a) Hillshade relief map of the barranco de la Sima alluvial fan rendered from digital elevation model  
1265 (DEM, 5 m grid) of the Instituto Geográfico Nacional. See location in Figure 2. (b) Residual magnetic  
1266 field anomalies at the central sector of the alluvial fan, at the contact between domains A and B. (c)  
1267 Detailed topographic profile showing a slope anomaly in the longitudinal profile of the alluvial fan  
1268 surface, from which an apparent antithetic throw of ca. 2.5 m can be inferred.

1269 **Figure 11:**

1270 (a) Uninterpreted photomosaic of La Sima trench, see location in Figure 2. (b) Detailed log. 1 to 12:  
1271 Quaternary units described in the text. Greek characters: faults referred in the text. The location and  
1272 age of samples dated by OSL is indicated. Stereoplots (equal area, lower hemisphere) show  
1273 orientations of faults and fractures measured within the trench: (c) Central fault zone. (d) Footwall  
1274 block, including monocline. (e) Synthetic stereoplot of fault planes, including a main set parallel to the  
1275 prevailing structural trend (NNW-SSE, black great circles) and a subsidiary set oriented NNE-SSW  
1276 (blue great circles); fault planes rotated at the monocline have been restored to their original  
1277 orientation. (f) Synthetic stereoplot of fractures without displacement.

1278 **Figure 12:**

1279 Evolutionary model of sedimentation and deformation recorded at the La Sima trench from  
1280 retrodeformational analysis. Each sketch represents a stage subsequent to the paleoseismic event (and,  
1281 in some cases, to deposition of sedimentary units) labelled above. Unexposed sectors below the trench  
1282 have been locally reconstructed in the sketches in order to complete the evolutionary model. Bold  
1283 traces indicate which faults are active during each event. Total horizontal extension and throw  
1284 calculated in Table 2 are shown.

1285 **Figure 13:**

1286 (a) Refined cross section of the Jiloca graben at its central sector, in which the new inferred, subsidiary  
1287 faults have been incorporated. (b) Upper fringe of the same cross section (vertical scale x2) showing  
1288 offset of planation surfaces *FES2* and *FES3*.

1289 **Figure 14:**

1290 Plot of  $S_{mf}$  (mountain-front sinuosity index) vs.  $V_f$  (valley width/height ratio, measured 250 m  
1291 upstream from the fault trace), showing the relative position of the Sierra Palomera Fault among  
1292 extensional fault-generated mountain fronts of eastern Spain. For comparison, the  $S_{mf}$ - $V_f$  plots for the  
1293 neighbouring Conclud fault (Lafuente et al, 2011b), faults bounding the Maestrat grabens (eastern  
1294 Iberian Chain; Perea, 2006), and Valencia region and Betic chains (Silva *et al.*, 2003) are also  
1295 included. Class 1, 2, 3: activity classes (active, moderate and inactive, respectively); the curve  
1296 represents the tendency for normal faults in SE Spain according to Silva *et al.* (2003).

1297 **Figure 15:**

1298 Interpretation of paleostress axes from orientation of non-rotated, conjugate fault planes measured  
1299 within La Sima trench. Stress inversion based on model by Anderson (1951).

1300 **Table 1:**

1301 Parameters and results of OSL dating of samples collected at the La Sima trench (S1 to S7;  
1302 Luminescence Dating Laboratory of University of Georgia, USA), and La Cecilia and La Sima alluvial  
1303 fans (Laboratorio de Datación y Radioquímica de la Universidad Autónoma de Madrid, Spain).

1304 **Table 2:**

1305 Synthesis of deformation events inferred at La Sima trench: faults activated during each event; net slip  
1306 values calculated from the trench log and the retrodeformational analysis (positive: synthetic with the  
1307 Sierra Palomera fault; negative: antithetic; Figs. 11, 12), and associated values of horizontal extension.  
1308 Further explanation in text.

**Table 1:**

Sample	Laboratory reference	Stratigraphic location	Depth (m)	H <sub>2</sub> O (%)	Quartz Grain (μm)	<sup>238</sup> U (ppm)	<sup>232</sup> Th (ppm)	K (%)	Dose rate (Gy/ka)	Equivalent dose (Gy)	Age (ka)
S1	UGA15OSL-1013	Unit 9 (top)	1.0	5±2.5	80-125	1.42±0.33	5.86±1.14	0.6±0.1	1.50±0.15	146.0±3.9	97.4±10.2
S2	UGA15OSL-1014	Unit 9b	2.1	5±2.5	80-250	0.73±0.12	2.24±0.46	0.2±0.1	0.68±0.10	>256	>378
S3	UGA15OSL-1015	Unit 8	1.6	5±2.5	125-250	0.95±0.15	2.45±0.54	0.3±0.1	0.84±0.11	>300	>355
S4	UGA15OSL-1017	Unit 6 (base)	2.8	5±2.5	150-250	1.35±0.25	5.42±0.88	0.5±0.1	1.27±0.13	>300	>236
S5	UGA15OSL-1018	Unit 11	0.4	5±2.5	125-250	1.29±0.20	4.15±0.71	0.5±0.1	1.26±0.12	62.0±3.4	49.2±5.4
S6	UGA15OSL-1019	Unit 7 (top)	0.7	5±2.5	125-250	0.96±0.20	4.73±0.71	0.5±0.1	1.21±0.12	>300	>248
S7	UGA15OSL-1020	Unit 6 (top)	1.2	5±2.5	80-125	1.41±0.21	4.54±0.75	0.8±0.1	1.56±0.13	>300	>193
La Cecilia	MAD-6326BIN	Alluvial fan	3.0	2.31	2-10	2.97	1.54	0.01±0.1	1.63	47.1±2.5	28.9±2.0
La Sima	MAD-6327BIN	Alluvial fan	0.4	6.25	2-10	3.73	1.90	0.18±0.1	2.31	44.3±1.4	19.2±1.1

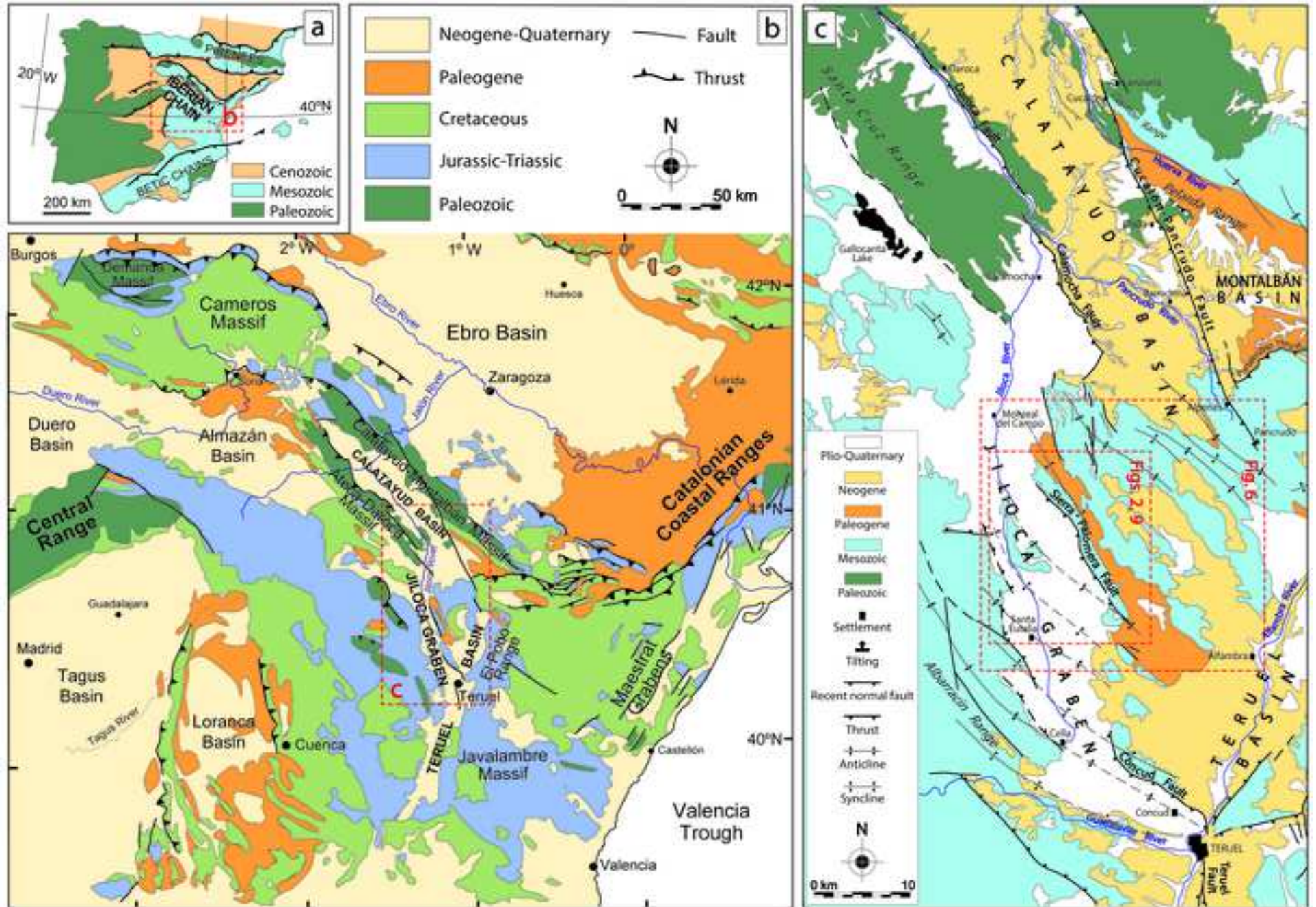
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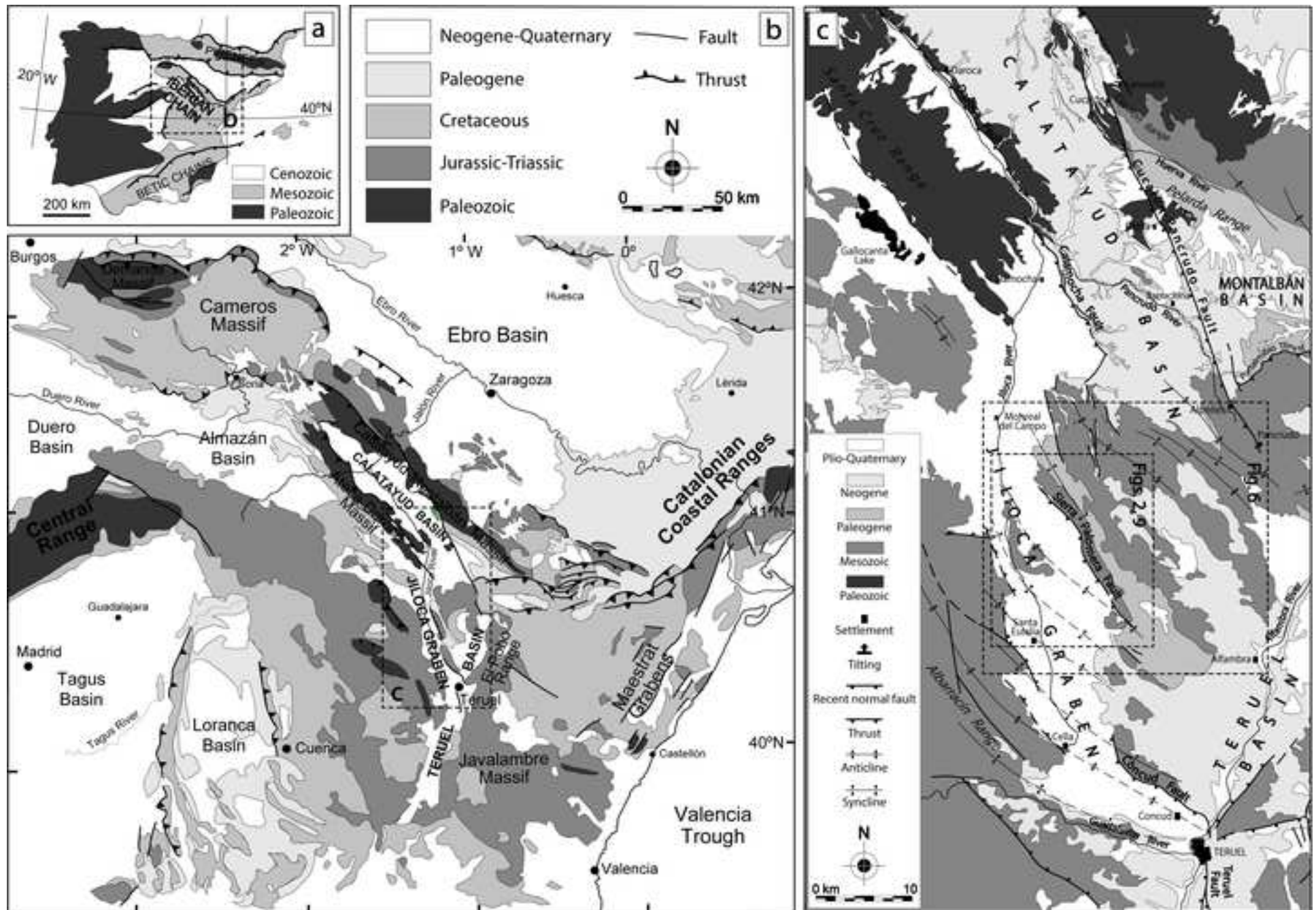
Event	Active faults	Net slip <sup>(1)</sup> (cm)	Average dip (°)	Horizontal extension <sup>(1)</sup> (cm)	Net slip <sup>(1)</sup> per event (cm)	Horizontal extension <sup>(2)</sup> per event (cm)
T	$\sigma$	+ 10	53	6	+ 45	15
	$\tau$	+ 5	60	2		
	$\pi 1$	+ 15	70	5		
	$\rho$	+ 15	64	7		
U	$\varepsilon 1$	+ 15	74	4	+ 105	45
	$\lambda 1 + \lambda 2$	+ 40	60	20		
	$\chi$	+ 20	59	10		
	$\mu$	+ 15	60	7		
	$\pi 2$	+ 15	60	7		
V	$\theta 2$	- 10	63	5	- 10	5
W	$\alpha$	+ 10	86	1	+ 60	80
	$\varepsilon 0 + \varepsilon 1$	+ 115	64	50		
	$\beta$	- 30	74	8		
	$\theta 1 + \theta 2 + \kappa 1$ to $\kappa 4$	- 35	63	16		
X	$\varepsilon 2$	+ 5	62	2	- 45	65
	$\theta 2 + \theta 3$	- 50	74	14		
Y	$\varepsilon 3$	0	55	0	- 35	20
	$\gamma 1 + \gamma 2 + \gamma 3$	- 35	80	6		
Z	$\varepsilon 1$	+ 10	64	4	- 110	80
	$\varepsilon 4$	- 10	42	7		
	$\theta 2 + \theta 3$ (+ open fissure)	- 110	74	30		
<i>Total synthetic faults</i>		+ 290		125 (7.8 %) <sup>(3)</sup>		
<i>Total antithetic faults</i>		- 280		86 (5.4 %) <sup>(3)</sup>		
<b>Accumulated deformation:</b>			<b>Throw<sup>(2)</sup> (cm)</b>			<b>Horizontal extension<sup>(2)</sup> (cm)</b>
<i>Bending monocline</i>		$\approx$ - 220				$\approx$ 100 (6.2 %) <sup>(3)</sup>
<i>Total structures</i>		- 210				$\approx$ 310 (19.4 %) <sup>(3)</sup>

<sup>(1)</sup> Excluding deformation associated to the monocline.

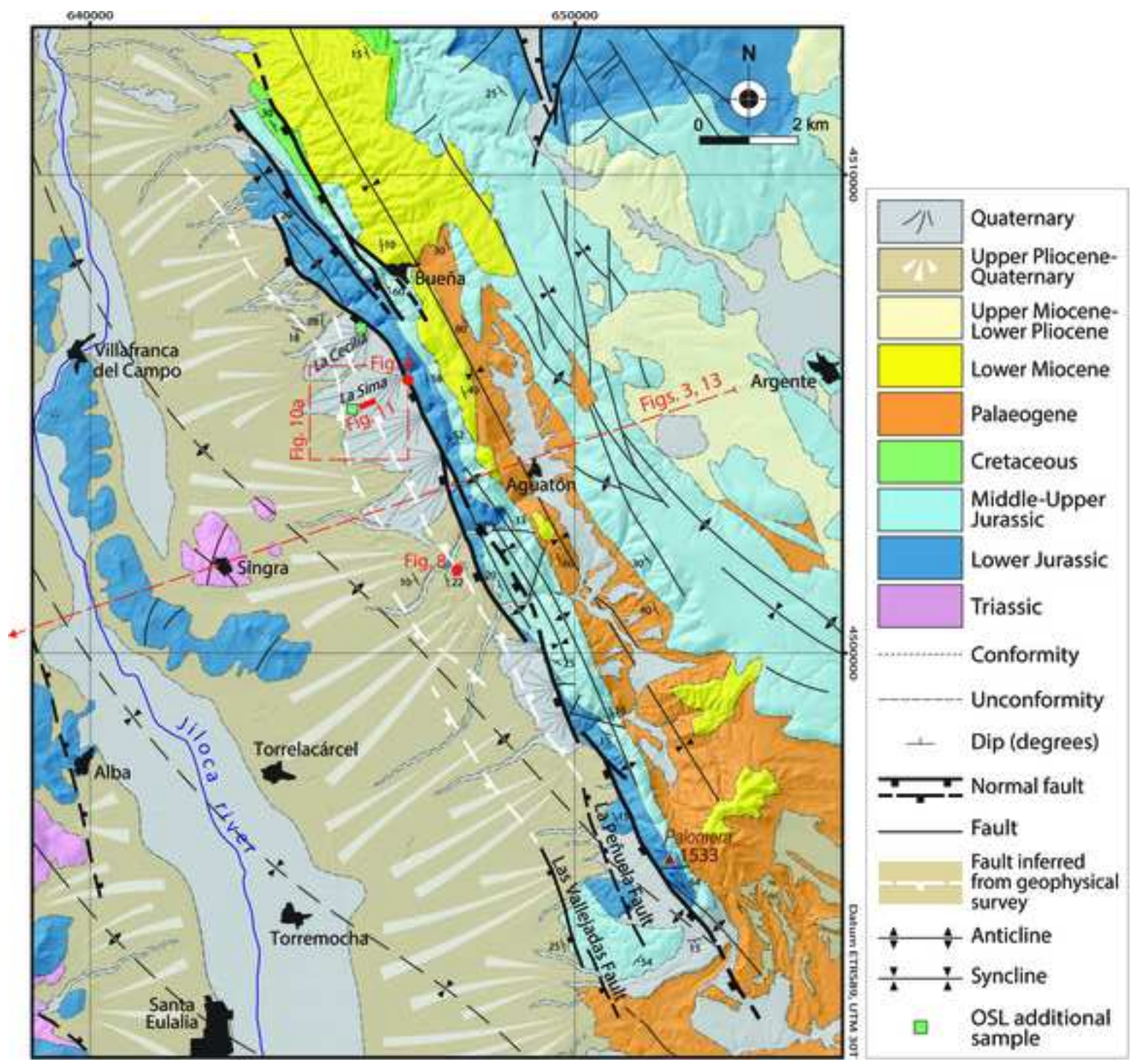
<sup>(2)</sup> Including deformation associated to both faults and monocline.

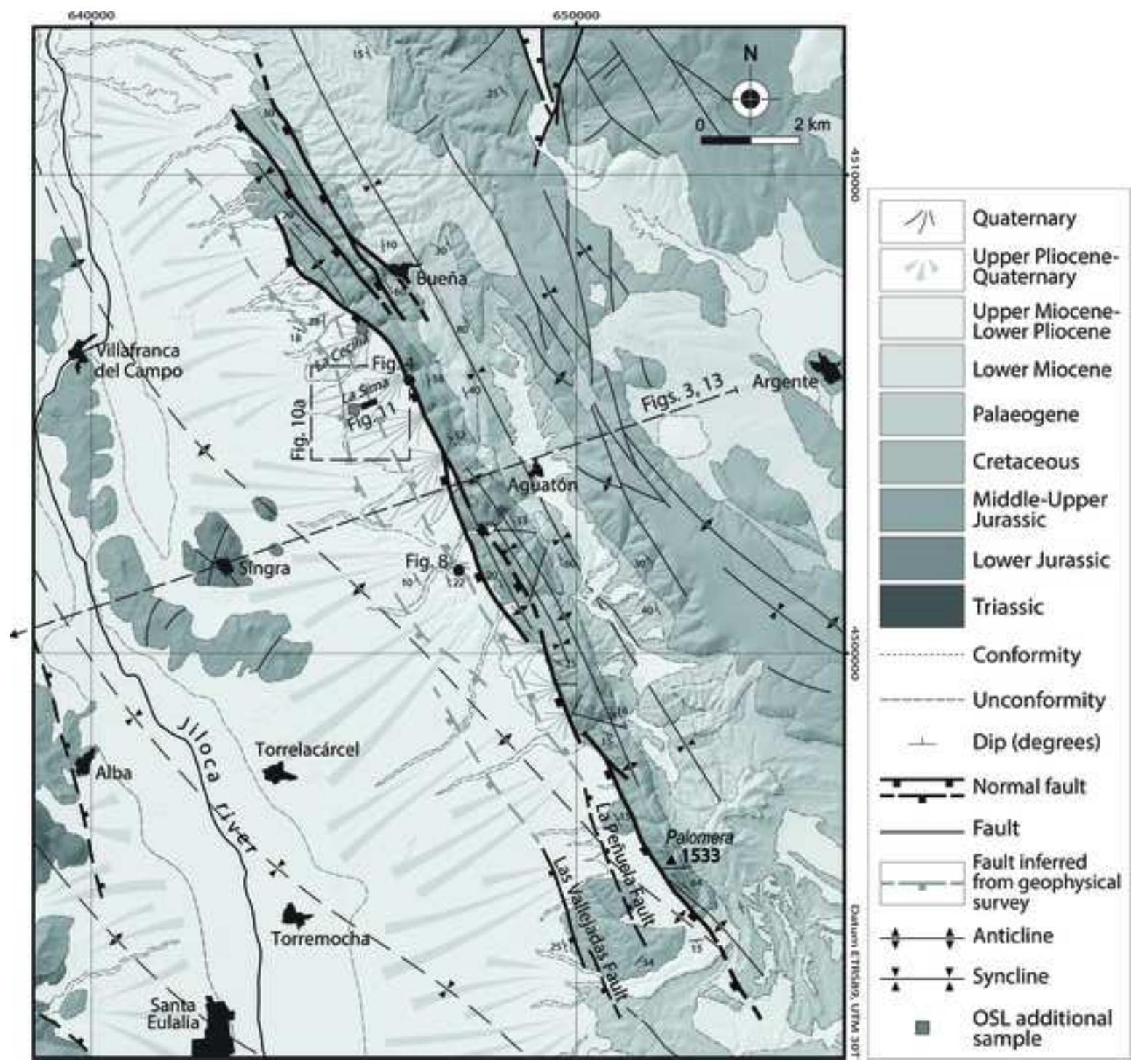
<sup>(3)</sup> Percentage with respect to the restored log length  $\approx$  1600 cm.

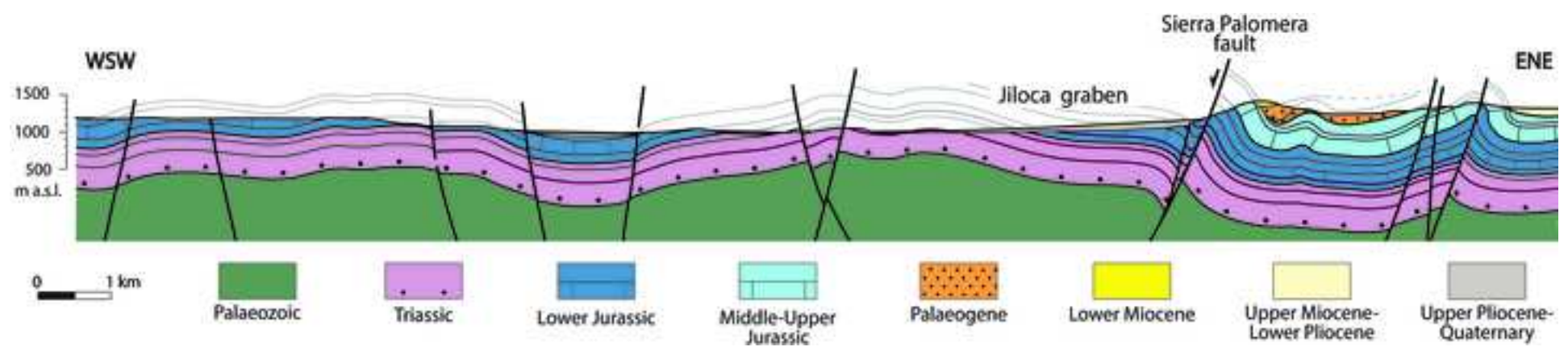


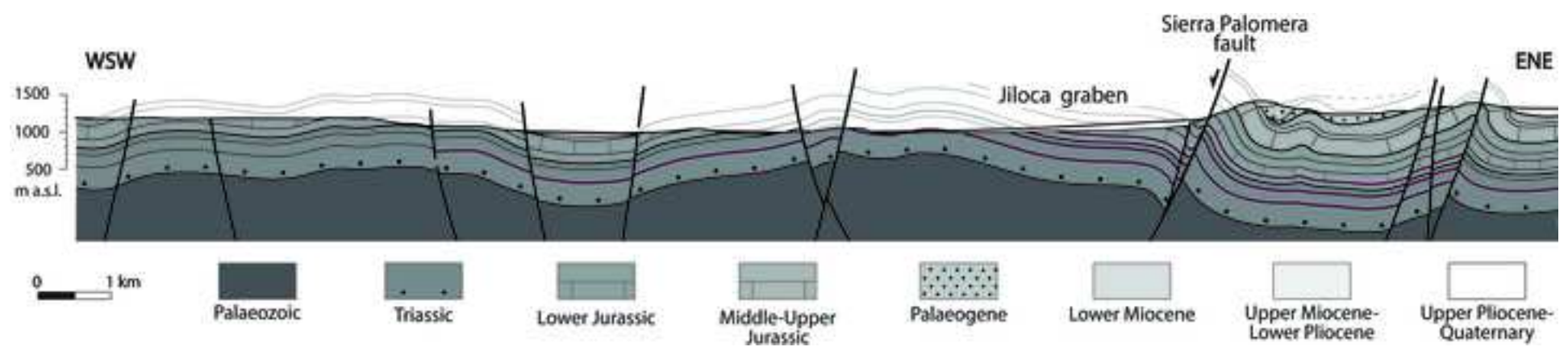


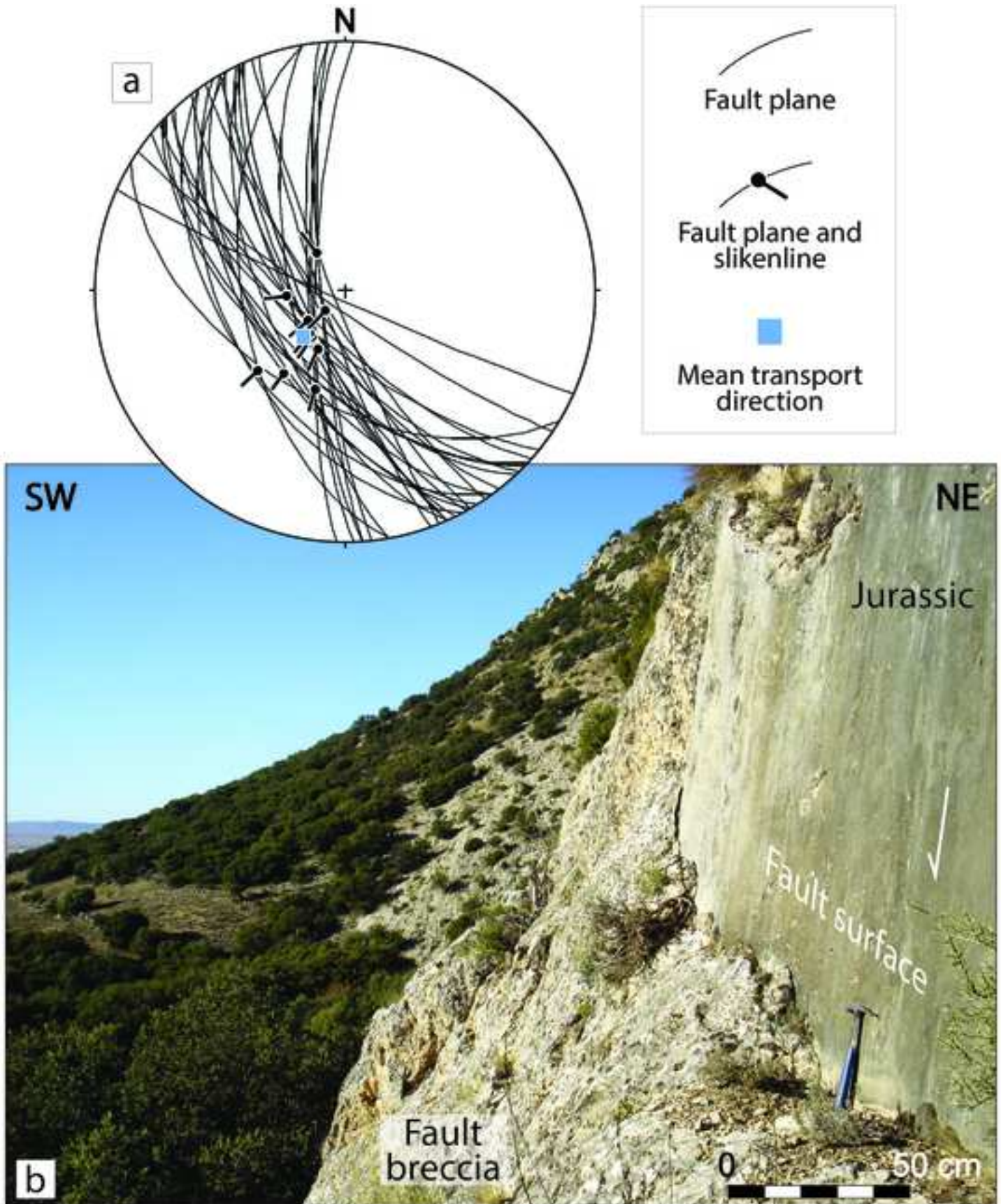


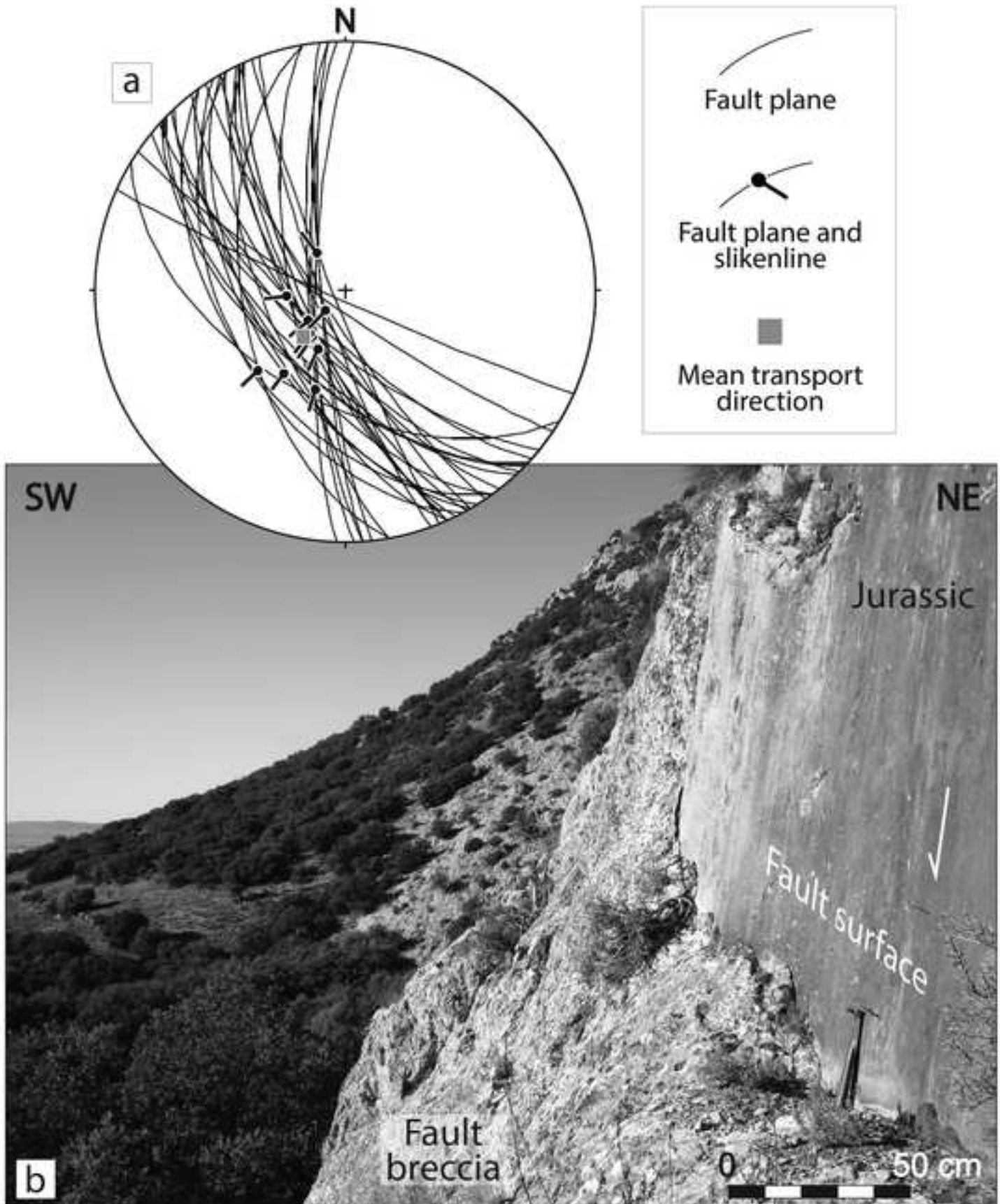


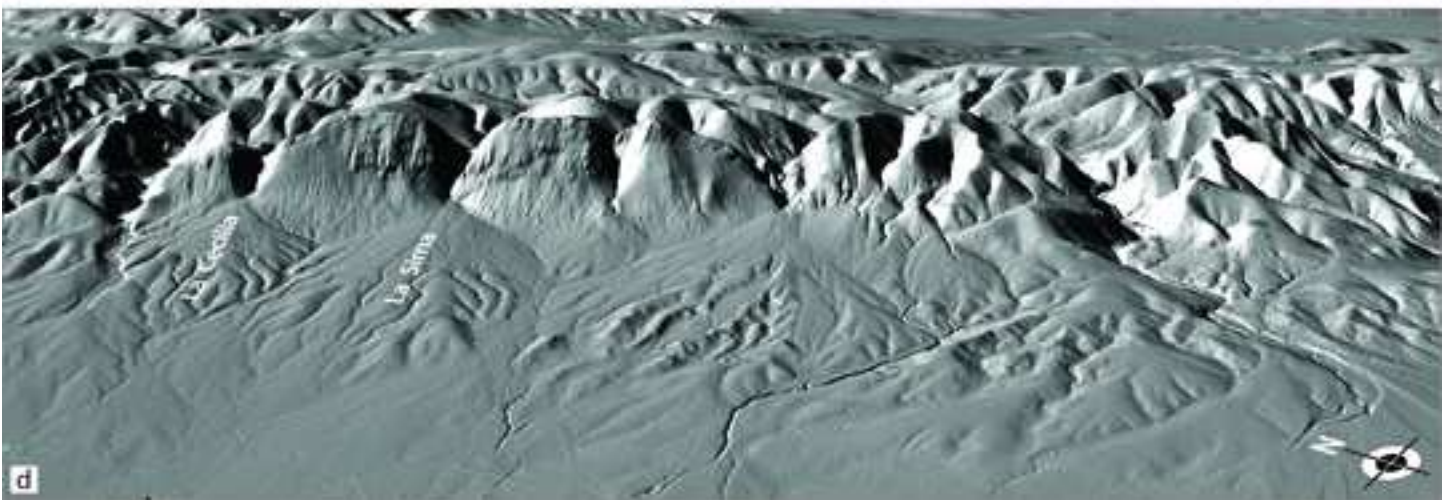
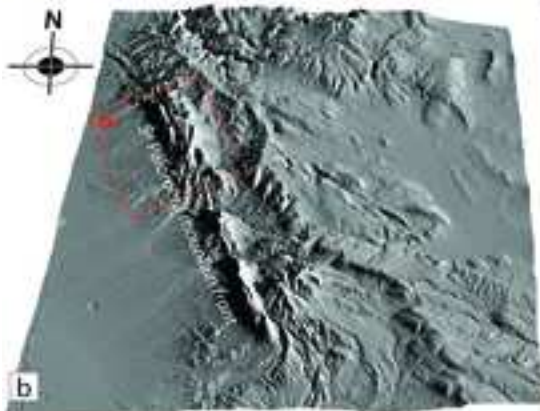


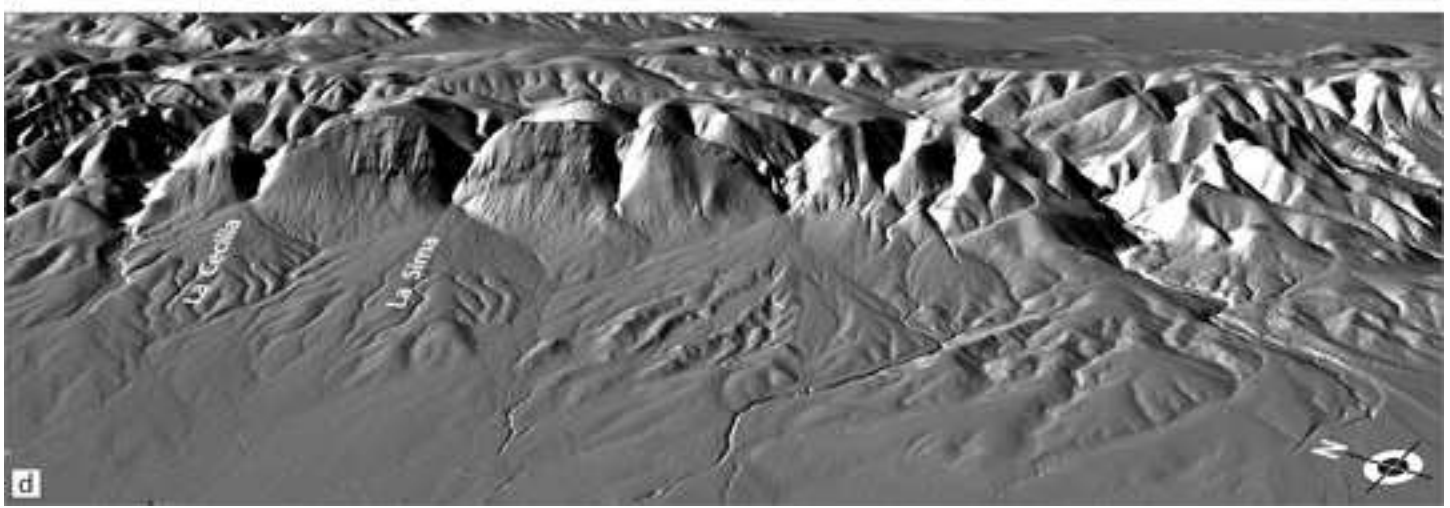
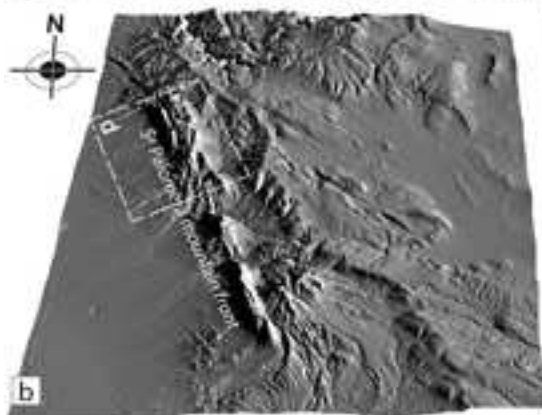




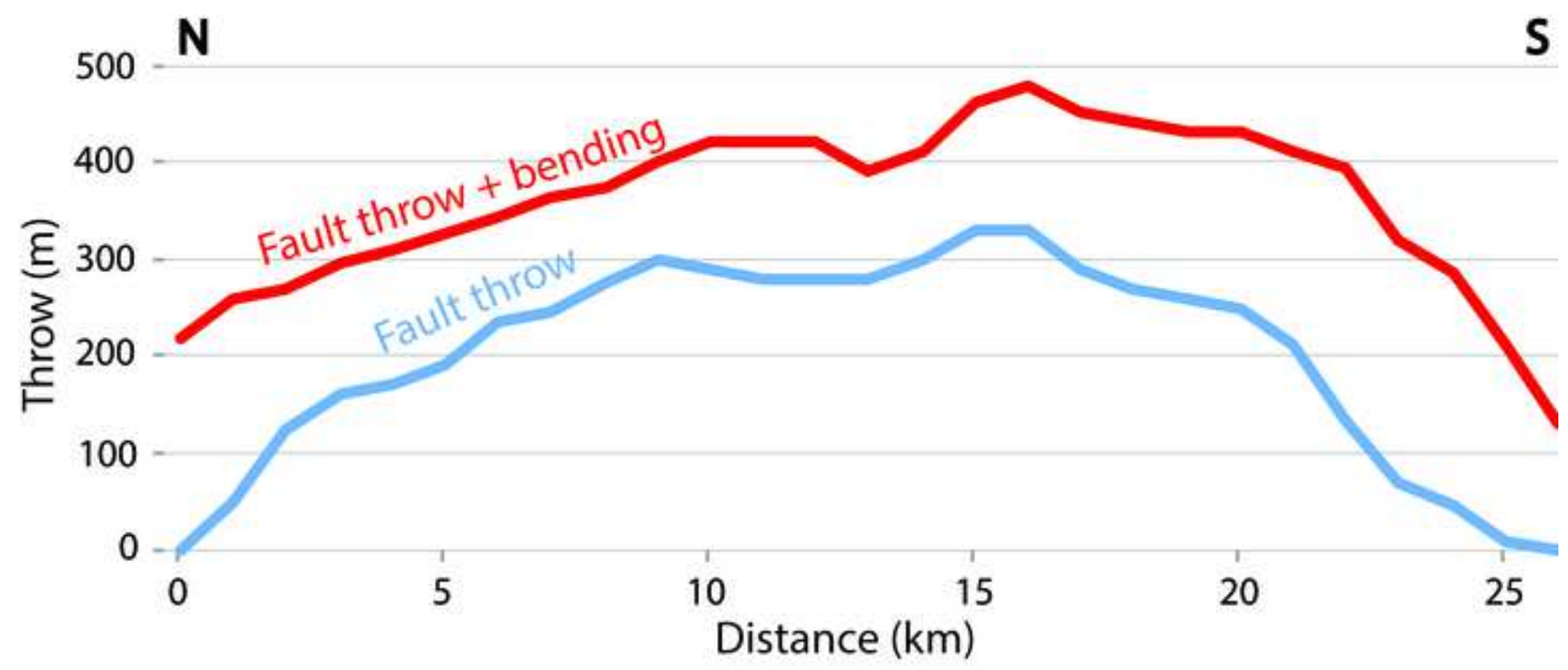


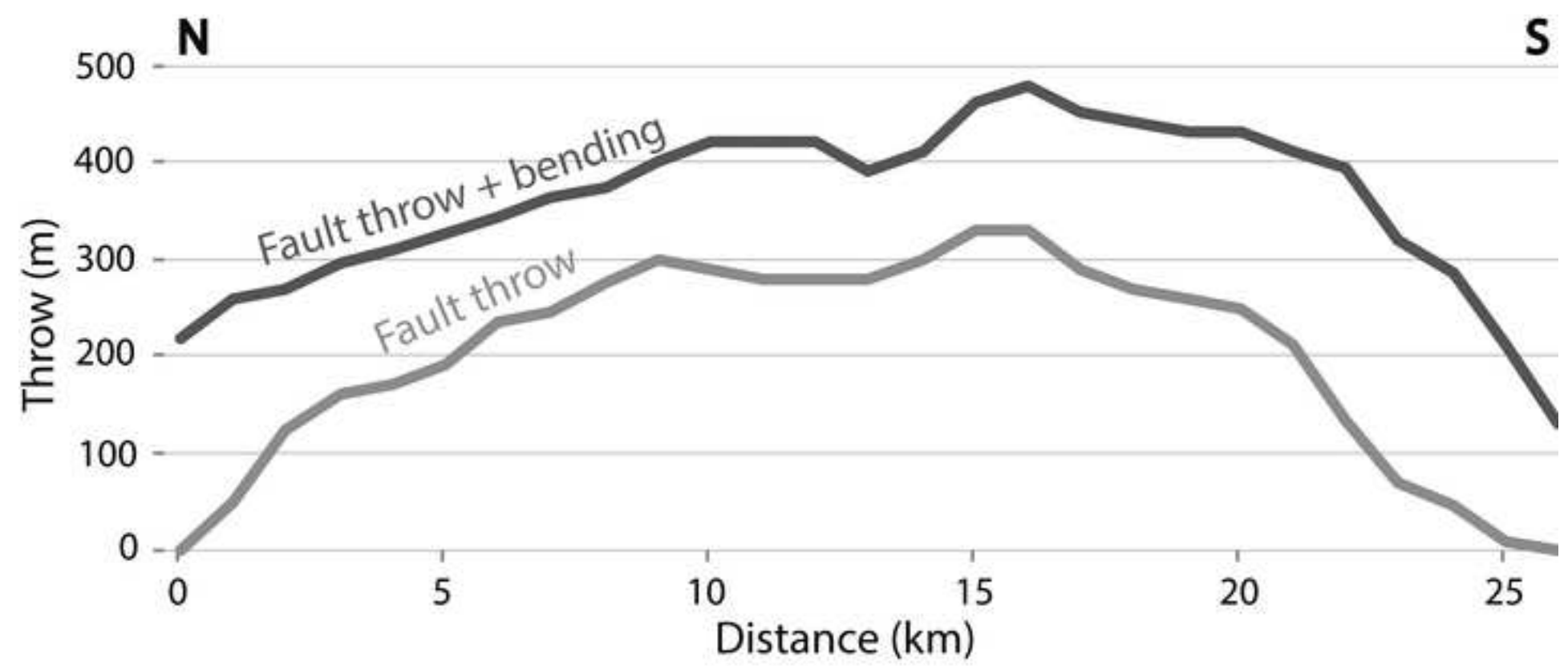


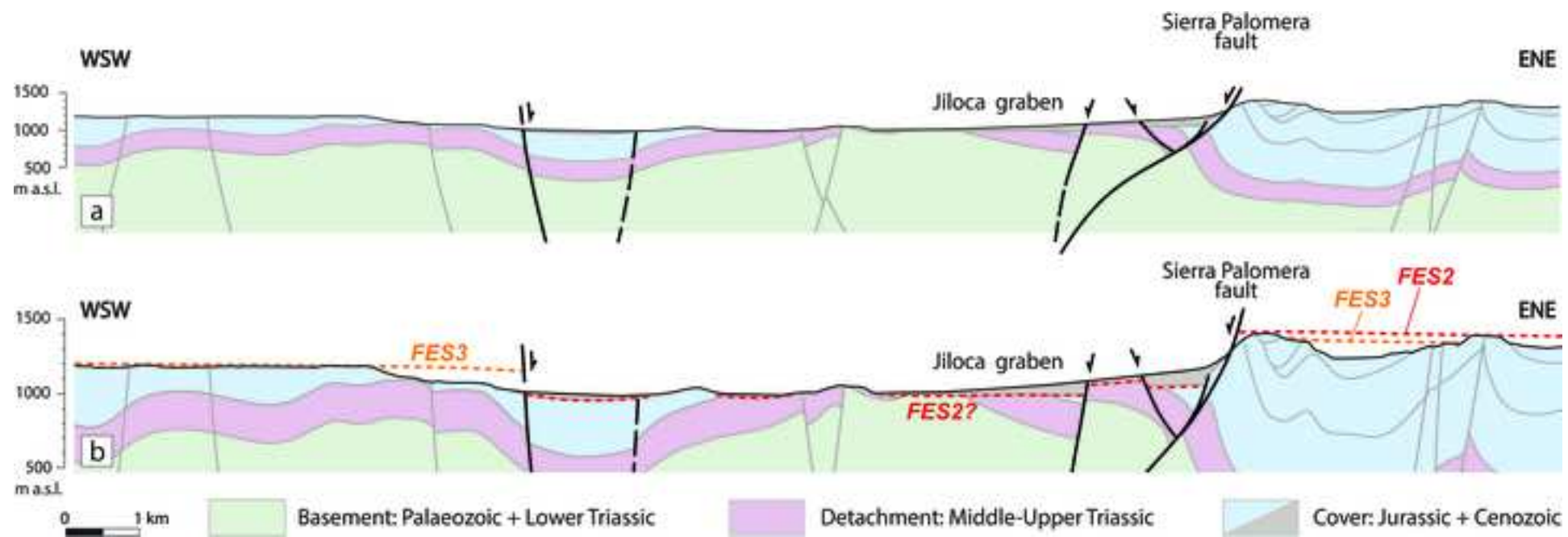


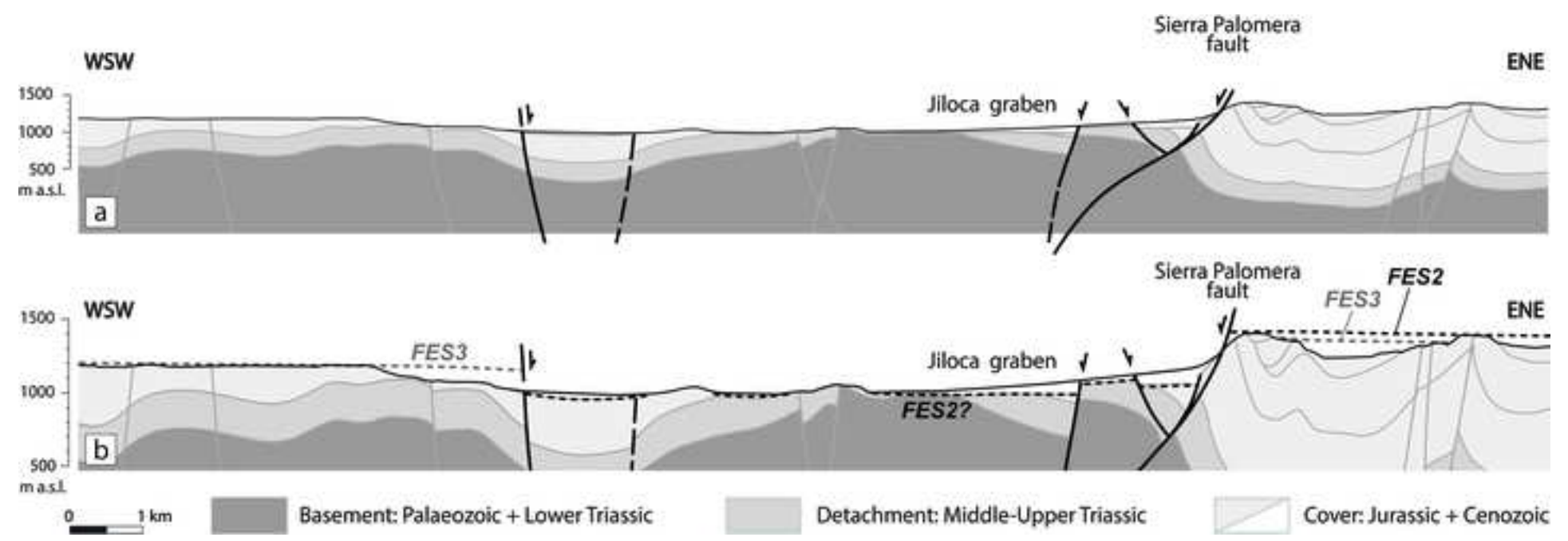


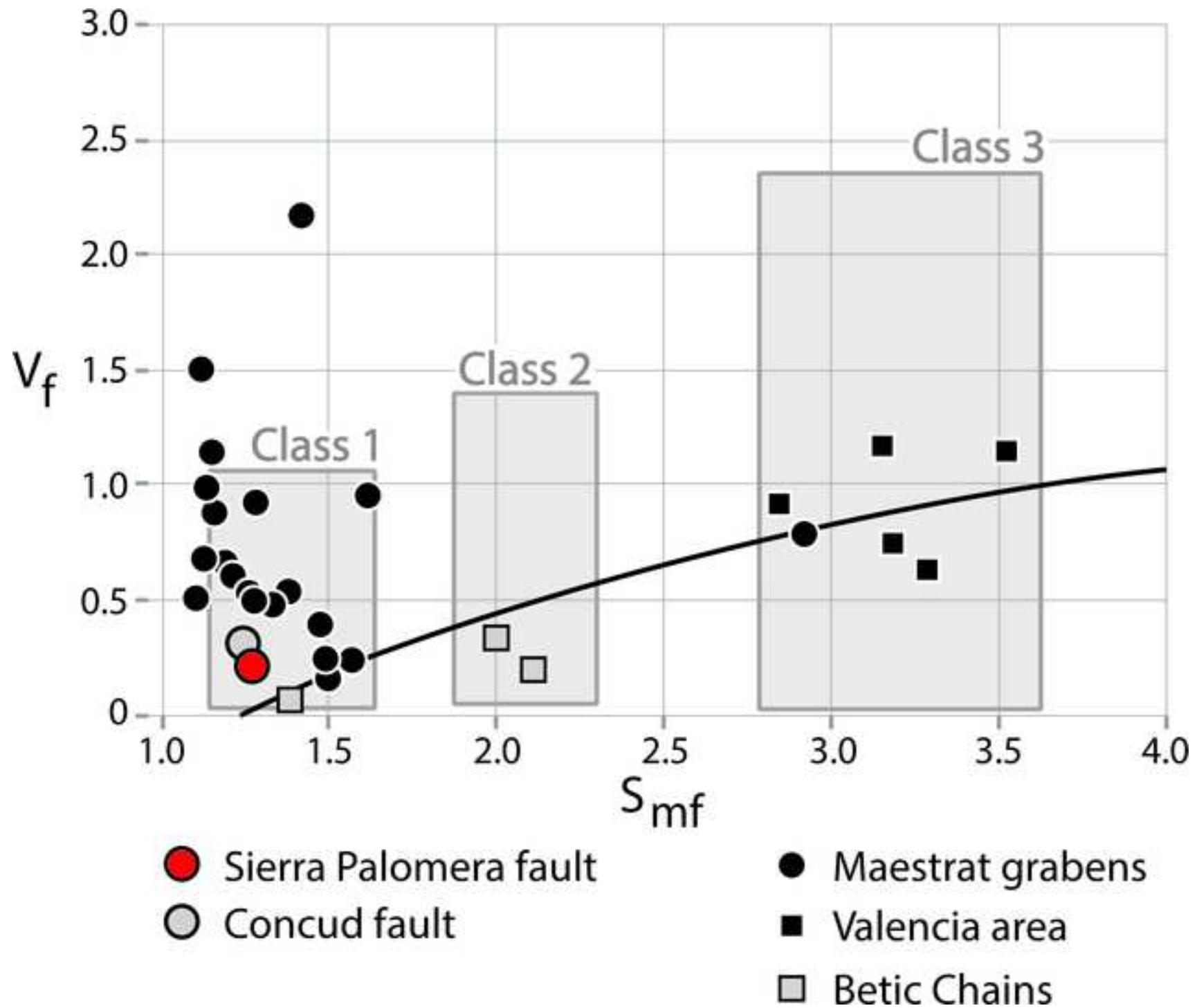




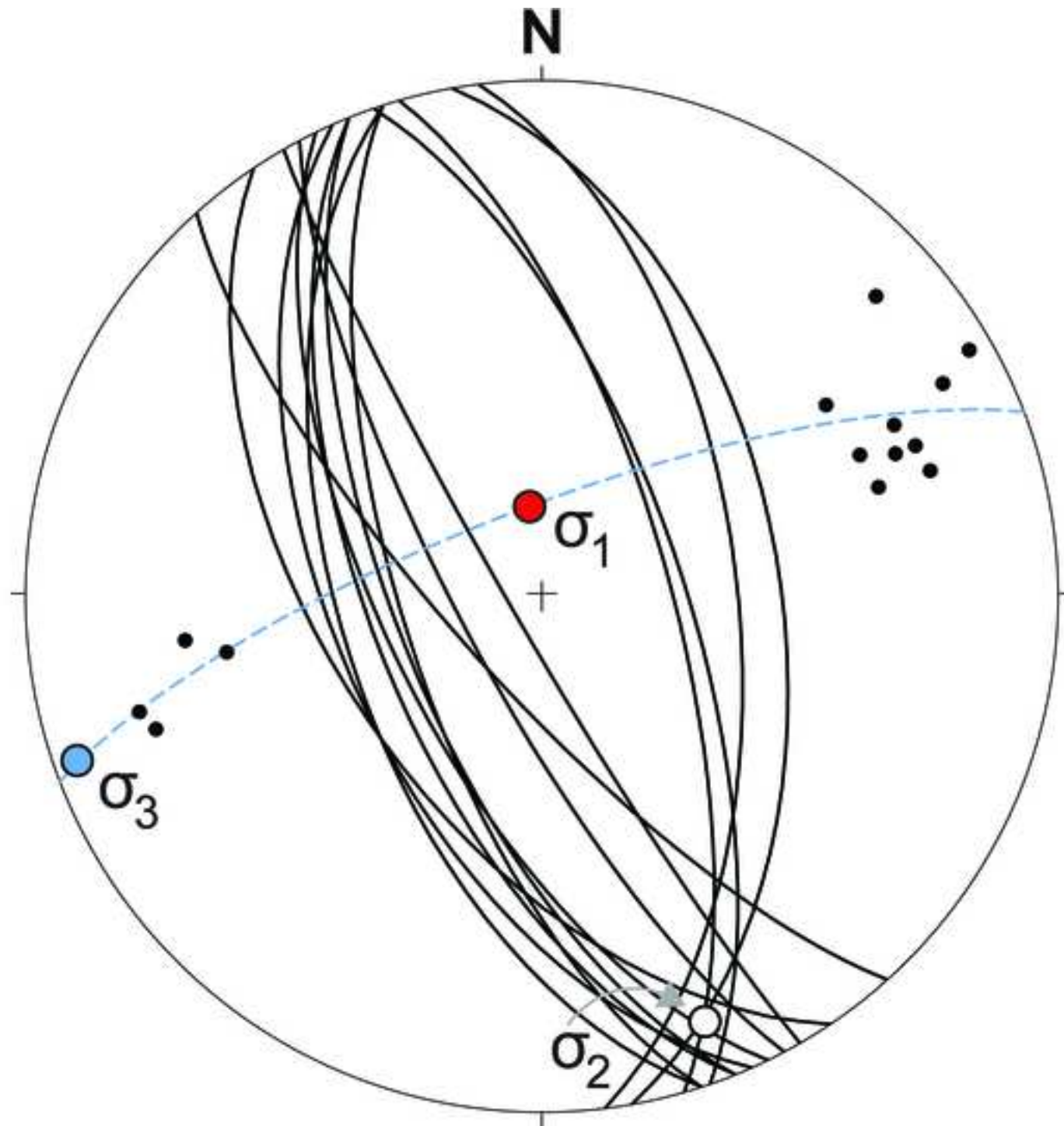


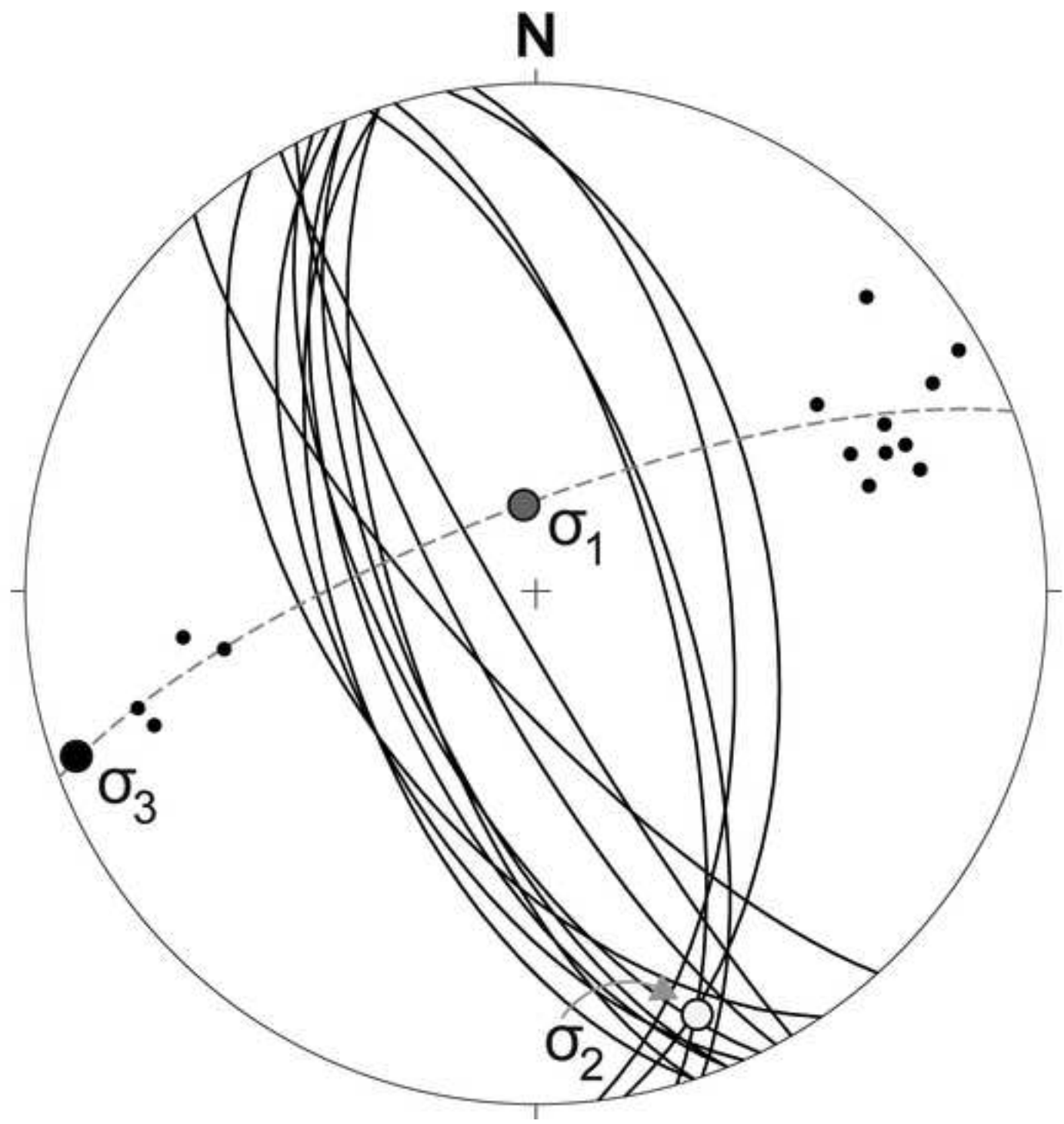




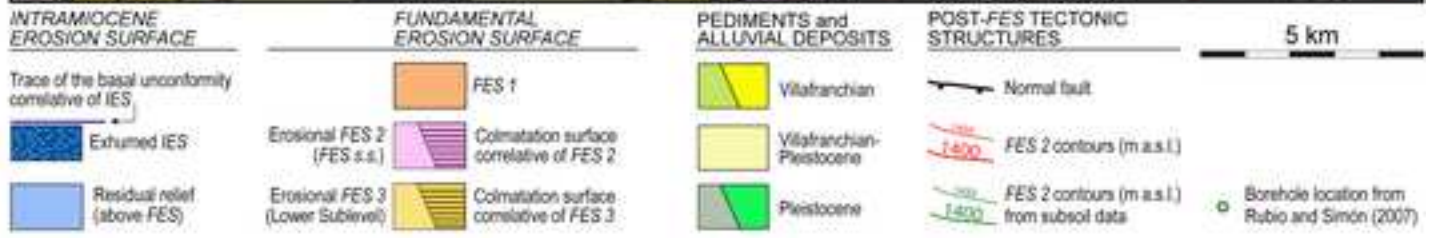
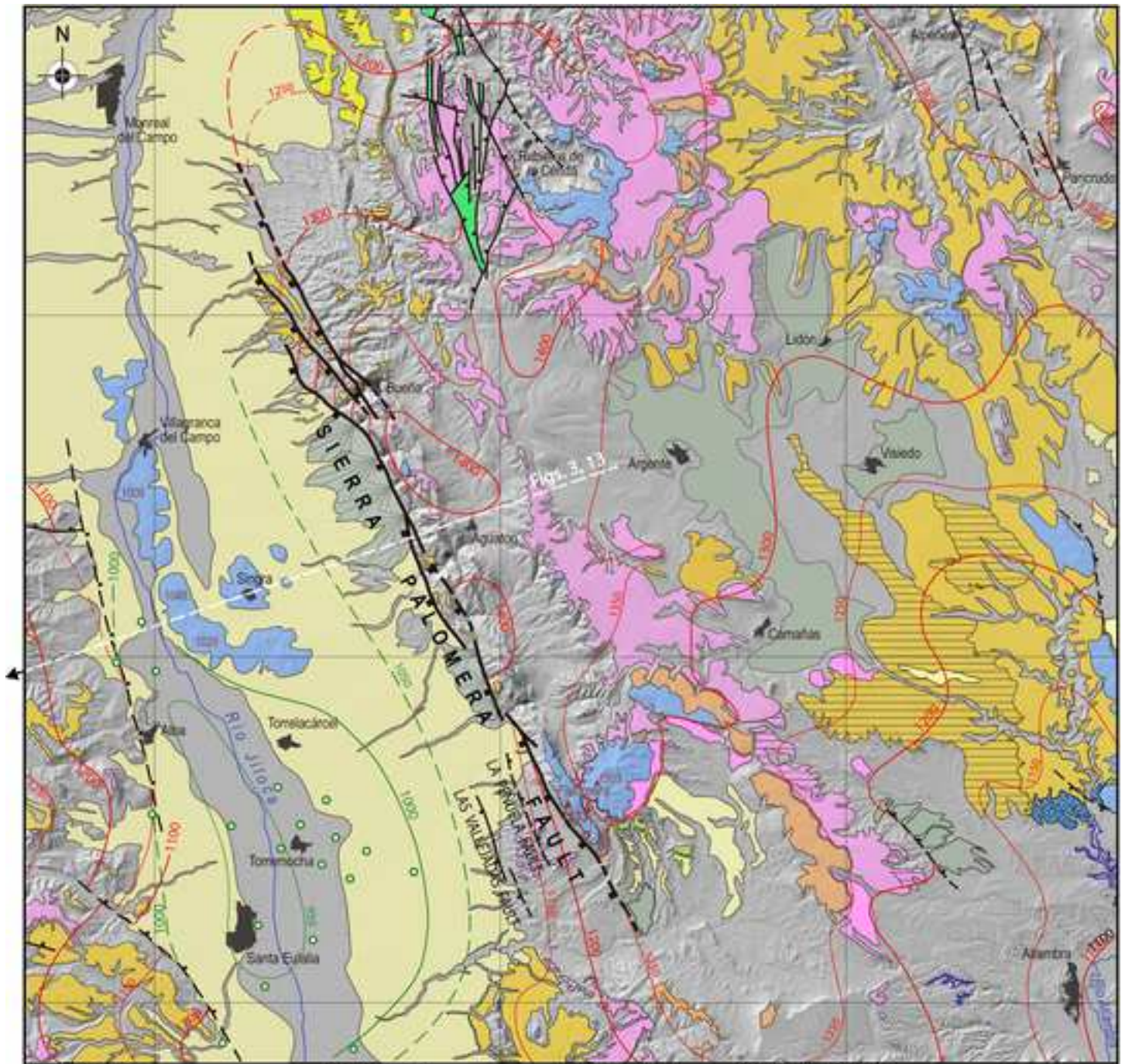




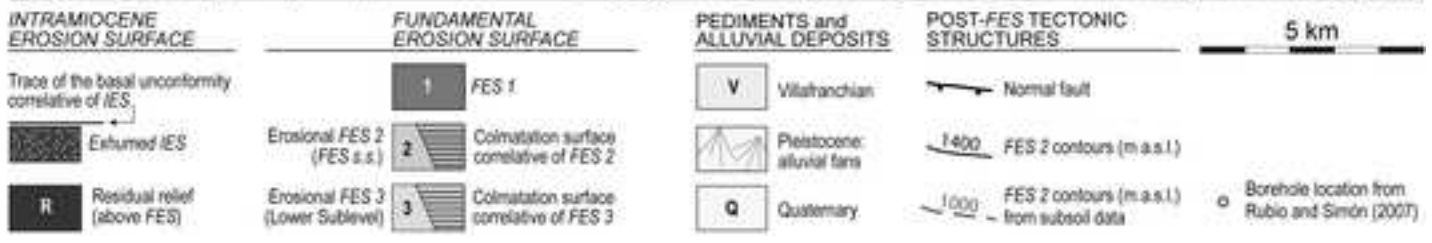
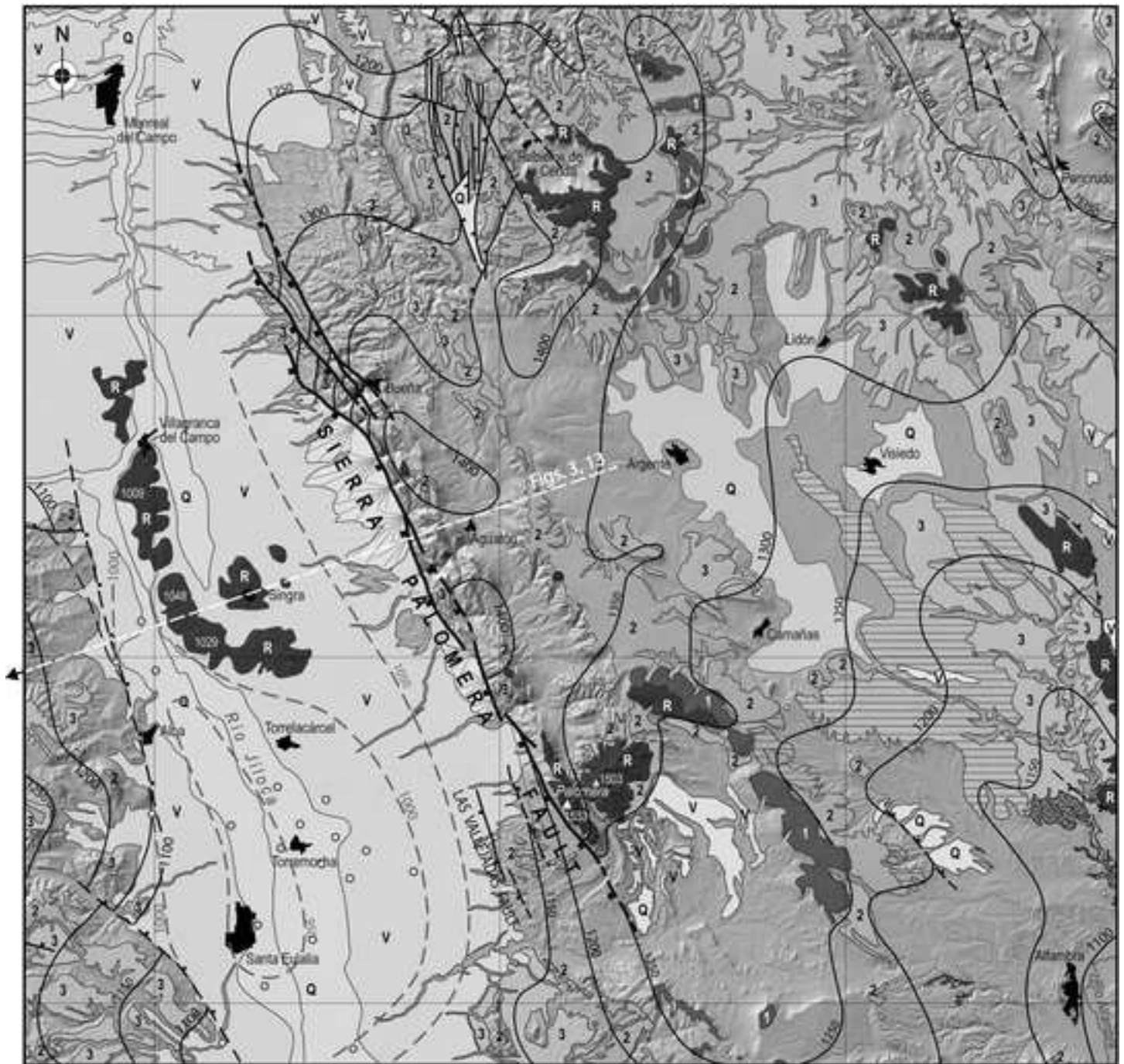




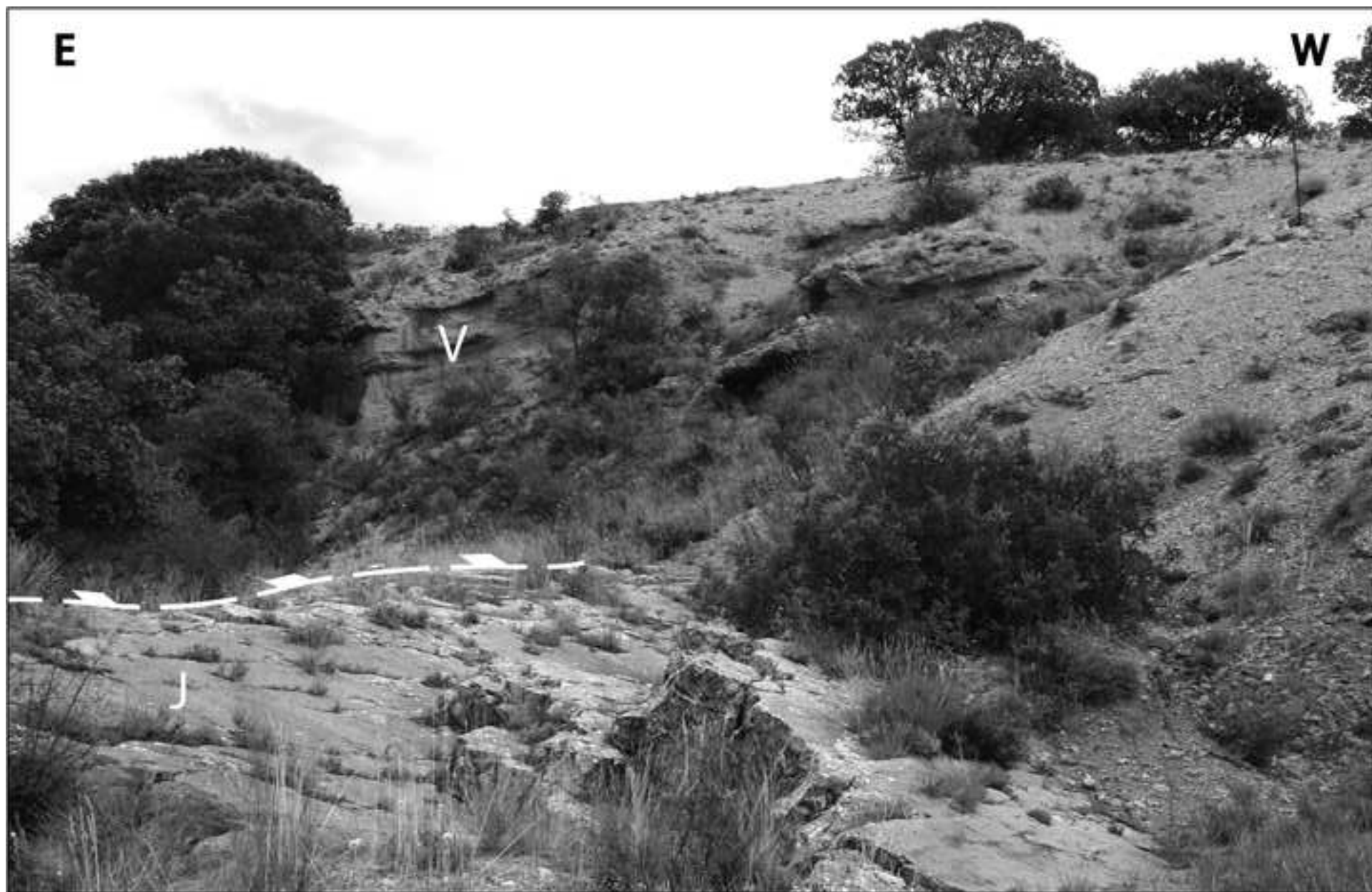


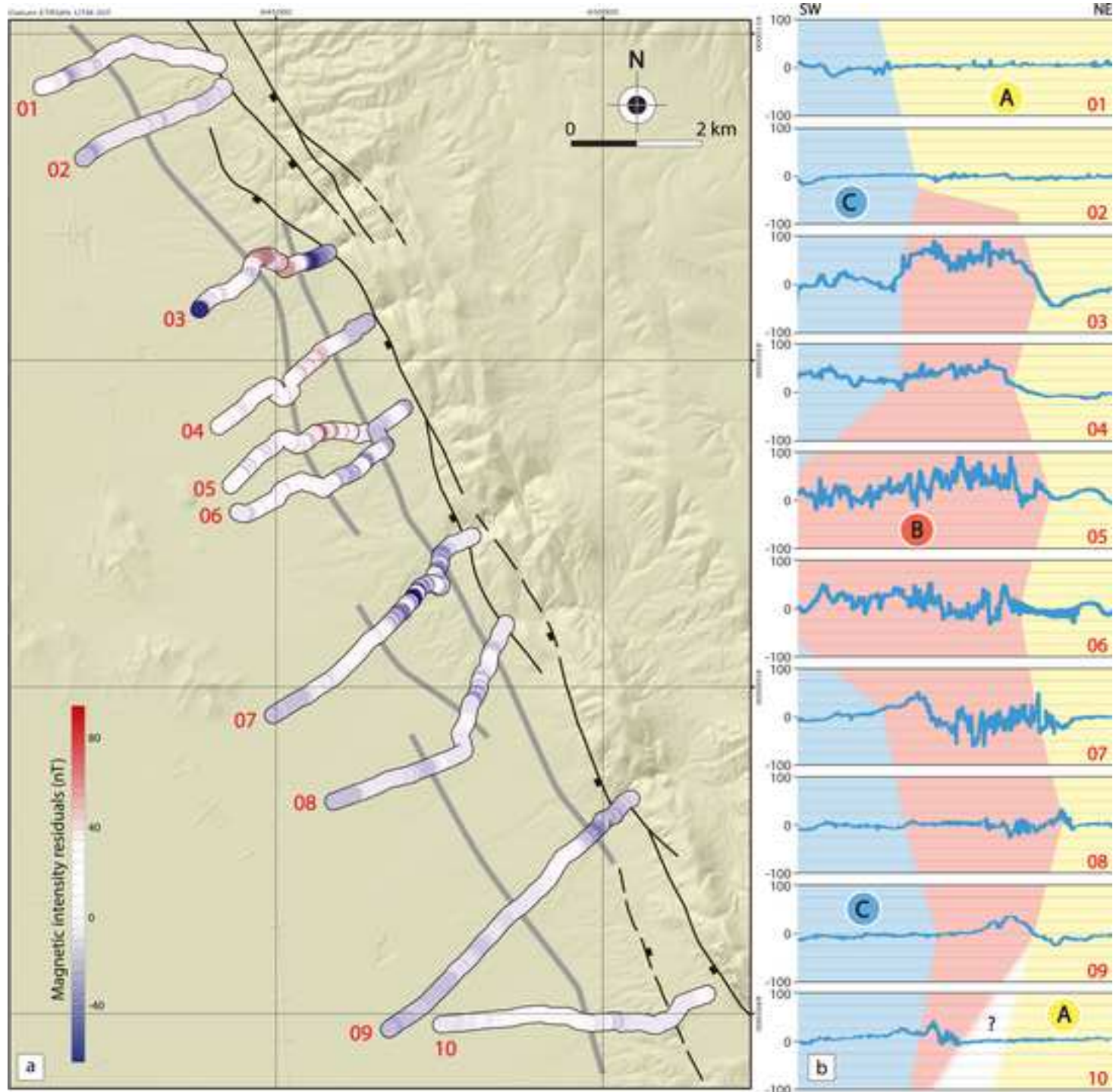


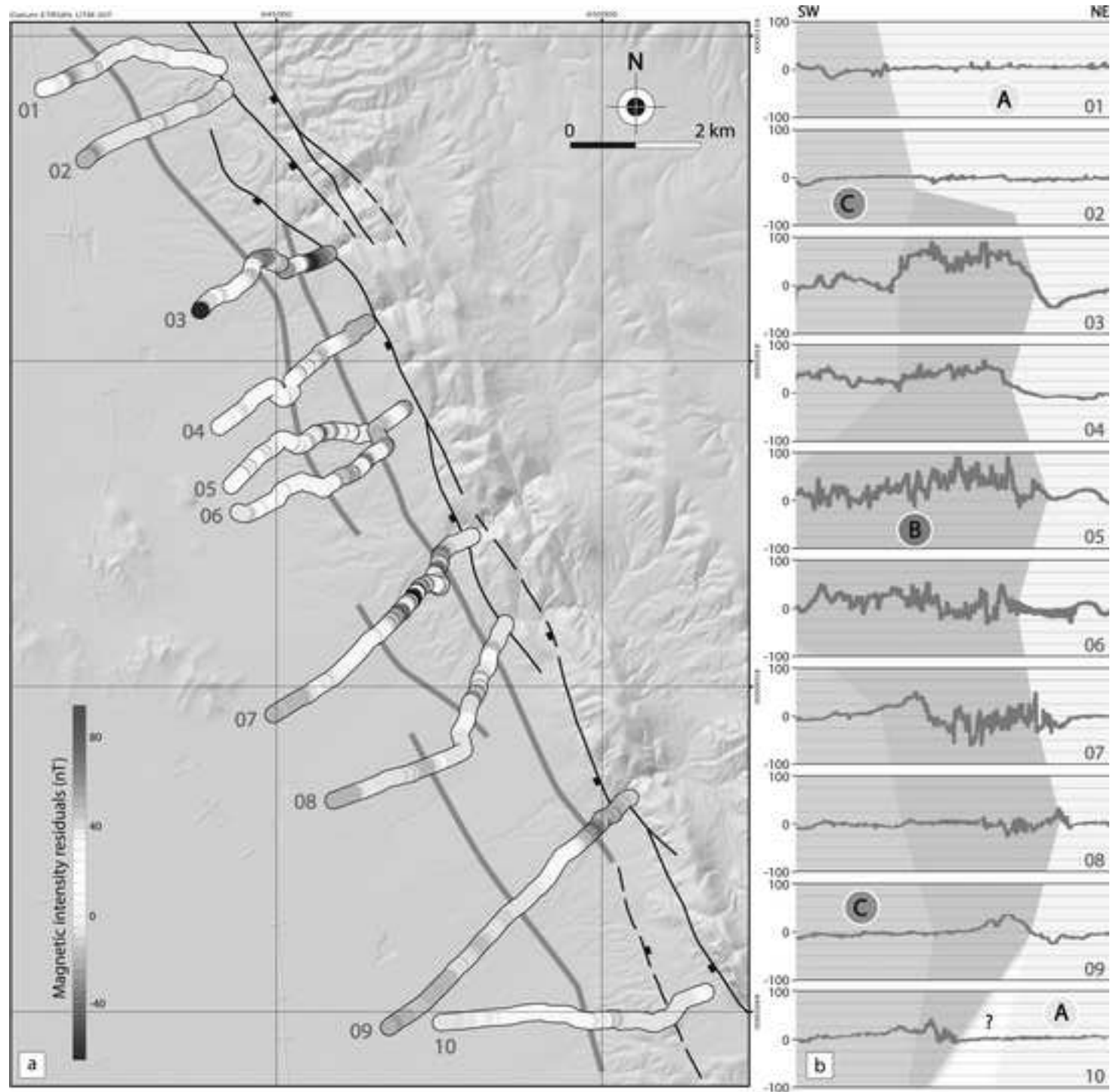
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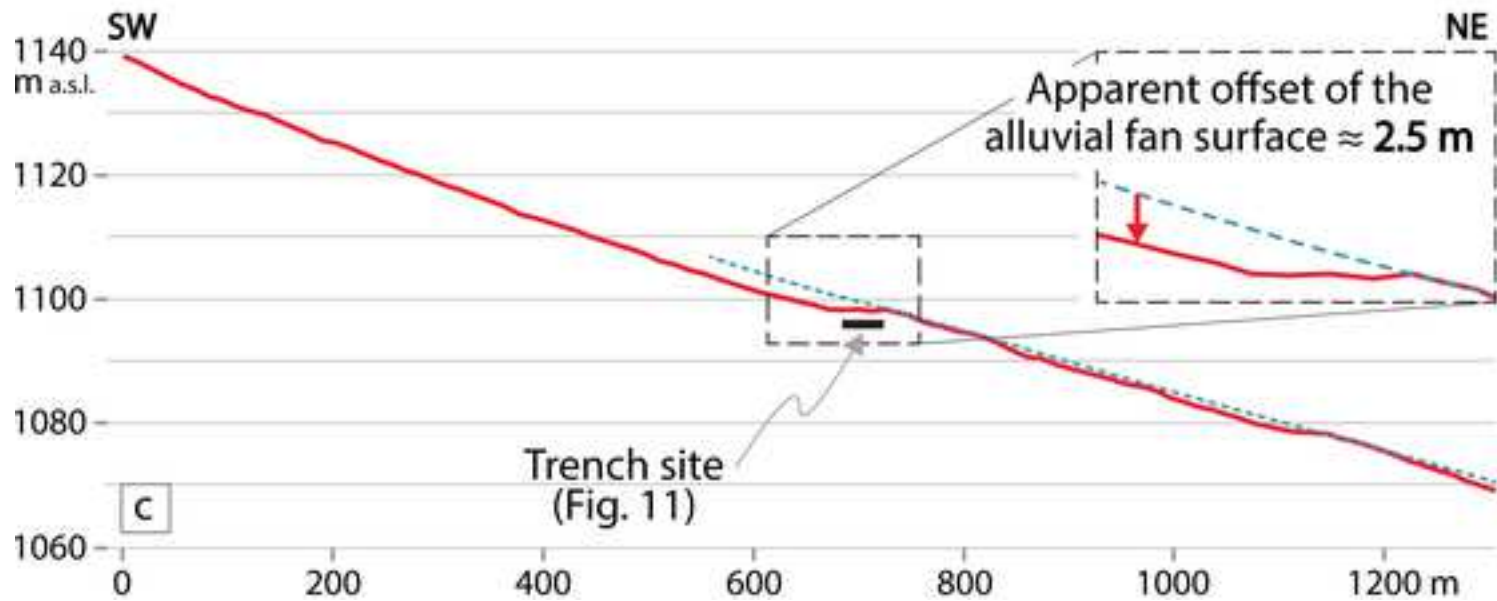
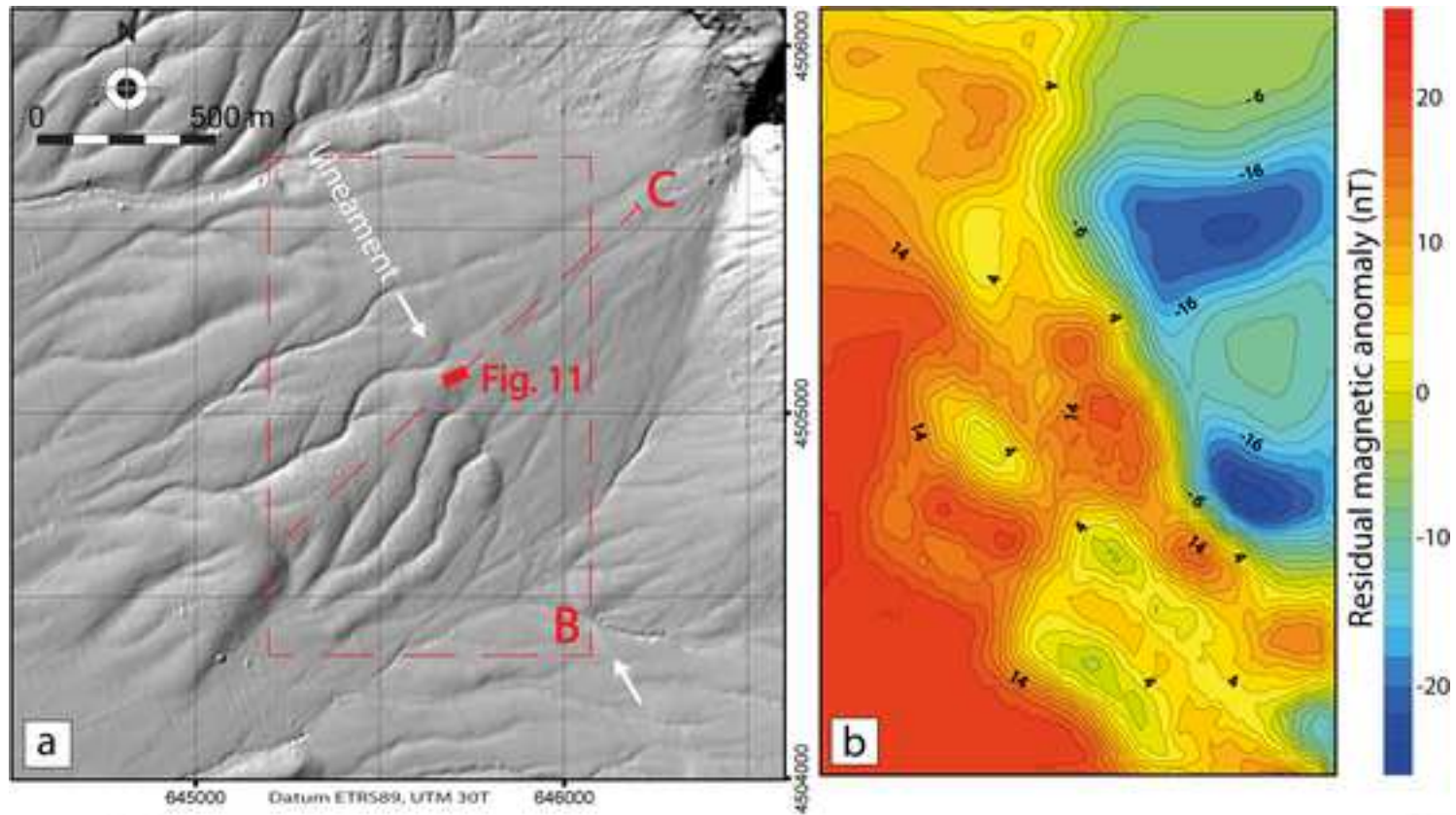


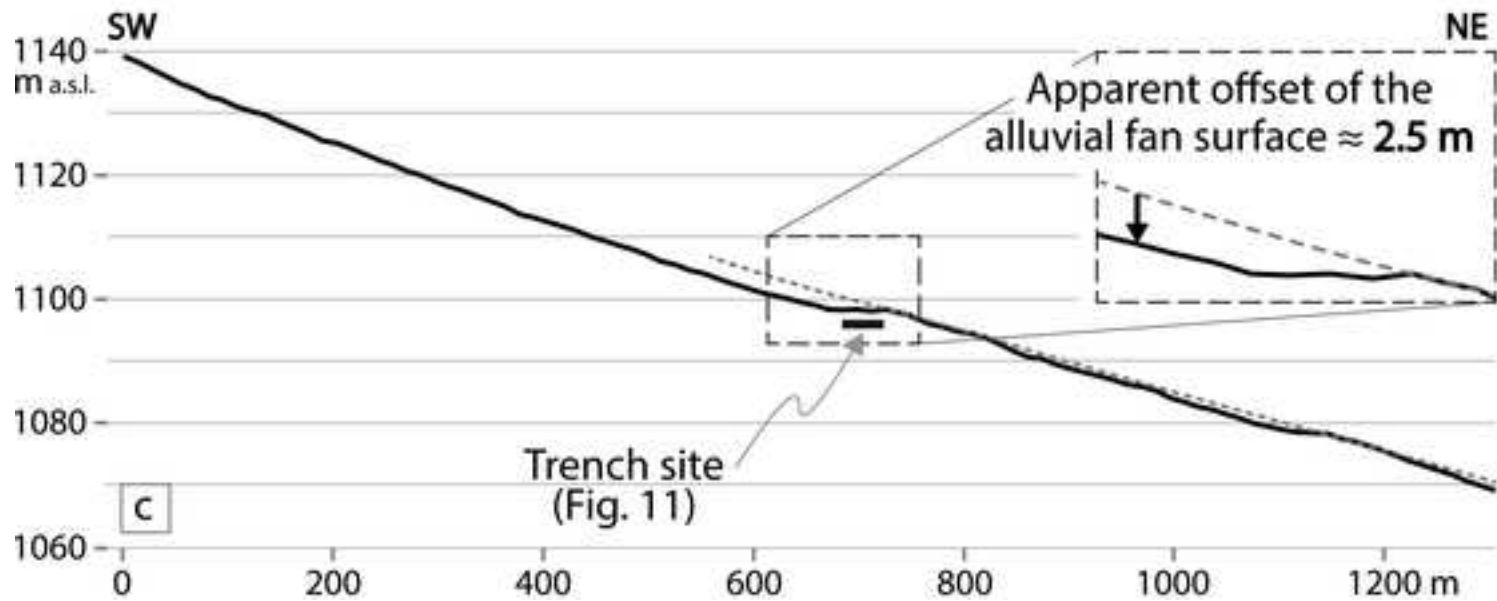
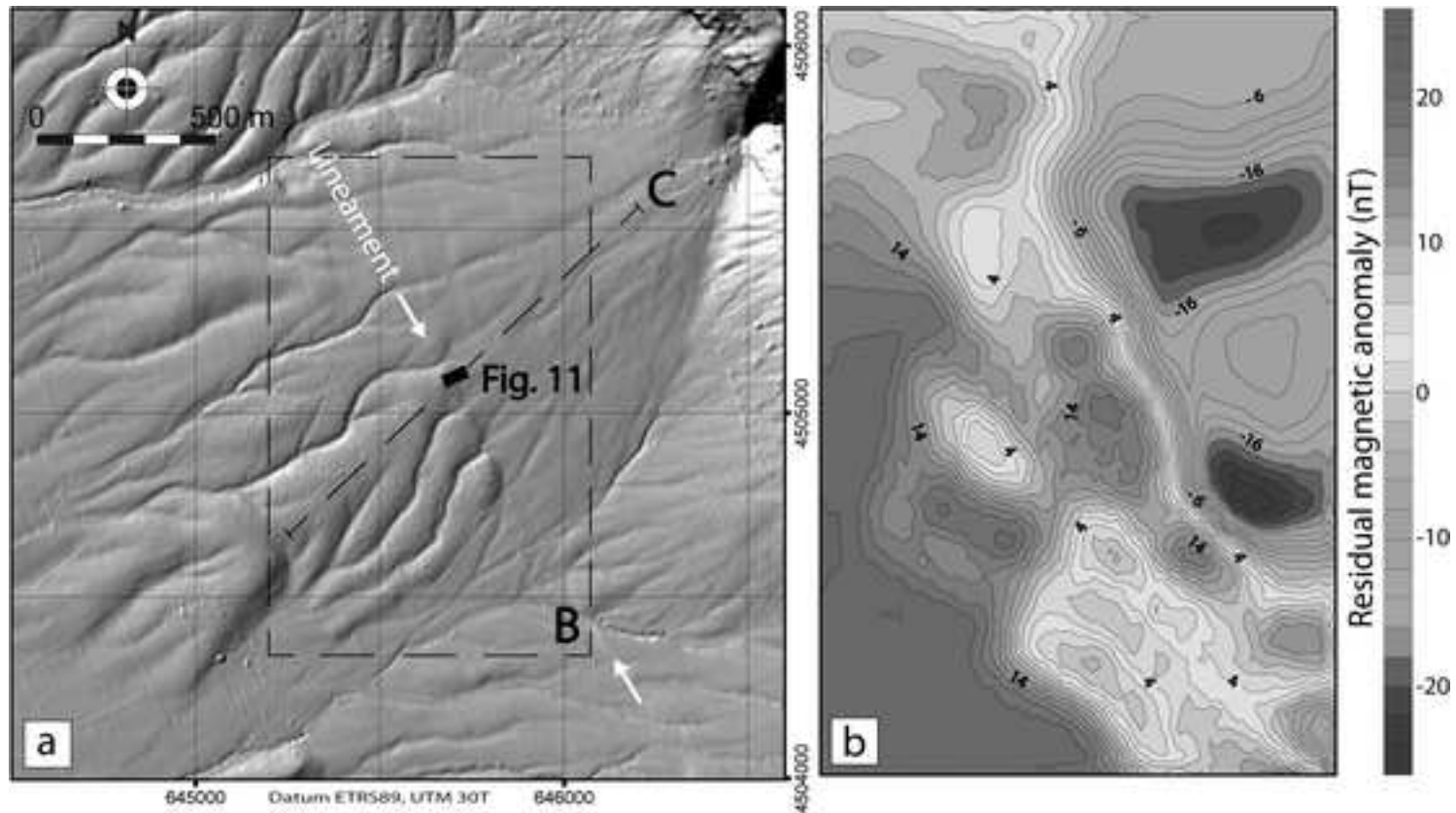




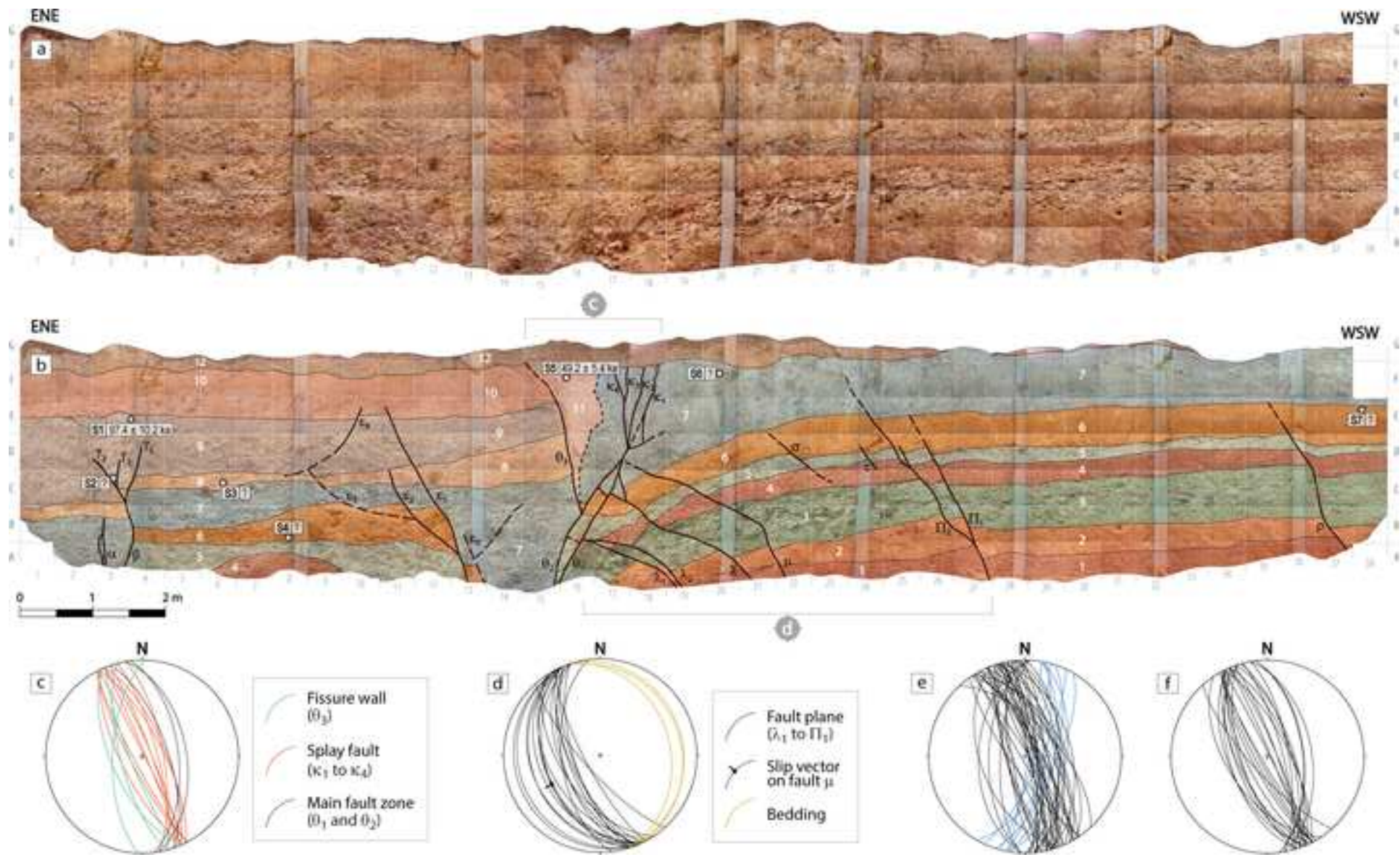


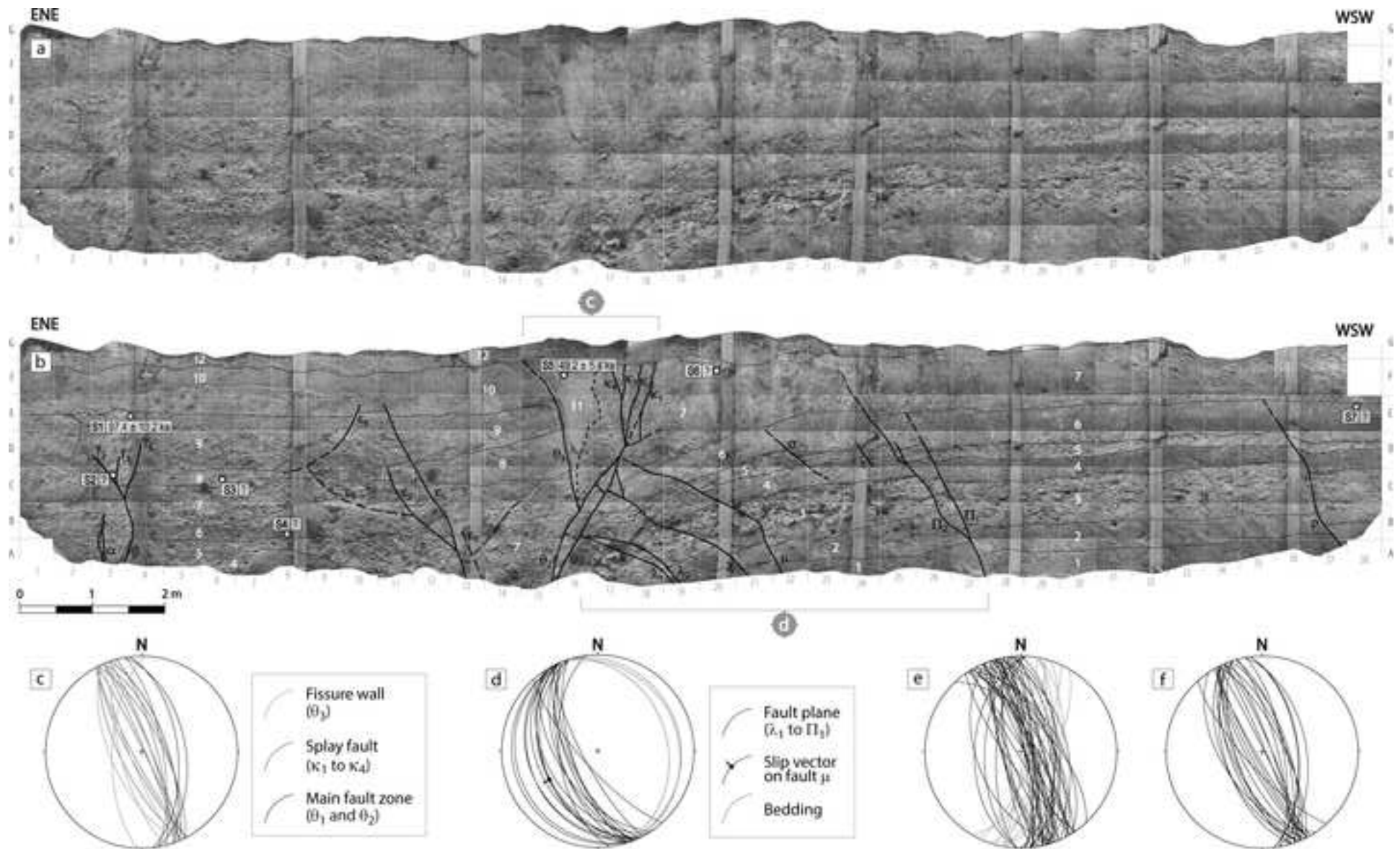


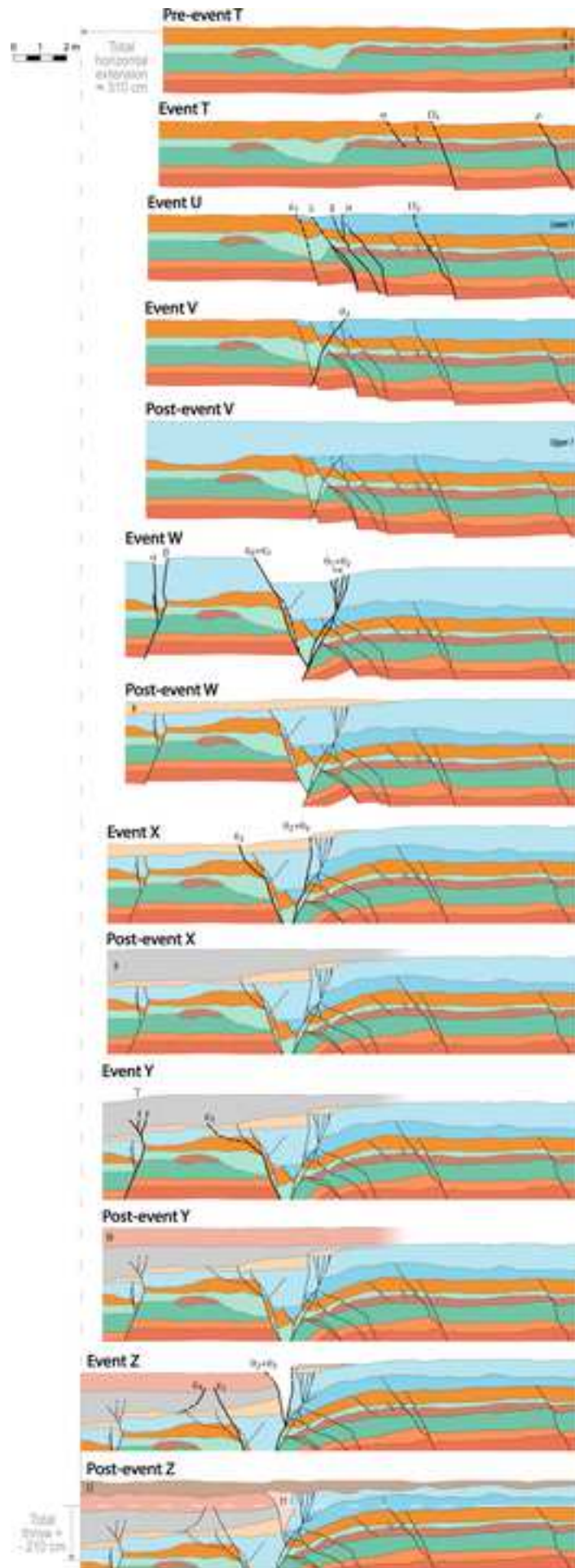


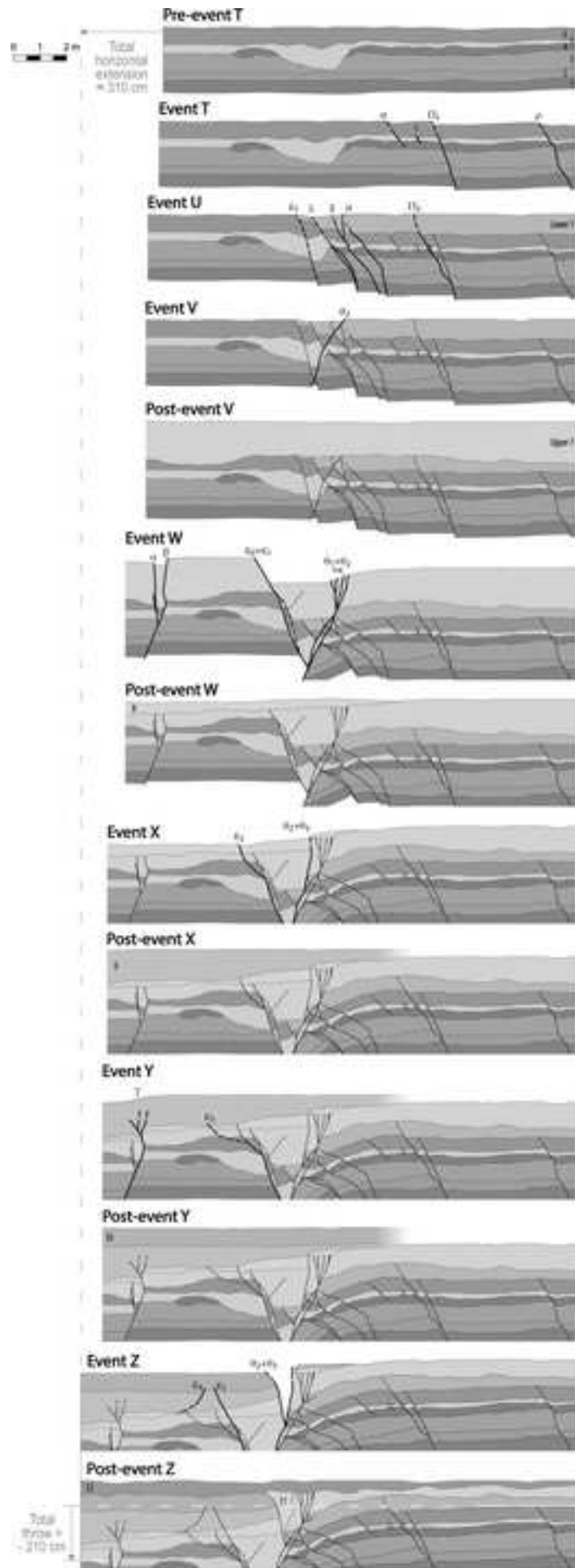












**Declaration of interests**

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

### **CRedit author statement**

**A. Peiro:** Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization; **J.L. Simón:** Conceptualization, Validation, Investigation, Writing - Original Draft, Supervision; **L.E. Arlegui:** Investigation, Visualization; **L. Ezquerro:** Validation, Investigation; **A.I. García-Lacosta:** Formal analysis, Investigation, Visualization; **M.T. Lamelas:** Formal analysis, Investigation, Visualization; **C.L. Liesa:** Validation, Investigation, Writing – Review & Editing; **A. Luzón:** Validation, Investigation, Writing - Original Draft; **L. Martín-Bello:** Investigation; **Ó. Pueyo-Anchuela:** Investigation, Methodology, Formal analysis, Writing - Original Draft; **N. Russo:** Investigation, Visualization.