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Title: Assessing interaction of extensional active faults from structural and paleoseismological analysis: the Teruel and Concud faults (eastern Spain)

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Abstract: The relationship of independence, interaction or linkage between two neighbouring intraplate active extensional faults, the Teruel and Concud faults, are investigated from structural and paleoseismological data, and the results are discussed to improve seismic hazard assessment for the region. This paper provides the structural and paleoseismological characterization of the almost unknown Teruel Fault from detailed mapping and trench analysis, and discusses its kinematic and kinematic relationships with the Concud Fault. Four individual events occurred between 76.0 ka and 9.2 ka BP have been recorded at two branches of the Teruel Fault. Unfortunately, these only represent a small fraction of its overall activity during such time lapse, and their time constraints do not allow correlating them with those at the Concud Fault. The Teruel and Concud faults are independent structures from the geometric and kinematic point of view, as evinced by their distinct (i) transport directions (N275°E and N220°E, respectively), and (ii) average coseismic displacements (0.5 m and 1.9 m, respectively). These displacements are consistent with their respective lengths (9.0 km and 14.2 km) and significantly smaller than those expected for a hypothetically joint Concud-Teruel, 23 km-long fault. However, their displacement gradients close to the relay zone indicate that both faults undergo dynamic interaction, thus suggesting a transient stage from independence to linkage. We hypothesize that slip on both structures occurred, at the scale of the seismic cycle, in a broadly alternating manner, which induced strain partitioning between them and allowed accommodating bulk biaxial extension in the region. Such deformation pattern would have increased the earthquake frequency with respect to the scenario of a hypothetically linked Concud-Teruel Fault, but diminished the potential seismic magnitude.

COVER LETTER Paper SG-D-17-00002

Dear Editor:

Herewith, we send the revised version of our work entitled “Assessing interaction of active extensional faults from structural and paleoseismological analysis: the Teruel and Concud faults (eastern Spain)”, according to suggestions made by the reviewers Drs. Nicol and Caputo.

Two versions of the manuscript are uploaded. One of them is a clean version with the changes already in place. The second one (marked version) details the changes done, with the following colour code:

- Yellow background: changes made according to referees' comments.
- Blue background: changes aimed to reduce the length of the manuscript, as required by the Editor. The main text has been shortened from 58,824 to 52,866 characters (10.1%), bibliography from 13,692 to 13339 (2.6%), and Appendix 1 from 6661 to 5649 (15.2%).

Most suggestions annotated on the manuscript by both reviewers have been considered. This has greatly improved the text; we are very grateful to them for their intense work with this respect.

Next we add some comments to a number of referees' suggestions. Some of them refer to proposals that we have not assumed; in such cases, we explain our reasons for keeping the original text. Line numbers in the first version of the manuscript have been used for reference.

Answers to comments by Reviewer 1 (A. Nicol):

- Lines 270-282. In our opinion, relay ramps are a geometrical result of fault relay arrangement, independently on the kinematics of each individual fault. Therefore, it does not involve kinematic interdependence between faults, and the opening sentence of this paragraph can be kept.
- Line 308. We substitute 'Overall' by 'Preliminary' in the title, but we cannot write just 'Paleoseismicity of the Concud Fault' because only preliminary paleoseismological assessing is included in this section.
- Lines 322-324. We prefer to keep this paragraph in its present location, as it deals with an aspect of the preliminary paleoseismological characterization, and it refers to numerical results also shown in Table 1.
- Lines 390-392: We cannot follow the suggestion by the reviewer because it would produce a longer and somehow ambiguous sentence (the ambiguity concerns the timing of the six mentioned units).
- Lines 498-499: O.K., we remove the argument of cross-cut relationships, which was not quite solid and was very laxly stated.

- Lines 546-554: It is true that our estimates of coseismic slip values are minimums, but all of them are significantly lower than that provided by Stirling's empirical correlation. We believe that the essential of the sentence should be kept, although minor changes to text style are accepted.

- Line 619: We believe that such transport direction is anomalous, but not 'inconsistent' with connection of the Las Ramblillas faults to the Teruel fault. Indeed, we describe a case in the Conclud fault surface where a second striation oriented towards NW overprints the SW-oriented prevailing striation, therefore recording such an 'anomalous' movement on the main fault.

- Line 622: We prefer to write 'striation' as a singular name (an striation is a set of parallel striae or slickenlines), in order to avoid confusion when we refer to two or more sets of striae exhibiting distinct rakes on the fault surface. In this second case we talk about several 'striations' (plural).

Answers to comments by Reviewer 2 (R. Caputo):

- Lines 194-200: Rephrasing as suggested by the reviewer and removing the reference to *stress partitioning* change the sense of the sentence. We believe that such changes are not adequate, hence we prefer to keep the original text. Nevertheless, we find opportune referring here to a publication (suggested by R. Caputo for being included in Section 8.6, but useful as well for this one) that deals with a similar stress setting in the Italian Alps.

- Abstract and lines 206, 256-257, 303: the 'transport direction' (trend of the slip vector on a fault or shear zone, as usual in Structural Geology) is conceptually different from the 'stretching direction' (trend of the X axis of the strain ellipsoid). In our case, we deal with transport directions s.s. on faults and we should kept this term.

- Line 326 (and others throughout the manuscript): 'mid Pliocene' means 'approximately in the middle of the Pliocene'. We avoid 'Middle Pliocene' since this division does not officially exist.

- Lines 325-329: It is true that a very long-term average slip-rate as that calculated since 3.6 Ma B.P. is not the optimum in this case. Nevertheless, it is the only reliable rate available for the fault prior to the present research, therefore the only one that should be used for this 'preliminary characterization'.

- Line 422: In the same way as discussed for the transport direction on a fault, the 'movement plane' of a fold (plane orthogonal to the fold axis) is conceptually different from 'shortening direction'. We keep 'movement plane'.

- Lines 435-441: We agree with Dr. Caputo's comment about the computed number of paleoseismic events. We minimize the importance of event(s) previous to Pleistocene sediments in trenches Pitraque 1 and Pitraque 2; we explain that it

(they) could actually represent a succession of several seismic episodes, either Pleistocene or even Pliocene in age; we denote it as 'Event 0' in Section 8.1; and we do not use it when the average recurrence period is estimated.

- Lines 451-453 (also 430-432): Concerning bending of units 4-5 in trench Pitraque 1, we have smoothed the inference of a relationship with fault F δ , and we generically refer to 'a hypothetical underlying, blind fault'.

- 483-484: We explain in more detail our interpretation of reactivation of a previous structure from analysis of splay faults linked to a fault tip.

Highlights:

Teruel and Concul faults: independent structures, but undergoing dynamic interaction

Four paleoseismic events recorded at the Teruel Fault since 70.7 to 9.9 ka BP

Hypothetical alternating slip on both faults would involve strain/stress partitioning

Higher earthquake frequency, but lower seismic magnitude than a full linked fault

1 • **Assessing interaction of active extensional faults from structural and**
2 **paleoseismological analysis: the Teruel and Conclud faults (eastern Spain)**

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19 **Key words:** fault linkage, fault relay, intraplate extension, paleoseismicity, seismic hazard,

20 Teruel Basin.

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24 **Abstract**

25 The relationship of independence, interaction or linkage between two neighbouring
26 intraplate active extensional faults, the Teruel and Concud faults, are investigated from
27 structural and paleoseismological data, and the results are discussed to improve seismic
28 hazard assessment for the region. This paper provides the structural and paleoseismological
29 characterization of the almost unknown Teruel Fault from detailed mapping and trench
30 analysis, and discusses its kinematic and kinematic relationships with the Concud Fault.
31 Four individual events occurred between 76.0 ka and 9.2 ka BP have been recorded at two
32 branches of the Teruel Fault. Unfortunately, these only represent a small fraction of its
33 overall activity during such time lapse, and their time constraints do not allow correlating
34 them with those at the Concud Fault. The Teruel and Concud faults are independent
35 structures from the geometric and kinematic point of view, as evinced by their distinct (i)
36 transport directions (N275°E and N220°E, respectively), and (ii) average coseismic
37 displacements (0.5 m and 1.9 m, respectively). These displacements are consistent with their
38 respective lengths (9.0 km and 14.2 km) and significantly smaller than those expected for a
39 hypothetically joint Concud-Teruel, 23 km-long fault. However, their displacement gradients
40 close to the relay zone indicate that both faults undergo dynamic interaction, thus suggesting
41 a transient stage from independence to linkage. We hypothesize that slip on both structures
42 occurred, at the scale of the seismic cycle, in a broadly alternating maner, which induced
43 strain partitioning between them and allowed accommodating bulk biaxial extension in the
44 region. Such deformation pattern would have increased the earthquake frequency with
45 respect to the scenario of a hypothetically linked Concud-Teruel Fault, but diminished the
46 potential seismic magnitude.

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49 **1. Introduction**

50 In the last few decades, great efforts have been made to improve our understanding of
51 the geometric interaction and linkage of segments of extensional fractures and normal faults
52 showing overlapping or en-échelon arrays (e.g., Gibbs 1984; Childs et al., 1995; Nicol et al.,
53 1996; Ferrill et al., 1999; Peacock, 2002; Walsh et al., 2003; Fossen and Rotevatn, 2016).
54 Recognition of linked en-échelon fault systems in the early stages of development is critical
55 in seismic hazard assessment because seismic hazard analyses rely also on the ability to
56 predict whether an earthquake will terminate at a fault tip or propagate onto adjacent faults
57 (Ferrill et al., 1999; Wesnousky, 2008; Biasi and Wesnousky, 2016).

58 In moderately active intraplate areas, the historical seismic record is not long enough
59 to include large earthquakes, owing to their large average recurrence intervals. Therefore, to
60 reconstruct the true seismic history of faults, it is necessary to rely on paleoseismological
61 studies (McCalpin, 1996; Caputo et al., 2008). Paleoseismology also provides additional
62 information about fault kinematics: the pattern of incremental or ‘infinitesimal’ slip on
63 individual faults, and hence the possibility of approaching the progressive bulk deformation
64 of a tectonically active area.

65 This study assesses the state of geometric, kinematic and dynamic interaction of two
66 neighbouring active faults, the Teruel and Concud faults, and discusses its influence on
67 seismic hazard assessment for the region. These faults are located at the junction of the
68 Teruel and Jiloca grabens (Fig. 1), which represent the largest Neogene-Quaternary
69 extensional basins in the intraplate Iberian Chain (eastern Spain). The west-dipping Concud
70 and Teruel faults strike NW-SE and N-S, respectively, and show a right-stepping
71 arrangement with a 1.3 km-wide relay zone (Fig. 2a). The Concud Fault, the best
72 documented active structure in the region, is expressed in the relief by a prominent scarp. It
73 is located in the southern sector of the Jiloca Graben, and shows paleoseismological
74 evidence of recurrent activity during Late Pleistocene (Lafuente, 2011; Lafuente et al.,
75 2011a, 2014; Simón et al., 2012, 2016).

76 While the paleoseismological behaviour of the Concud Fault is reasonably established,
77 the Teruel Fault remain almost unknown. Most of the Teruel Fault trace, somehow
78 “invisible” through the local landscape, mainly crosses Neogene units, while Quaternary
79 deposits along its trace are very scarce. Such differences between the Concud and Teruel
80 faults are due to their distinct morpho-sedimentary setting during Pleistocene times.
81 Sedimentary aggradation dominated at the hanging-wall block of the Concud Fault (alluvial
82 fans making the piedmont of the Concud mountain front); on the contrary, downcutting of
83 the drainage network (Alfambra and Turia rivers) in both the footwall and hanging-wall
84 blocks of the Teruel Fault caused the lack of deposition. Therefore, the geological record of
85 its Quaternary activity is expected to be much poorer than that of the Concud Fault.

86 Based on the proximity of the Teruel and Concud faults (Fig. 2a), Gutiérrez et al.
87 (2012) have suggested that they make a single seismogenic structure (Concud-Teruel Fault),
88 which would therefore involve the possibility of larger earthquakes than those generated by
89 each separate structure. However, previous macro and mesostructural data indicate that they
90 are independent structures from the geometric and kinematic point of view (Lafuente, 2011;

91 Lafuente et al., 2011b), therefore our hypothesis is that they are also seismically
92 independent.

93 This paper presents the paleoseismological characterization of the Teruel Fault based
94 on the results obtained in three trenches, together with a comprehensive structural study.
95 The paleoseismic data will contribute both to evaluate seismic hazard and to discern the
96 kinematic and kinematic relationships between the Conclud and Teruel faults on short time
97 scales. Our specific objectives are:

98 (1) Characterizing the structure and kinematics of the Teruel Fault, estimating its slip
99 rates for different time intervals.

100 (2) Reconstructing the paleoseismological record of the Teruel Fault, and comparing it
101 with that of the nearby Conclud Fault. Additionally, analysing the representativeness of such
102 paleoseismic record taking into account the morpho-sedimentary framework.

103 (3) Understanding the geometric, kinematic and dynamic interactions between the
104 Conclud and Teruel faults. In particular, examining their hypothetical structural linkage (and
105 hence their potential joint activity as a single seismogenic structure) vs. hypothetical strain
106 partitioning through independent, commonly alternating slip events on both of them.

107 (4) Discussing the implications for seismic hazard assessment.

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109 **2. Methodology**

110 In order to evaluate Quaternary activity of the Teruel Fault, three explorative trenches
111 were excavated across the fault. Ideal trench locations are those where recent sediments are
112 affected by the fault, so that a geological record is present at least in the hanging-wall block
113 enabling us to identify the sequence and timing of seismic events. Following a general
114 survey of the fault, a study area (Pitraque-Valdelobos area; Fig. 2a) was selected in the
115 central-southern sector, where the main fault splits into distinct branches. This area contains
116 the only remnants of Quaternary sediments extending across the fault zone.

117 A detailed geological map of this area was made, based on field survey and
118 orthoimage analysis, complemented with low-height aerial photographs taken from a drone.
119 We also acquired topographic data: GPS coordinates (using a Garmin Oregon 450 device);
120 height measurements for controlling the position of critical markers (Nikon hypsometer
121 Forestry 550 pro); a laser-level (Leica Sprinter 100) profile along the Rambla de Valdelobos
122 talweg across the Teruel fault zone, in order to check the hypothesis of a topographic drop.

123 Once selected the location of the trenches, we applied the classical methodology
124 (e.g., McCalpin, 1996), which includes: excavating the trench; cleaning and gridding the
125 selected walls; identifying, interpreting and marking sedimentary units and structures; taking
126 a photograph and drawing a detailed log of each cell; analysing the relationship between
127 units and faults to identify individual events; and collecting samples for absolute dating,
128 especially those that pre- and post-date seismic events. Owing to clastic lithology of
129 sediments, the dating method was that based on Optically Stimulated Luminescence (OSL);
130 the samples were analysed in the Laboratorio de Datación y Radioquímica of Universidad
131 Autónoma de Madrid (Spain).

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3. Geological setting

135 The Neogene-Quaternary, NNW-SSE to NNE-SSW trending extensional basins of
136 the eastern Iberian Chain (Fig. 1) cut in an oblique direction, and postdate the Alpine
137 contractional structures (Vegas et al., 1979). The extensional faults represent the onshore
138 deformation linked to rifting of the Valencia Trough, which is accommodated by a listric
139 extensional fault system detached at a depth of 11-14 km (Roca and Guimerà, 1992).

140 The Teruel Basin, where the Teruel Fault is located, is a N-S to NNE-SSW trending
141 half graben (Fig. 1). Its active, eastern boundary shows prominent mountain fronts
142 separating the floor of the graben (usually at 800-1000 m a.s.l.) from El Pobo and
143 Javalambre massifs (around 1700 and 2000 m, respectively). The graben is filled with
144 Neogene alluvial deposits that grade basinwards into lacustrine carbonates and evaporites.
145 Several units based on either lithostratigraphy (Weerd, 1976; Godoy et al., 1983) or changes
146 in allocyclic factors (Alcalá et al., 2000; Ezquerro et al., 2014) have been defined, their ages
147 being constrained by mammal ages and magnetostratigraphy (Alcalá et al., 2000). The
148 informal units proposed by Godoy et al. (1983) are commonly used in maps of the Neogene
149 Teruel Basin: Rojo 1 (red clastics; Vallesian); Páramo 1 (white carbonates, Turolian); Rojo 2
150 (red lutites, Upper Turolian-Ruscinian); Páramo 2 (white carbonates, Ruscinian); and Rojo 3
151 (red lutites, Ruscinian-Villafranchian).

152 During the Late Pliocene-Quaternary the graben infill was excavated by the Alfambra
153 and Turia rivers and their tributaries. Four main fluvial terrace levels developed (Peña, 1981;
154 Godoy et al., 1983), some of them locally splitting into several sublevels (Sánchez Fabre,
155 1989; Moissenet, 1993; Simón et al., 2016). Table 1 compiles the available information on
156 the height and age of these terrace levels.

157 During graben development, the tectonic stress field evolved from: (i) triaxial
158 extension with minimum stress (σ_3) trajectories oriented WNW-ESE, prevailing during the
159 first, Late Miocene rift episode, to (ii) almost radial extension (σ_1 vertical, $\sigma_2 \approx \sigma_3$) with
160 nearly WSW-ENE trending σ_3 , prevailing during the second, Pliocene to Quaternary rift
161 episode (Simón, 1982, 1989; Capote et al., 2002; Arlegui et al., 2005). The latter has
162 remained active up to the present-day (Herraiz et al., 2000), although both WSW-ENE and
163 WNW-ESE σ_3 directions are recorded by fracture systems formed during the Pliocene and
164 Quaternary. In summary, this regional ‘multidirectional’ extensional stress field has been
165 partitioned (in the sense of Simón et al., 2008) into two stress systems, with S_{Hmax}
166 (maximum horizontal stress axis) nearly parallel to trends of the Jiloca and Teruel grabens,
167 respectively, and directly linked to the main tectonic stress sources during the Neogene-
168 Quaternary in eastern Spain: the intraplate NNW-SSE compression produced by Africa-
169 Iberia convergence, and the WNW-ESE extension induced by rifting at the Valencia trough
170 (Simón, 1989; Herraiz et al., 2000; Capote et al., 2002; Arlegui et al., 2005). A similar ‘time
171 dissociation’ of the overall stress field into distinct genetic stress systems (although in a
172 compressional setting) has been described in the Italian Alps as *Twist Tectonics* by Caputo et
173 al. (2010). Moreover, minor-order stress heterogeneities (deflection of stress trajectories,
174 veering to become either parallel or perpendicular to major faults; swapping between σ_2 and
175 σ_3 axes) are also frequent within this complex stress field (Simón, 1989; Arlegui et al.,
176 2005, 2006).

177 The Conclud Fault is a NW-SE trending, west-dipping fault, which shows an average
178 transport direction N220°E, has been active since the mid Pliocene, and totalizes a net slip of
179 255-300 m. Paleoseismological studies have been carried out on the Conclud Fault based on
180 analysis of five trenches (Lafuente, 2011; Lafuente et al., 2011a, 2014; Simón et al., 2016).
181 The results indicate that the fault underwent eleven events since ca. 74 ka BP, with an
182 average recurrence period of 7.1 to 8.0 ka (according to different hypotheses on the age of
183 the youngest recorded event; Simón et al., 2016). Timing of paleoearthquakes on the fault
184 has been constrained by a total of 37 OSL ages. The net accumulated slip during this time
185 interval was 20.5 m, with average coseismic slip of 1.9 m. The displacement pattern shows
186 alternating ‘fast periods’ (up to 0.53 mm/a) and ‘slow periods’ (0.13 mm/a), resulting in an
187 average slip rate of 0.29 mm/a. A potential moment magnitude up to $M_w = 6.8$ has been
188 estimated by Lafuente et al. (2011a) based on the empirical correlation proposed by Wells
189 and Coppersmith (1994), Stirling et al. (2002) and Pavlides and Caputo (2004). Recent

190 calculations made by Ezquerro et al. (2015) using the equation by Hanks and Kanamori
191 (1979), considering (i) a hypothetical rupture of the total length (14.2 km) up to a 14 km-
192 deep detachment level with an assumed dip angle of 60°, and (ii) the average coseismic slip
193 inferred from paleoseismological studies, renders $M_w = 6.6$.

194 Historic and instrumental seismicity of the Teruel Graben and the surrounding region
195 is low to moderate. There exists a moderate epicentre clustering along the Teruel Fault (see
196 e.g. Simón et al., 2016, fig. 2). Measured magnitudes (M_b) usually range from 1.5 to 3.5,
197 with maximum $M_b = 4.4$ in the Teruel Graben (data from Instituto Geográfico Nacional,
198 2010). Before the instrumental period, intensities up to VIII were recorded in the Teruel
199 Basin, and IV-V in the Jiloca Graben. Focal depths typically range from 5 to 15 km, at the
200 brittle layer above the basal detachment level identified by Roca and Guimerà (1992). Most
201 of the available focal mechanisms correspond to normal faults, and are consistent with the
202 regional recent stress field (Herraiz et al., 2000).

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205 **4. Structure and kinematics**

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207 *4.1. The Teruel Fault*

208 The Teruel Fault is a N-S striking, 9.0 km-long normal fault that offsets the Neogene
209 infill of the Teruel basin (Fig. 2a). In detail, it shows a single, N170°E trending trace in its
210 northern sector, while southwards it branches into two main fault traces trending N-S and
211 NNW-SSE, respectively. The latter, together with additional minor faults, progressively die
212 out in the red lutites of Rojo 2 unit and the coeval Castalvo gypsum succession.

213 The hanging-wall block shows a rollover structure reflected by tilting of the Páramo
214 2 unit (Figs. 2b, 3a). This unit exhibits an average dip of 2°E, its base decreasing in height
215 from 1010 m a.s.l. at the highest point to less than 880 m a.s.l. west of Teruel city. In the
216 footwall block, the base of the Páramo 2 unit lies at about 1130 m a.s.l., from which a
217 cumulative throw of ca. 250 m can be estimated. This displacement has been partially
218 accommodated by bending (perhaps, a monocline above a blind fault in a previous
219 evolutionary stage), with dips up to 17° at the east of the Teruel city. The combination of
220 rollover and monocline gives rise to a synformal sag parallel to the fault (Figs. 2b, 3a,b).

221 Field measurements of rupture surfaces within the Teruel Fault show average strike
222 close to N-S and dip ranging from 60° to 80° W (average: 68°; Fig. 2c,d). Striations observed

223 on the main fault surfaces indicate an almost-pure normal movement with average transport
224 direction towards N275°E.

225 Considering (i) the above calculated throw, (ii) the average fault dip, and (iii) a pure
226 normal movement, a net slip of ca. 270 m can be inferred for the base of the Páramo 2 unit.
227 Given an age of ~ 3.6 Ma (latest Ruscinian, Godoy et al., 1983; Opdyke et al., 1997; Alcalá
228 et al., 2000) for this stratigraphic marker, the long-term slip rate is ca. 0.075 mm/a.

229 *4.2. The relay zone between Teruel and Concud faults*

230 Surface structural information, together with results of geophysical (magnetic,
231 electromagnetic and georadar) surveys, suggest that the Teruel and Concud faults are
232 geometrically and kinematically independent structures (Lafuente et al., 2011b). These faults
233 do not show any evidence of a physical link: the northern tip of the Teruel Fault is located at a
234 distance of 1.3 km from the Concud Fault (Fig. 2a), and both have distinct hanging-wall
235 transport directions (N275°E and N220°E, respectively). They exhibit a right-stepping relay
236 geometry, their displacement being transferred by means of a relay ramp dipping towards N or
237 NNW, which can be clearly identified in Fig. 3a,b. Their displacement-length (D-L) profiles
238 show high displacement gradients approaching the relay zone (Fig. 3c), indicating sharp slip
239 transference between the faults. Further structural complexity at the relay zone occurs due to
240 the presence of a transverse faulted syncline (Mansuetos-Valdecebro syncline; Fig. 2a, 3a,b).

241 Although the northern tip of the fault is apparently located to the north of Teruel city,
242 there exist two sites aligned with the main trace where deformation structures affecting the
243 fluvial terrace T2b are exposed. These could hypothetically reveal a prolongation of the
244 Teruel Fault to the north, either at surface or as a blind fault (Figs. 2a, 3a). At Las Ramblillas
245 site, T2b is offset by two synthetic faults decametre-scale throw, and separated into two tilted
246 blocks where bedding dips up to 10° E and 18° E, respectively (Fig. 4). The western
247 synthetic fault has an average orientation 157, 48 W and striations that pitch 70°S. The
248 measured fault plane is nearly parallel to that of the southern Concud Fault, as well as to the
249 northern Teruel Fault (Fig. 2a). Cuesta de la Bajada site shows two main rupture surfaces
250 striking NNW-SSE, with minimum offsets of 7 m and 2.5 m, and associated rollover
251 monoclines that tilt T2b beds up to 28° E and 10° E, respectively (Peiro, 2016). If the
252 described deformation features actually represent the northwards propagation of the Teruel
253 Fault parallel to the adjacent Concud Fault after the Middle Pleistocene, its total length
254 would be more than 11 km.

255 The only misfit concerns the kinematics of Las Ramblillas faults. The transport
256 direction (N 218°E, inferred from a single striation measure) closely approaches the average
257 calculated for the Conclud Fault (N220°E; Lafuente et al., 2011a,b), and clearly differs from
258 that recorded for the entire Teruel Fault (N275°E; Fig. 2e). Nevertheless, the possibility of
259 occasional slip of one of these faults following the typical transport direction of the other
260 fault cannot be ruled out. Indeed, Lafuente et al. (2014) describe striations recording two
261 distinct movements along transport directions SW and WNW superposed on a single rupture
262 plane of the Conclud fault zone. This issue will be examined later when discussing strain
263 partitioning between these structures.

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5. Preliminary paleoseismological characterization of the Teruel Fault

268 Several empirical relationships allow the expected maximum moment magnitude
269 (M_w) of a fault and its associated coseismic displacement to be estimated. Those proposed by
270 Wells and Coppersmith (1994), Stirling et al. (2002), Pavlides and Caputo (2004), and
271 Mohammadioun and Serva (2001) have been applied in this study. Considering a length of
272 9.0 km for the Teruel Fault and applying the mentioned relationships, values of M_w ranging
273 from 6.1 to 6.6 are obtained (Table 2). For the coseismic displacement. Wells and
274 Coppersmith (1994) and Pavlides and Caputo (2004) correlations yield values of 0.40 m and
275 0.65 m, respectively, while that by Stirling et al. (2002) attains 1.32 m (Table 2). These
276 estimates will be later compared with real offsets measured in trenches. As mentioned above,
277 there exists the possibility of a prolongation of the Teruel Fault to the north, reaching a total
278 length of at least 11 km. If this length was considered, the inferred M_w values and coseismic
279 displacements would be a little higher (Table 2).

280 Combining the potential coseismic displacement based on empirical relationships
281 (0.37 m to 1.28 m, considering a 9 km-length fault) with the long-term slip rate calculated
282 since mid Pliocene times (0.075 mm/a; only reliable rate available for the fault prior to the
283 present research), a recurrence interval between 4.9 ka and 17.1 ka is tentatively approached.
284 If the fault were 11 km long, the recurrence periods would slightly increase (5.3-17.6 ka).

285

286 6. Detailed structure of the Pitraque-Valdelobos area

287 In the Pitraque-Valdelobos area the Teruel Fault cuts Quaternary deposits, so it has
288 been selected for trenching study. Puntal del Pitraque is a conical hill located 1.2 km south of

289 Teruel city, in the area where the Teruel Fault splits southwards into several synthetic fault
290 branches (M, N, P, Q, R, S in Fig. 5a; see location in Fig. 2a). A remnant of the lower
291 sublevel of the Middle Terrace (T2a) occupies the top of the hill. A larger remnant of the
292 same terrace appears on a horizontal platform some 100 m westwards. T2a unconformably
293 overlies Neogene units (Rojo 2 and Páramo 2), and had previously provided an OSL age of
294 76.0 ± 5.0 ka (Simón et al., 2012). The Rambla de Valdelobos is a gully transverse to the
295 Teruel Fault that drains westwards into the Turia River, and shows a relatively wide bottom
296 filled with Holocene clastic sediments.

297 The main Teruel Fault branch (M) crops out north of Puntal del Pitraque site (Fig.
298 5b), where it has an average strike N033°E and juxtaposes the Páramo 2 (hanging-wall
299 block) and Rojo 2 (footwall block) units. The other macro-scale faults are also clustered
300 around NNE-SSW (N024°E in average) and show westwards dip ranging from 52° to 84°
301 (68°W in average) (Fig. 5c,d). Each individual fault offsets several metres to several tens of
302 metres the Neogene beds. Together with the main fault and the monocline visible at the
303 footwall block, the total displacement accommodated across this transect is estimated at 190
304 m (Figs. 2b, 3a).

305 The top of Middle Terrace (T2a) at Puntal del Pitraque lies 8.2 m higher than that at
306 the western, horizontal platform (Fig. 5e). Such a height difference can be attributed to
307 displacement on fault branches M and N. The corresponding net slip, assuming the average
308 dip of the rupture surface (68°) and the inferred transport direction (N275°E), is ca. 8.8 m. If
309 the younger OSL age provided in the present work (46.5 ± 3.2 ka; Table 3) is assigned to the
310 terrace top, a slip rate of 0.19 ± 0.01 mm/a is obtained. Since the displacement is only
311 recorded at two (among five) synthetic branches within the fault zone, the total slip rate for
312 the overall structure should exceed this value. The absence of Quaternary deposits displaced
313 by the eastern branches of the fault makes impossible to test such hypothesis.

314 The primary target for our paleoseismological study was the M fault branch west of
315 Puntal del Pitraque. Two paleoseismological trenches (Pitraque 1 and Pitraque 2) were
316 excavated at this site, exposing Neogene lacustrine limestones and lutites unconformably
317 overlain by the Pleistocene materials. Detailed inspection after trench digging showed that,
318 within the M branch, the main observed fault surface (F_{μ}), locally striking N020°E to
319 N030°E, is cut by a second fault (F_{α}) striking N050°E, which is exposed in Pitraque 2 trench
320 and apparently extends below Pitraque 1 (Fig. 6a). In addition, a third fault striking N019°E
321 is exposed in Pitraque 2 (F_{β}) as well as at the natural terrace scarp. F_{β} constitutes the

322 prolongation of F_{μ} , but their physical linkage could not be observed in the field. The
323 described structural relationships suggest local segmentation of the main NNE-SSW fault
324 surfaces, these being articulated with (and their displacement being locally transferred to)
325 NE-SW striking faults. Fracture patterns observed at a mesostructural scale, both in trenches
326 and on natural outcrops (Fig. 6b,c,d,e), are consistent with the general structure of the
327 Pitraque-Valdelobos area, although the range of strike values (from NNE-SSW to ENE-
328 WSW) is wider than that expressed at macroscale (Fig. 5d).

329

330 **7. Trench study at the Pitraque-Valdelobos area**

331

332 *7.1. Pitraque 1 trench*

333 The Pitraque 1 trench was excavated for studying deformation associated to the main
334 branch of the Teruel fault zone (M in Fig. 5a,c). This trench trends N148°E, is 12.5 m long
335 and 4.5 m deep; its western wall was selected for detailed logging and analysis (Fig. 7a).
336 Neogene sedimentary units (Rojo 2 and Páramo 2) crop out in the lower part of the trench,
337 overlain by Pleistocene coarse clastic, materials that have been subdivided into six units (1 to
338 6 in Fig. 7a; see description in Appendix 1).

339 The largest deformation structure exposed in this trench is a gentle bending fold that
340 occupies most of the logged section shown in Fig. 7a. The geometry of the fold is continuous
341 along both the Pliocene and Pleistocene beds (units 2 to 5), which suggests that folding
342 essentially occurred after sedimentation of unit 5. The boundary between both lithological
343 successions represents an erosional discontinuity, not an angular unconformity.

344 The Páramo 2 unit is also deformed by a number of normal, NE-SW striking faults
345 (domain 4 in Fig. 7a) that make a rough conjugate system (Fig. 7e). The overlying
346 Pleistocene units in the northwestern sector are affected by numerous fractures also with an
347 average NE-SW strike (domain 2; Fig. 7a,c). These fractures include a few small faults with
348 centimetre-scale offsets, small closed joints, and a large tensile crack filled with carbonate
349 (C1 in Fig. 7a) that attains about 2 m in length and 20 cm in thickness. The fracture systems
350 affecting domains 2 and 4 are disconnected from each other; indeed, the only Pleistocene
351 fracture that could be rooted in a Neogene fault does not clearly show any physical linkage
352 with it (see cell 10c in Fig. 7a). Domain 1 shows the same types of faults and fractures as in
353 domain 2 (although in domain 1 these are mostly close to vertical; Fig. 7b), as well as a
354 second large open crack filled with carbonate (C2 in Fig. 7a). Finally, domain 3 contains a

355 number of small faults close to the Neogene-Pleistocene boundary. One of them (F_{γ}),
356 oriented NE-SW, produces an offset of about 0.1 m and propagates within the lower part of
357 Unit 2. The others are oriented NNW-SSE (Fig. 7d) and do not produce any visible
358 displacement.

359 Most fractures in the lower structural domains (3 and 4) express the prevailing
360 extensional fracture pattern in the region, represented by sets oriented NNW-SSE and NNE-
361 SSW. In contrast, most fractures within domains 1 and 2 seem to be induced by local
362 deformation conditions, i.e. the bending fold. This interpretation is based on two pieces of
363 evidence: (i) most of the fractures are concentrated within the outer arc at the hinge zone
364 (cells 9d and 10d in Fig. 7a); (ii) the movement plane of the bending fold, as defined by
365 poles of bedding (Fig. 7f), is nearly orthogonal to NE-SW fractures of domains 1 and 2
366 (including cracks C1 and C2, which accommodate an important part of stretching affecting
367 units 3, 4 and 5 in the outer arc). Although at present most of these fractures dip towards SE,
368 they probably originated as nearly vertical fractures, as can be inferred by restoring bed
369 tilting. The genetic dependence of these fractures with respect to local bending, as well as
370 the rheological contrast between Pleistocene cemented clastic deposits and Neogene
371 carbonates, could explain why the fracture systems affecting domains 2 and 4 appear to be
372 independent from each other. Bending, and hence the associated tensional fractures, could be
373 related to movement on an underlying blind fault.

374 Considering the structural relationships between faults and sedimentary units, as well
375 as their OSL ages (Fig. 7a; Table 3), three paleoseismic events have been identified:

376 - **Event(s) X_{P1}** . Interpreted by the rupture and displacement (not quantified) of
377 Neogene materials along fault F_{α} , and maybe other faults in domain 4, prior to local
378 sedimentation of the Pleistocene terrace. More than one paleoearthquake could have resulted
379 in such faulting, but they cannot be distinguished. This event (or events) occurred before
380 70.7 ± 5.3 ka BP (earliest OSL age obtained in the lower part of Unit 1). From the geologic
381 record in the trench, it is not possible to estimate the associated displacement.

382 - **Event Y_{P1}** . Interpreted by the rupture along a small fault (F_{γ}), which produces a
383 throw of 0.1 m at the base of the Pleistocene Unit 2. Predated by the upper part of Unit 1
384 (OSL age of 70.7 ± 5.3 ka BP) and postdated by overlying materials of Unit 2 (OSL age of
385 71.8 ± 5.1 ka BP).

386 - **Event Z_{P1}** . Represented by bending of Neogene (R2, P2) and Pleistocene (2, 3, 4, 5)

387 units and development of associated tensional fractures, including opening of cracks (C1 and
388 C2) subsequently filled with carbonate. This event is predated by the youngest available OSL
389 age (48.5 ± 3.8 ka BP; middle-upper part of Unit 5), and postdated by the regolith (Unit 4,
390 probably Holocene in age). Considering the amplitude of the bending fold, a minimum
391 coseismic throw of 1.0 m is estimated on a hypothetical underlying, blind fault (coseismic
392 net slip >1.1 m for a 70° dipping plane).

393

394 7.2. Pitraque 2 trench

395 Pitraque 2 trench also exposes the main branch of the Teruel fault zone (M in Fig.
396 5a,c). It trends $N133^\circ E$, is 7.5 m long and 2.5 m deep, the southwest wall being selected for
397 study (Fig. 8a). As in Pitraque 1 trench, Rojo 2 and Páramo 2 Pliocene units underlie
398 Pleistocene conglomerates and sandstones, which have been subdivided into four units (1 to
399 4 in Fig. 8a); see description in Appendix 1).

400 Two main normal faults are exposed in Pitraque 2 trench. To the northwest, fault $F\alpha$
401 (domain 2; Fig. 8a,d), locally striking $N035^\circ E$, offsets the Neogene units sinking its NW
402 block and being responsible for erosion of Páramo 2 unit at the SE one; then $F\alpha$ is overlain
403 by non-affected Pleistocene deposits. To the southeast, $F\beta$ ($N019^\circ E$) offsets Pleistocene units
404 1, 2 and 3, producing the same throw (0,5 m) on each of them, and splits upwards into
405 several splay faults (domain 1, Fig. 8a,b,c). The association of splay faults to the main fault
406 makes a *horse tail* structure (as defined by Granier, 1985), which is interpreted to be the
407 product of local stretching close to the fault tip while fault $F\beta$ was activated and propagated
408 through the overlying Pleistocene deposits. This fracture system is also exposed on the
409 opposite trench wall, with the same NNE-SSW to NE-SW strike and exhibiting pure-normal
410 striations on the main fault $F\beta$ (Fig. 8e). Finally, a tensile crack filled with carbonate (C3),
411 similar to C1 and C2 of Pitraque 1 trench, overprints this system of splay faults. Although
412 included within the main fault zone, C3 represents a kinematically distinct deformation
413 pattern. Its opening vectors, with homogeneous length about 2-3 cm, are nearly orthogonal to
414 the crack walls (Fig. 8a,b). Such a displacement pattern does not fit slip parallel to fault $F\beta$,
415 and instead is consistent with tangential stretching at the outer arc of an accommodation
416 monocline.

417 Three paleoseismic events have been interpreted (Fig. 8a; Table 3):

418 **Event(s) X_{P2}**. As in the case of Event X_{P1}, deformation previous to deposition of the
419 observed Pleistocene units is attributed to a first local event, although it may represent more
420 than one paleoearthquake. Two inferred fault movements can be assigned to such a
421 ‘composite’ X_{P2} event: (i) movement of F β that cut the Neogene Rojo 2 unit previously to
422 deposition of Unit 1, therefore before 78.3 ± 5.2 ka BP; its associated *horse tail* structure (a
423 fracture pattern typically found at extensional fault tips) involves activation of a blind, pre-
424 existent fault through the overlying Pleistocene deposits; (ii) rupture and displacement of
425 Rojo 2 and Páramo 2 units along fault F α , as well as northwards tilting, previous to $50.0 \pm$
426 3.4 ka BP (age of the base of Unit 2, not affected). Since F α is also exposed in Pitraque 1
427 trench, where it is postdated by OSL 70.7 ± 5.3 ka BP, we can assume this time constrain for
428 it. These two fault movements cannot be chronologically distinguished and their associated
429 displacements remain unknown.

430 **Event Y_{P2}**. Rupture and displacement of Pleistocene units 1, 2, and 3 along fault F β
431 and its associated splay faults. Predated by the youngest OSL age available in the trench, at
432 the base of Unit 3 (46.5 ± 3.1 ka). The associated coseismic slip along fault F β can be
433 estimated at 0.5 m.

434 **Event Z_{P2}**. Represented by opening of tensile crack C3, which was subsequently
435 filled with carbonate. As with the previous event, this one is predated by the youngest
436 available OSL age (46.5 ± 3.1 ka), and postdated by the regolith (Unit 4, probably Holocene
437 in age). We infer that the Z_{P2} event is distinct from the former event based on the kinematic
438 differences between the tensile crack and the structures linked to Event Y_{P2}. The geometry of
439 deformation does not permit measurement of coseismic slip.

440

441 7.3. Valdelobos trench

442 This N100°E trending trench was excavated in the T0 terrace of Rambla de
443 Valdelobos south of Puntal del Pitraque, where the gully apparently crosses the fault branch
444 P (Fig. 5a), and its talweg exhibits a discrete gradient anomaly inferred from the laser-
445 levelling profile (Fig. 5f). An exposure of around 5 m long and 2.5 m deep along the
446 southern wall of the trench was studied in detail. The trench shows massive red Neogene
447 lutites (Rojo 2) at its base, which are covered by Quaternary clastic deposits subdivided into
448 five units (1 to 5 in Fig. 9; see description in Appendix 1).

449 The Neogene materials are displaced by a normal fault (F_{ϵ}) striking N155°E (Fig. 9).
450 This fault also affects the lowermost Quaternary deposits (Units 1 and 2), and is covered by
451 Unit 3. The minimum fault throw is 0.3 m, but it could be much larger since the fault scarp
452 was eroded below the base of Unit 2. A single event has been interpreted in this case,
453 referred to as **Event Z_{VL}** , occurred between 26.7 ± 1.9 ka BP (age of Unit 2) and 9.9 ± 0.7 ka
454 BP (age of Unit 3).

455

456 **8. Interpretation and discussion**

457

458 *8.1. Paleoseismic record of the Teruel Fault: correlation of events*

459 Correlation of events between the Pitraque and Rambla de Valdelobos trenches
460 (Table 4; Fig. 10) has been accomplished on the basis of geological judgement and OSL
461 ages. It can be conventionally assumed that Event(s) X is common to both Pitraque 1 and
462 Pitraque 2 trenches and inferred to be the same event (now renamed as Event 0): this event
463 only affects Neogene materials, exhibiting upper time limits 70.7 ± 5.3 and 78.3 ± 5.2 ka BP,
464 respectively, for each trench. We are aware that this event could actually represent a
465 succession of several seismic episodes, either Pleistocene or even Pliocene in age.
466 Considering the OSL ages that constrain their timing, Y_{P1} and Y_{P2} are interpreted as being
467 two independent events: Event 1, with absolute time brackets 76.0 and 66.7 ka BP (central,
468 most probable age: 70-71 ka BP), and Event 2, younger than 49.6 ka BP. Z_{P1} and Z_{P2} are
469 interpreted as a single event (renamed Event 3, younger than 49.6 ka BP), taking into
470 account their postdating OSL ages, the style of deformation (crack opening, subsequent
471 carbonate filling) and the orientation of coseismic fractures (around NE-SW in both cases).
472 Finally, Event Z_{VL} , only recorded at the Rambla de Valdelobos trench and therefore at a
473 different fault branch, represents the youngest event (renamed Event 4, with absolute time
474 brackets 28.6 and 9.2 ka BP).

475 In summary, the trench study has yielded one (or several) uncertain event prior to
476 73.1 ka BP, and four events occurred between 76.0-66.7 ka and 28.6-9.2 ka BP. This four-
477 event-succession yields an average recurrence period in the range of 9.5-16.7 ka.
478 Nevertheless, the individual interseismic periods remain unknown, as only the timing of
479 events 1 and 4 are constrained (quite widely in the case of the second one).

480 *8.2. Representativeness of the paleoseismic record of the Teruel Fault*

481 Events 1, 2 and 3 occurred on the western, main branch (M) of the Teruel Fault, while

482 Event 4 occurred on a minor branch (P; see map in Fig. 5a). Events 1, 2 and 3 represent a
483 minimum accumulated net slip of 1.7 m on branch M. The average coseismic slip for these
484 three events (0.57 m) lies close to the estimates made from the empirical correlations of
485 Wells and Coppersmith (1994) and Pavlides and Caputo (2004) (see section 5 and Table 2).
486 This suggests that (i) these correlation models better describes our data than that of Stirling
487 et al. (2002), and (ii) the recorded paleoseismic single event displacements approach the
488 *characteristic earthquake* of the Teruel Fault (in the sense of Schwartz and Coppersmith,
489 1984). If Event 4 is incorporated, the results do not change substantially: minimum net slip
490 on branches M+P (as recorded in trenches) will attain 2.0 m, with average coseismic slip of
491 0.50 m, and local slip rate of 0.04 ± 0.01 mm/a (Fig. 11d).

492 This paleoseismic succession only represents a fraction of the total activity on the
493 western branches of the fault system during the sampled time interval. It should be reminded
494 that the total offset of the fluvial terrace T2a represents a net slip of 8.8 m, with slip rate =
495 0.19 ± 0.01 mm/a for the last 46.5 ± 3.2 ka (Fig. 11d; see Section 6 and Table 5). Therefore,
496 only a small part of the paleoseismic history of the Teruel Fault during the studied time
497 window has been recorded in the studied trenches, and the calculated average recurrence
498 period (9.5 to 16.7 ka) has little meaning. Assuming the average coseismic slip of 0.57 m
499 and the accumulated net slip of 8.8 m, the total number of paleoseismic events on branches
500 M+N since 76.0 ± 5.0 ka BP could attain fifteen, with a shorter average recurrence period of
501 5.1 ± 0.3 ka (close to the minimum estimated from empirical correlation, 4.9 ka).

502 8.3. Comparison with the paleoseismic record of the Concud Fault

503 The paleoseismic results for the Teruel Fault can be compared with those previously
504 obtained on the neighbouring Concud Fault (Lafuente, 2011; Lafuente et al., 2011a, 2014;
505 Simón et al., 2016) in order to analyse the seismogenic dependence or independence
506 between them. At first glance, the recorded paleoseismic activity of the Teruel Fault seems
507 significantly lower than that of the Concud Fault during a similar time period (76 ka vs. 74
508 ka BP; Fig. 10; Table 5): four events with average coseismic slip of ca. 0.6 m vs. eleven
509 events with average coseismic slip of 1.9 m. Nevertheless, we should remind that the
510 paleoseismic record obtained for the Teruel fault zone only includes the seismic events
511 occurred on two fault branches (M and P). With this respect, it would be more realistic a
512 comparison with the paleoseismic record obtained at a single fault branch in the the central
513 sector of the Concud Fault (Fig. 11b,d; Table 5). Two trenches excavated across its southern
514 branch (El Hocino site) provided a sequence of five events occurred since 74 ka BP, with an

515 accumulated net displacement of 3.9 m, average coseismic slip close to 0.8 m, and slip rate
516 of 0.05 mm/a (Fig. 11b) (Lafuente et al., 2014). These results are closer to those obtained for
517 the Teruel Fault in the present work, which allows us to estimate that the likely degree of
518 activity of both faults has been similar. Unfortunately, due to the poor time constraint on
519 individual events interpreted for the Teruel Fault, comparing and correlating events recorded
520 on the Teruel and Concud faults is impractical (Fig. 10).

521 *8.4. Structural and seismotectonic relationships between the Teruel and Concud faults*

522 As stated above, surface and shallow subsoil information does not support the
523 hypothesis of full structural link between the Teruel and Concud faults (hard linkage in the
524 sense of Walsh and Watterson, 1991). Moreover, their distinct transport directions (N275°E
525 vs. N220°E) indicate that they behave as two independent structures from the kinematic
526 point of view. Their separate displacement-length profiles at the relay zone (Fig. 3c) are also
527 consistent with such independence, although the sharp gradients of these profiles close to the
528 fault tips suggest some dynamic interaction between them.

529 Our paleoseismological study provides further evidence for autonomous activity on
530 each fault. Time constraints of events in the Teruel Fault do not allow us to either confirm or
531 disprove that some events ruptured both faults (Fig. 10). Nevertheless, coseismic
532 displacements observed at the Teruel Fault helps us to suggest that the Teruel and Concud
533 faults behave as two independent seismogenic sources instead of as a single seismogenic
534 structure. Displacement values of the Teruel Fault (0.1 to 1.1 m; average = 0.5-0.57 m): (i)
535 are consistent with those expected for a 9.0 km-long fault according to empirical correlation;
536 (ii) are significantly smaller than those actually recorded on the 14.2 km-long Concud Fault
537 (1.9 m, in average); and (iii) are less consistent with a hypothetically joint Concud-Teruel, 23
538 km-long fault (expected coseismic slip ranging from 0.7 m to 2.4 m, according to empirical
539 correlation; see section 5 and Table 2). Moreover, the difference between their prevailing
540 transport directions, previously noticed from overall kinematic data at both faults, has been
541 confirmed from faults exposed in paleoseismological trenches (Fig. 11a,c).

542 Another different issue concerns the location of the true northern tip, and hence the
543 true length of the Teruel Fault and its distance to the Concud Fault. Faults and associated
544 tilted beds observed in Middle Pleistocene deposits at two sites (Cuesta de la Bajada and Las
545 Ramblillas; see location in Fig. 2a) suggest a prolongation of the Teruel Fault some 2 km
546 northwards from the mapped tip point located north of Teruel city. As in the case of the
547 Concud Fault, no trace can be identified through the flood plain of the Alfambra River

548 (Holocene, T0 terrace), but the Teruel Fault could cut the underlying Neogene and
549 Pleistocene units.

550 The transport direction inferred at Las Ramblillas (N218°E) differs from that of the
551 Teruel Fault (N275°E) and is approximately parallel to that of the Concul Fault (N220°E).
552 This observation plays against the full connection of the Las Ramblillas structure to the
553 Teruel Fault, and points to two alternative hypothesis: (i) the outcropping Las Ramblillas
554 fault is a smaller, recent synthetic rupture kinematically associated with the Concul Fault,
555 although it could play a role within an eventual linkage process with the Teruel Fault; (ii) the
556 striation measured on the Las Ramblillas fault is not representative of its prevailing transport
557 direction: in the same way that a second striation exists on the Concul Fault surface at El
558 Hocino site, oriented towards NW and overprinting the SW-oriented prevailing striation
559 (Fig. 11a; Lafuente et al., 2014), an ‘anomalous’ movement towards SW could have been
560 recorded on the Teruel Fault.

561 In any case, the tentative propagation and linkage of the Teruel Fault with the Las
562 Ramblillas structure would represent a recent, incipient process, as suggested by the
563 pronounced bell-shape of its D-L profile. In this profile a high D-L gradient at the relay zone
564 (around the abscise 14 km in Fig. 3c) is followed by a sharp reduction of the gradient near
565 the northern tip (frictional breakdown zone; Cowie and Scholz, 1992; Cowie and Shipton,
566 1998).

567 *8.5. Dynamic interaction and future linkage?*

568 Although the Teruel and Concul faults remain two independent structures, future
569 linkage is possible, as proposed by Ezquerro et al. (2012) and Lafuente et al. (2012). Linkage
570 would be consistent with the mechanical state inferred for the relay zone. The steep gradients
571 of their displacement-length (D-L) profiles in the relay zone indicate that both faults undergo
572 dynamic interaction, according to theoretical models. The elastic strain fields of two adjacent
573 faults interfere close to their tip lines, which tends to hinder propagation while displacement
574 increases, resulting in anomalously high displacement gradients (Huggins et al., 1995; Nicol
575 et al., 1996; Cartwright and Mansfield, 1998; Gupta y Scholz, 2000; Peacock, 2002).

576 According to this hypothesis, the relay zone between the Teruel and Concul faults is
577 in a transient stage from independence to linkage. It cannot be anticipated how such full
578 connection would happen. The coalescence of Las Ramblillas fault with both the Teruel and
579 Concul faults could be the most probable one, the southernmost, NNW-SSE trending

580 segment of the Concud Fault probably remaining as an inactive splay fault (Childs et al.,
581 1995). Alternatively, transverse faults of the Mansuetos-Valdecebro structure could cut the
582 relay ramp, resulting in hard linkage.

583 *8.6. A scenario of strain and stress partitioning at the scale of the seismic cycle*

584 Owing to their dynamic interaction, it is expected that displacement on one fault
585 results in stress perturbation of the rock volume surrounding the other fault, and vice versa.
586 At the scale of individual earthquakes, static Coulomb stress changes could trigger seismic
587 events on segments of the other fault that were approaching critical conditions for rupture
588 (Freed, 2005; King et al., 1994).

589 This suggests a scenario of slip on both structures taking place in a broadly
590 alternating manner: stress release on one fault after a seismic event, and stress instability
591 induced in the surrounding volume, will favour the next event to occur in the other fault (Fig.
592 12). Indeed, the average recurrence period may be similar for both structures during the Late
593 Pleistocene times, with 7.1 ± 3.5 to 8.0 ± 3.3 ka on the Concud fault (Simón et al., 2016),
594 and 10-15 ka on the Teruel Fault, as estimated from empirical correlation proposed by
595 Villamor and Berryman (1999) using the average slip rate. This scenario involves local strain
596 partitioning between the Teruel and Concud faults at the scale of the seismic cycle,
597 representing a small incremental deformation episode within overall strain partitioning
598 between NNW-SSE and NNE-SSW normal faults.

599 It is known that conjugate fault systems formed according to Mohr-Coulomb's failure
600 criterium only accommodate plane strain ($\lambda_2 = 1$). In order to accommodate 3D finite strain,
601 movement on multiple-set fault patterns (such as those typically made of four sets with
602 orthorhombic symmetry) is necessary (Reches, 1978; Krantz, 1989; Nieto-Samaniego,
603 1999). Therefore, the biaxial extensional deformation that characterizes the recent tectonic
604 setting of eastern Iberian Chain (Simón, 1982, 1989; Capote et al., 2002) could not be
605 accommodated by a single fault set, or by a single conjugate normal fault system;
606 progressive slip on diversely orientated fault planes and along diverse transport directions is
607 needed.

608 However, this does not occur as a linear, steady process, but as a non-linear sequence
609 of rupture episodes, during discontinuous deformation. The bulk 3D deformation is
610 partitioned into a number of slip events on individual faults, which in their turn involve a
611 sequence of episodic, systematic (not chaotic) stress changes that Simón et al. (2008) define

612 as *stress partitioning*. Each failure event is compatible with stress-based models, while the
613 finite 3-D strain fits kinematic boundary conditions.

614 The described process can occur at any spatial scale between e.g. tensile joints up to
615 intraplate regions, and also at a wide range of time scales. In our study region, the long-term,
616 Neogene-Quaternary tectonic evolution of eastern Iberia is characterized by both spatial
617 transition and time shifting between regional stress systems with NNW-SSE and NNE-SSW
618 S_{Hmax} trajectories, coexisting with local switching to orthogonal, either ENE-WSW or ESE-
619 WNW trending ones (Simón, 1989; Cortés et al., 1996; Herraiz et al., 2000; Arlegui et al.,
620 2005). At a much shorter time scale, it is known that earthquake focal mechanisms
621 frequently reveal stress instabilities during aftershock sequences, some fault mechanisms
622 being representative of the regional stress field while others represent second-order stresses
623 including episodes of stress axis swapping (Mercier et al., 1989; Bowman et al., 2003;
624 Caputo, 2005). Similar outcomes arise from laboratory experiments carried out by Reches
625 and Dieterich (1983), which describe how fracture patterns made of four sets with
626 orthorhombic symmetry (needed for accommodating 3D finite strain) developed through two
627 yielding events with swapping of the two major stress axes between them.

628 Our hypothesis is that strain/stress partitioning also occurs at an intermediate time
629 scale, i.e. the scale of seismic cycle (as postulated as well for the notion of *Twist Tectonics* by
630 Caputo et al., 2010) giving rise to broadly alternating slip on the Teruel and Conclud faults.
631 Dynamic interaction between neighbouring faults (described in the previous section)
632 provides the way for that process to come about. In this way, our scenario: (i) is consistent
633 with the structural and dynamic relationships between faults, (ii) is consistent with the
634 intrinsic stress changes in the complex regional stress field, and (iii) allows accommodation
635 of bulk biaxial extension in the Teruel region.

636 *8.7. Implications for seismic hazard assessment*

637 The relationship interpreted for the Teruel and Conclud faults has undeniable
638 implications for seismic hazard assessment of the Teruel region. In general, an intermediate,
639 transient stage (structural decoupling but dynamic interaction) implies a different seismic
640 hazard level than that involved by the alternative, extreme options: (i) full independence, or
641 (ii) linkage.

642 A hypothetically linked Conclud-Teruel fault, with a total length of 23 km, would
643 represent a seismogenic structure able to produce larger earthquakes than those generated by

644 each separate structure. Their characteristic earthquake would show maximum moment
645 magnitude $M_w \approx 6.6-7.0$, while $M_w \approx 6.1-6.6$ and $M_w \approx 6.6-6.8$ for the single Teruel and
646 Conclud faults, respectively (Table 2). In the case of two independent seismic sources, with
647 each having a similar recurrence period to that of the hypothetical linked structure, the
648 probability of occurrence of such characteristic earthquakes in a given term would be
649 significantly increased.

650 On the other hand, dynamic interaction between both faults involves shortening of
651 the seismic cycle. Local stress perturbations induced by movement on one fault can trigger
652 movement on the other one, which is found to be most evident within short distances (up to
653 ≈ 5 km), although only for events that are relatively late in their respective earthquake cycle
654 (Chen et al., 2010).

655

656 **9. Conclusions**

657 (1) Surface and shallow subsoil information indicates that the Teruel and Conclud faults
658 are not structurally linked. They also behave as kinematically independent structures, with
659 distinct transport directions: $N275^\circ E$ and $N220^\circ E$, respectively.

660 (2) The Pleistocene paleoseismic record of the Teruel Fault includes four events
661 (Events 1, 2, 3, and 4) occurred between 76.0 and 9.2 ka BP (Table 4, Fig. 10). Since timing
662 of individual events is poorly constrained, the duration of interseismic periods remains
663 unknown. The recorded paleoseismic activity only represents a limited succession of slip
664 events in two fault branches (therefore far from embodying the total activity of the Teruel
665 fault zone).

666 (3) This paleoseismic record is significantly lower than that of the overall Conclud
667 Fault during a similar studied time lapse (76 ka BP vs. 74 ka), but comparable to that
668 obtained in the southern branch of the Conclud Fault at its central sector (Fig. 11). Hence we
669 estimate that the overall degree of activity of both faults could be similar. The most
670 representative slip rates obtained from morpho-sedimentary markers (see Table 5) are \approx
671 0.075 mm/a for the last ~ 3.6 Ma on the overall Teruel fault zone, and 0.19 ± 0.01 mm/a for
672 the last 46.5 ± 3.2 ka on two branches at Pitraque site. Strictly considering the events
673 recorded at trenches, such slip rate is reduced to 0.04 ± 0.01 mm/a. These values are
674 comparable to those previously obtained at the Conclud Fault: $0.07-0.08$ mm/a for the last \sim
675 3.6 Ma, and 0.29 mm/a since ~ 74 ka BP on the entire fault zone; 0.05 mm/a since ~ 74 ka BP
676 on a single branch (Lafuente, 2011; Lafuente et al., 2011a, 2014; Simón et al., 2016).

677 (4) Owing to the poorly constrained timing of events identified at the Teruel Fault,
678 comparing and correlating them with those on the Concud Fault is not feasible, neither
679 discerning whether some rupture event have simultaneously occurred on both faults.
680 Nevertheless, the observed coseismic displacements on the 9.0 km-long Teruel Fault
681 (average = 0.5-0.57 m) are consistently smaller than those previously measured on the 14.2
682 km-long Concud Fault (average = 1.9 m), and unsuitable for a hypothetically joint Concud-
683 Teruel, 23 km-long fault. We therefore interpret that the Teruel and Concud faults behave as
684 two independent seismogenic sources.

685 (5) In spite of their geometric and kinematic independence, both structures undergo
686 dynamic interaction (i.e. stress perturbation at the rock volume surrounding one fault
687 subsequent to activation of the other one). This could have induced broadly alternating slip
688 on both faults along their distinctive transport directions, which would involve a certain type
689 of strain partitioning at the scale of the seismic cycle (Fig. 12): combining multiple slip
690 events on both fault surfaces would allow accommodation of bulk 3D deformation in the
691 Teruel region, within the framework of a biaxial extensional stress regime. The described
692 scenario represents a transient stage from independence to linkage; future connection
693 (probably through coalescence with an intermediate fault, Las Ramblillas fault) is a potential
694 process.

695 (6) Structural relationships between the Teruel and Concud faults clearly influences
696 seismic hazard. Two independent seismic sources will produce smaller, although more
697 frequent earthquakes than those generated by a hypothetically linked Concud-Teruel fault.
698 Dynamic interaction between both faults probably involves shortening of the seismic cycle,
699 therefore increasing the probability of seism occurrence, but distributing the total released
700 energy into smaller events.

701

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710

711

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884

885 **FIGURE CAPTIONS**

886

887 Fig. 1. Location of the Teruel Fault within the Teruel Graben system, eastern Spain. Inset:
888 sketch of the main Alpine chains within the Iberian Peninsula.

889

890 Fig. 2. Structure of the Teruel Fault. (a) Geological map. MVS: Mansuetos-Valdecebro
891 syncline. (b) Cross section (see location in a). (c) Partial outcrop view of the main fault zone
892 cutting the Rojo 2 unit within the Teruel urban area (see location in a). (d) Equal-area plot
893 (lower hemisphere) showing orientations of measured planes and striations along the main
894 fault. Black: data from central and southern sectors, showing an overall transport direction
895 (red dot) towards N275°E. Grey: Las Ramblillas fault.

896

897 Fig. 3. (a) Structural contour map of the base of Páramo 2 (youngest pre-rift unit relative to
898 the Late Pliocene-Quaternary extensional period) at the relay zone between the Teruel and
899 Concud faults. (b) 3D scheme of the relay structure reconstructed from the previous map. (c)
900 Distribution of vertical displacement (throw) along fault length (D-L profiles) for the
901 Concud and Teruel faults, obtained from the structural contour map. Modified from Lafuente
902 et al. (2011b).

903

904 Fig. 4. Deformation at Las Ramblillas site, revealing hypothetical prolongation of the Teruel
905 Fault. (a) Panoramic view. (b) Interpretation sketch. V: Villafranchian pediment; T2b:
906 Middle Terrace of Alfambra River; T0: Holocene terrace; Qa: Quaternary alluvial pediment.

907

908 Fig. 5. Aspects of local geology of the Pitraque-Valdelobos area. (a) Detailed geological map
909 (see location in Fig. 2a). (b) Outcrop view of the main Teruel Fault branch (M) north of
910 Puntal del Pitraque (see location in Fig. 2a). (c) Overall field view. (d) Equal-area plot (lower
911 hemisphere) of the main macroscale fault planes, and one observed striation. (e) Schematic
912 cross section showing offset of the Middle Terrace T2a (see location on Fig. 5a). (f) Laser-
913 levelling profile along the talweg of Valdelobos gully (sector shown in map a), showing the

914 location chosen for the Valdelobos trench. M, N, P, Q, R, S: fault branches referred to in the
915 text; R1, R2, and P2: Rojo 1, Rojo 2, and Páramo 2 units, respectively; T2a: Middle Terrace
916 of the Turia River; T0: Holocene terrace; QA: Holocene alluvium and colluvium.

917

918 Fig. 6. Meso-scale fracturing at the Pitraque 1 and Pitraque 2 site (equal-area plots, lower
919 hemisphere). (a) Vertical, low height aerial photograph with structural sketch. (b) Fault
920 planes and striations observed on the natural terrace scarp. (c) Idem in Pitraque 1 trench. (d)
921 Idem in Pitraque 2 trench. (e) Synthetic rose diagram of fault strikes measured in the whole
922 site. $F\mu$, $F\delta$, $F\alpha$, $F\beta$: faults referred to in the text; R2: Rojo 2 unit; P2: Páramo 2 unit; T2a:
923 Middle Terrace of the Turia River.

924

925 Fig. 7. (a) Detailed cross section of Pitraque 1 trench. R2: Rojo 2 unit; P2: Páramo 2 unit; 1,
926 2, 3, 4, 5, 6: Pleistocene units described in the text; light-grey stripes: carbonate; $F\gamma$, $F\alpha$, $F\delta$:
927 faults referred to in the text; location (asterisks) and age of samples dated by OSL is
928 indicated. (b) (c) (d) (e) Stereoplots (equal-area, lower hemisphere; symbols as in Fig. 6) of
929 meso-scale fractures measured in domains 1, 2, 3 and 4, respectively. (f) Poles to bedding
930 measured in all sedimentary units, and inferred movement plane (M).

931

932 Fig. 8. (a) Detailed cross section of trench Pitraque 2. R2: Rojo 2 unit; P2: Páramo 2 unit; 1,
933 2, 3, 4: Pleistocene units described in the text; light-grey stripes: carbonate; $F\beta$, $F\alpha$: faults
934 referred to in the text; location (asterisks) and age of samples dated by OSL is indicated. (b)
935 Detail photograph of domain 1 in (a). (c) (d) Stereoplots (equal-area, lower hemisphere;
936 symbols as in Fig. 6) of meso-scale fractures measured in domains 1 and 2, respectively. (e)
937 Idem in the opposite, not logged trench wall.

938

939 Fig. 9. Detailed cross section of Valdelobos trench. R2: Rojo 2 unit; 1, 2, 3, 4, 5: Quaternary
940 units described in the text; $F\epsilon$: active fault; location (asterisks) and age of samples dated by
941 OSL is indicated.

942

943 Fig. 10. Chronological sketch of paleoseismic events recorded at the overall Concul Fault
944 (complete paleoseismic succession reconstructed by Simón et al., 2016), its southern branch
945 (El Hocino trenches; Lafuente et al., 2104), and the Teruel Fault (this work).

946

947 Fig. 11. Comparison between seismic succession reconstructed for the southern branch of the
948 Concul Fault (Lafuente et al., 2014) and for the Teruel Fault (M and P branches, present
949 work). (a) Kinematic data for the southern branch of the Concul Fault at El Hocino site:
950 equal-area, lower hemisphere stereoplot of fault planes and striations, and prevailing
951 transport direction. (b) Slip history of the southern branch of the Concul Fault, as inferred
952 from the palaeoseismic succession at El Hocino trenches; slip rates inferred from that
953 succession and from offset of a morpho-sedimentary marker (pediment cover) are expressed
954 as dotted lines. (c) and (d): Idem as a and b, respectively, for the western branches of the
955 Teruel Fault at Pitraque-Valdelobos site (offset marker in this case: top of fluvial terrace
956 T2a).

957

958 Fig. 12. Proposed model of stress/strain partitioning at the scale of seismic cycle for the
959 activity of the Teruel and Concul faults. (a) (b) (c) (d) Sketches of successive, alternating slip
960 on both faults favoured by stress release on each fault after a seismic event (see explanation
961 in text); large arrows: transport directions; stereoplots: active fault (plane and prevailing
962 striation) for each seismic event, and orientation of stress axes (σ_1 , σ_2 and σ_3) of the most
963 representative stress systems (according to palaeostress analysis by Lafuente, 2011). (e)
964 Simplified model for the overall fracture systems in the Teruel area, and kinematic
965 interpretation according to the model proposed by Reches (1978); X, Y, Z: virtual strain axes
966 representing the bulk finite deformation.

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968

969 **TABLE 1:**

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Level	Age	Sublevel	Height above talweg (m)	Numerical age	Dating method	References
Upper	Early Pleistocene (?)	T3	85-90	Unknown		
Middel	Middle Pleistocene	T2b	45-65	250 (\pm 32) to 116 (\pm 4) ka	U/Th	Arlegui et al. (2005); Gutiérrez et al. (2008)
		T2a	40-45	90.5 (\pm 5.3) to 76.0 (\pm 5.0) ka	OSL	Lafuente et al. (2008); Simón et al. (2012)
Lower	Late Pleistocene	T1c	20-30	22.0 (\pm 1.6) ka	OSL	Lafuente (2011)
		T1b	15-20	14.9 (\pm 1.0) to 15.6 (\pm 1.3) ka	OSL	Lafuente et al. (2008); Gutiérrez et al. (2008)
		T1a	10-15	Unknown		
Subactual	Holocene	T0	3-5	3.4 (\pm 0.7) ka	OSL	Lafuente (2011)

971

972 **Table 1.** Levels of fluvial terraces defined in the Teruel area (Alfambra and Turia rivers).

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978 **TABLE 2:**

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Scenario	Paleoseismic parameters		Wells & Coppersmith (1994)	Stirling <i>et al.</i> (2002)	Pavlidis & Caputo (2004) (*) (**)	Mohammadioun & Serva (2001) (*) (***)	
<i>Length of 9 km</i>						100 bar	30 bar
	Moment magnitude (M_w)		6.12	6.64	6.35	6.26	5.73
	Coseismic slip (m)	Vertical	-	-	0.55	-	-
		Net	0.37	1.28	0.59	-	-
<i>Length of 11 km</i>							
	Moment magnitude (M_w)		6.23	6.71	6.41	6.39	5.87
	Coseismic slip (m)	Vertical	-	-	0.60	-	-
		Net	0.40	1.32	0.65	-	-
<i>Length of 23 km (linked Concud and Teruel faults)</i>							
	Moment magnitude (M_w)		6.66	6.96	6.62	6.88	6.36
	Coseismic slip (m)	Vertical	-	-	0.66	-	-
		Net	1.19	2.43	0.71	-	-

980

981 **Table 2.** Moment magnitude and coseismic slip for the Teruel Fault estimated from empirical relationships for three different982 scenarios. (a) Obtained M_s values have been transformed to M_w by applying the relationship of Konstantinou *et al.* (2005):983 $M_w = 0.76 M_s + 1.53$. (b) Vertical displacement initially yielded by this correlation has been translated into net displacement984 considering an average dip of 68° and a pure normal movement of the Teruel Fault. (c) Moment magnitudes according to

985 Mohammadioun and Serva (2001) have been calculated for stress drop scenarios of 100 and 30 bar.

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992 **TABLE 3:**
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Sample	Laboratory reference	Lithological unit	Equivalent dose (Gy)	Annual dose (mGy/yr)	Supralinearity (Gy)	K factor	OSL age (ka B.P.)
<i>Trench: Pitraque 1</i>							
P1-4	MAD-6076SDA	Fluvial terrace (Unit 1)	170.46	2.41	0	0.19	70.730 ± 5.259
P1-5	MAD-6077SDA	Fluvial terrace (Unit 2)	124.93	1.74	0	0.12	71.798 ± 5.059
P1-6	MAD-6078BIN	Fluvial terrace (Unit 5)	77.57	1.60	0	0.11	48.481 ± 3.801
<i>Trench: Pitraque 2</i>							
P2-1	MAD-6079SDA	Fluvial terrace (Unit 1)	130.05	1.66	0	0.14	78.343 ± 5.189
P2-7	MAD-6081BIN	Fluvial terrace (Unit 2)	91.95	1.84	0	0.11	49.972 ± 3.365
P2-5	MAD-6080SDA	Fluvial terrace (Unit 3)	127.80	2.75	0	0.14	46.472 ± 3.147
<i>Trench: Valdelobos</i>							
VL-C1	MAD-6073SDA	Fluvial terrace (Unit 2)	112.82	4.23	0	0.16	26.671 ± 1.912
VL-B2	MAD-6074SDA	Fluvial terrace (Unit 3)	16.97	1.71	0	0.23	9.923 ± 0.690

994
995 **Table 3.** OSL dating of samples collected from trenches at the Teruel fault.
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998

999 **TABLE 4:**

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Teruel Fault event (renamed)	Original event at individual trench	Predating OSL age (ka B.P.)	Postdating OSL age (ka B.P.)	Absolute age constraints (ka)	Coseismic net slip (m)
Event 0	XP1		70.7 ± 5.3	Pre-73.1	?
	XP2		78.3 ± 5.2		
Event 1	YP1	70.7 ± 5.3	71.8 ± 5.1	76.0 – 66.7	0.1
Event 2	YP2	46.5 ± 3.1		Post-49.6	0.5
Event 3	ZP1	48.5 ± 3.8		Post-49.6	> 1.1
	ZP2	46.5 ± 3.1			
Event 4	ZVL	26.7 ± 1.9	9.9 ± 0.7	28.6 – 9.2	> 0.3

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Table 4. Summary of paleoseismic events of the Teruel Fault interpreted and correlated from the studied trenches: Pitraque 1 (P1), Pitraque 2 (P2) and Valdelobos (VL). Absolute age constraints take into account the error bar for each OSL age.

1015 **TABLE 5:**
1016

Marker / data source	Age / time window	Teruel Fault (this work)		Concud Fault (*)			
		Net slip (m)	Slip rate (mm/a)		Net slip (m) (**)	Slip rate (mm/a)	
			Overall	Partial (In 1-2 branches among 4-5)		Overall	Partial (In 1 branches among 2-3)
<i>Trenching information</i>							
Compilation of coseismic slip values	since 76.0 to 9.9 ka BP	1.7 - 2.0	0.03 - 0.05				
	since ca. 74 to 3.4 ka BP			20.5 (3.9)	0.29	0.05	
<i>Stratigraphic marker</i>							
T2b terrace top	46.5 ± 3.2 ka	8.8	0.18 - 0.20				
T2a terrace top	282 - 112 ka			39	0.14 - 0.35		
Páramo 2 unit (Latest Ruscinian)	3.6 Ma	270	0.075	255 - 290	0.07 - 0.08		

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Table 5. Summary of slip rates calculated for the Teruel and Concud faults from different markers and for different time windows. (*) Data for the Concud Fault are compiled from Gutiérrez et al. (2008), Lafuente (2011), Lafuente et al. (2011a, 2014), and Simón et al. (2016). (**) In parentheses, partial net displacement measured on one fault branch.

1022 **APPENDIX 1:**

1023 **Description and age of sedimentary units exposed in trenches**

1024

1025 *Pitraqe 1 trench*

1026 Neogene sediments comprise: (i) pedogenized massive brown lutites (top of Rojo 2 unit); (ii)
1027 brecciated grey and white limestones interbedding black and green marls with remains of gastropods
1028 and charophytes, representing Páramo 2 carbonate unit. The Pleistocene succession has been
1029 subdivided into six units (1 to 6 in Fig. 7a):

1030 Unit 1. Gravel with Neogene limestone angular-subrounded pebbles boulders and rip up
1031 clasts. It is grain-supported and crops out discontinuously below the erosive base of unit 2. Sample
1032 P1-4 (see location in Fig. 7a) yielded an OSL age of 70.7 ± 5.3 ka (Table 2).

1033 Unit 2. Greyish and yellowish gravel with interbedded brown, fine- to coarse-grained sand.
1034 Gravel is grain-supported and made of angular-subangular carbonate and siliceous pebbles and
1035 cobbles up to 14 cm in diameter; it shows trough cross-bedding. Sand forms decimetre-scale, tabular
1036 levels with parallel and cross-lamination, and ripples. Sample P1-5 (see location in Fig. 7a) yielded
1037 an OSL age of 71.8 ± 5.1 ka (Table 2).

1038 Unit 3. Grey gravel with encased brown medium-grained sand lenses with floating clasts up
1039 to 3 cm in diameter. Gravel is grain-supported and made of angular-subrounded limestone and
1040 siliceous pebbles and cobbles up to 24 cm in diameter; it shows pebble-granule cycles and trough
1041 cross-bedding.

1042 Unit 4. Grey gravel with interbedded medium to coarse-grained brown sand. Gravel is grain-
1043 supported with subangular-subrounded limestone clasts up to 8 cm in diameter and trough cross-
1044 bedding. Sand makes laminated lensoid or tabular bodies.

1045 Unit 5. Grey gravel with encased coarse-grained brown sand. Gravel is grain-supported,
1046 composed of angular-subangular clasts up to 6 cm in diameter. Horizontal bedding (pebble-granule
1047 cycles) merges laterally into trough cross-bedding sets. Sand makes tabular levels with parallel
1048 lamination and floating grey limestone clasts up to 1 cm in diameter. Sample P1-6 (see location in
1049 Fig. 7a) yielded an OSL age of 48.5 ± 3.8 ka (Table 2).

1050 Unit 6. Regolith. Brown lutite with scattered centimetre-scale limestone clasts, carbonate
1051 nodules, and root traces.

1052

1053 *Pitraqe 2 trench*

1054 Neogene sediments are similar to those described in Pitraque 1 trench (Rojo 2 and Páramo 2
1055 units). The overlying Pleistocene materials have been subdivided into four units (1 to 4 in Fig. 8a):

1056 Unit 1. Grey and brown, grain-supported gravel with rare sand. Gravel is made of angular-
1057 subangular limestone and siliceous-pebbles and cobbles up to 18 cm in diameter; it shows planar
1058 cross-stratification and interbedded sand levels in the lower part. Sample P2-1 (see location in Fig.
1059 8a) has an OSL age of 78.3 ± 5.2 ka BP (Table 2).

1060 Unit 2. Grey and brown gravel with intercalated brown very coarse-grained sand towards the
1061 top. Gravel, matrix-supported at the base and grain-supported towards, consists of angular limestone
1062 and siliceous pebbles and cobbles up to 16 cm in diameter, and shows cross-bedding. Sand forms a
1063 slightly channelled body with angular, grey limestone floating clasts (up to 2 cm), and armoured clay
1064 balls (up to 16 cm). Sample P2-7 (Fig. 8a) yielded an OSL age of 50.0 ± 3.4 ka (Table 2).

1065 Unit 3. Gravel with interbedded centimetre-thick levels of fine- to coarse-grained sand.
1066 Gravel, mainly grain-supported, is made of angular limestone pebbles and cobbles. It forms a tabular
1067 body in the lower part and a channel in the upper part; the channel is composed by larger clasts (up to
1068 15 cm) and shows planar cross-bedding. Sand makes irregular levels with horizontal and cross-
1069 lamination. Its base has an OSL age (sample P2-5) of 46.5 ± 3.1 ka (Table 2).

1070 Unit 4. Regolith. Brown lutite with carbonate nodules, root traces and scattered centimetre-
1071 scale limestone clasts.

1072

1073 *Valdelobos trench*

1074 Massive red Neogene lutites (Rojo 2) are covered by Quaternary alluvial deposits in which
1075 five units have been distinguished (1 to 5 in Fig. 9):

1076 Unit 1. Massive brown lutite with grey patches, carbonate nodules and interbedded fine- to
1077 medium-grained sand with carbonate granules that grades laterally into brown silt.

1078 Unit 2. Coarse-grained sand with white and grey carbonate and black quartzite granules in a
1079 coarsening upward channelled body close to a fault plane in the middle part of the trench. Sample
1080 VL-C1 (Fig. 9) yielded an OSL age of 26.7 ± 1.9 ka BP (Table 2).

1081 Unit 3. Channelled highly erosive body with brown gravel in the lower part and medium-
1082 grained sand and lutites in the upper part. Gravel is made of subangular-subrounded white carbonate
1083 (up to 8 cm in diameter) and brown and red siliceous clasts (up to 3 cm); it shows horizontal bedding
1084 and imbricated clasts. Sand forms tabular levels with parallel lamination and low angle cross-
1085 stratification. Some mud boulders have been recognized, up to 88 cm exist. Sample VL-B2 (Fig. 9)
1086 yielded an OSL age of 9.9 ± 6.9 ka BP (Table 2).

1087 Unit 4. Gravel (lower part) and coarse-grained sand (upper part) arranged in a dominantly

1088 red, tabular and fining-upwards erosive body with locally channelled base. Gravel, matrix-supported,-
1089 made of white, subangular-subrounded carbonate clasts, up to 15 cm in diameter. Sand shows parallel
1090 lamination, ripples, scattered clasts and rare mud boulders.

1091 Unit 5. Greyish grain-supported gravel in a tabular body with erosive base and horizontal
1092 stratification made of fining upwards sequences. It is composed by subangular-subrounded white
1093 carbonate clasts (up to 7 cm in diameter), subrounded orange siliceous clasts (up to 4 cm), and rare
1094 mud boulders. It supplied two fragments of clay teals (historical times, post-Middle Age).

1 • **Assessing interaction of active extensional faults from structural and**
2 **paleoseismological analysis: the Teruel and Concud faults (eastern Spain)**

3

4

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19 **Key words:** fault linkage, fault relay, intraplate extension, paleoseismicity, seismic hazard,

20 Teruel Basin.

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23

24 **Abstract**

25 The relationship of independence, interaction or linkage between two neighbouring
26 intraplate active extensional faults, the Teruel and Concud faults, are investigated from
27 structural and paleoseismological data, and the results are discussed to improve seismic
28 hazard assessment for the region. This paper provides the structural and paleoseismological
29 characterization of the almost unknown Teruel Fault from detailed mapping and trench
30 analysis, and discusses its kinematic and kinematic relationships with the Concud Fault.
31 Four individual events occurred between 76.0 ka and 9.2 ka BP have been recorded at two
32 branches of the Teruel Fault. Unfortunately, these only represent a small fraction of its
33 overall activity during such time lapse, and their time constraints do not allow correlating
34 them with those at the Concud Fault. The Teruel and Concud faults are independent
35 structures from the geometric and kinematic point of view, as evinced by their distinct (i)
36 transport directions (N275°E and N220°E, respectively), and (ii) average coseismic
37 displacements (0.5 m and 1.9 m, respectively). These displacements are consistent with their
38 respective lengths (9.0 km and 14.2 km) and significantly smaller than those expected for a
39 hypothetically joint Concud-Teruel, 23 km-long fault. However, their displacement gradients
40 close to the relay zone indicate that both faults undergo dynamic interaction, thus suggesting
41 a transient stage from independence to linkage. We hypothesize that slip on both structures
42 occurred, at the scale of the seismic cycle, in a broadly alternating maner, which induced
43 strain partitioning between them and allowed accommodating bulk biaxial extension in the
44 region. Such deformation pattern would have increased the earthquake frequency with
45 respect to the scenario of a hypothetically linked Concud-Teruel Fault, but diminished the
46 potential seismic magnitude.

47

48

49 **1. Introduction**

50 In the last few decades, great efforts have been made to improve our understanding of
51 the geometric interaction and linkage of segments of extensional fractures and normal faults
52 showing overlapping or en-échelon **arrays** (e.g., Gibbs 1984, **Faulds et al., 1990**; Childs et
53 al., 1995; Nicol et al., 1996; Ferrill et al., 1999; Peacock, 2002; **Walsh et al., 2003**; Fossen
54 and Rotevatn, 2016). **Lateral propagation of curved fault tips and linkage by connecting**
55 **faults are two of the mechanisms by which increasing displacement eventually produces the**
56 **progressive evolution from the phase of fault overlap and relay zone stage to a fully**
57 **breached fault (Ferrill et al., 1999; Peacock, 2002; Fossen and Rotevatn, 2016).** Recognition

58 of linked en-échelon fault systems in the early stages of development is critical in seismic
59 hazard assessment because seismic hazard analyses rely also on the ability to predict whether
60 an earthquake will terminate at a fault tip or propagate onto adjacent faults (Ferrill et al.,
61 1999; Wesnousky, 2008; Manighetti et al., 2009; Frinzi and Langer, 2012; Biasi and
62 Wesnousky, 2016).

63 In moderately active intraplate areas, the historical seismic record is not long enough
64 to include large earthquakes, owing to their large average recurrence intervals. ~~In order to
65 overcome this lack of information~~ Therefore, to reconstruct the true seismic history of faults,
66 ~~and therefore to achieve realistic seismic hazard assessment,~~ it is necessary to rely on
67 paleoseismological studies (McCalpin, 1996; Pavlides et al., 1999; Caputo et al., 2008;
68 Simón et al., 2016). Paleoseismology also provides additional information about fault
69 kinematics: the pattern of incremental or ‘infinitesimal’ slip on individual faults, and hence
70 the possibility of approaching the progressive bulk deformation of a tectonically active area.

71 This study assesses the state of geometric, kinematic and dynamic interaction of two
72 neighbouring active faults, the Teruel and Concud faults, and discusses its influence on
73 seismic hazard assessment for the region. These faults are located at the junction of the
74 Teruel and Jiloca grabens (Fig. 1), which represent the largest Neogene-Quaternary
75 extensional basins in the intraplate Iberian Chain (eastern Spain). ~~This is an intraplate region
76 containing several active extensional faults, though it shows low instrumental and historical
77 seismicity.~~ The west-dipping Concud and Teruel faults strike NW-SE and N-S, respectively,
78 and show a right-stepping arrangement with a 1.3 km-wide relay zone (Fig. 2a). The
79 Concud Fault, the best documented active structure in the region, is expressed in the relief by
80 a prominent scarp. It is located in the southern sector of the Jiloca Graben, and shows
81 paleoseismological evidence of recurrent activity during Late Pleistocene (Lafuente, 2011;
82 Lafuente et al., 2011a, 2014; Simón et al., 2012, 2016).

83 While the paleoseismological behaviour of the Concud Fault is reasonably established,
84 ~~the seismogenic character and paleoearthquake history of~~ the Teruel Fault remain almost
85 unknown. Most of the Teruel Fault trace, somehow “invisible” through the local landscape,
86 mainly crosses Neogene units, while Quaternary deposits along its trace are very scarce.
87 Such differences between the Concud and Teruel faults are due to their distinct morpho-
88 sedimentary setting during Pleistocene times. Sedimentary aggradation dominated at the
89 hanging-wall block of the Concud Fault (alluvial fans making the piedmont of the Concud
90 mountain front); on the contrary, downcutting of the drainage network (Alfambra and Turia

91 rivers) in both the footwall and hanging-wall blocks of the Teruel Fault caused the lack of
92 deposition. Therefore, the geological record of its Quaternary activity is expected to be much
93 poorer than that of the Concud Fault.

94 Based on the proximity of the Teruel and Concud faults (Fig. 2a), Gutiérrez et al.
95 (2012) have suggested that they make a single seismogenic structure (Concud-Teruel Fault),
96 which would therefore involve the possibility of larger earthquakes than those generated by
97 each separate structure. However, previous macro and mesostructural data indicate that they
98 are independent structures from the geometric and kinematic point of view (Lafuente, 2011;
99 Lafuente et al., 2011b), therefore our hypothesis is that they are also seismically
100 independent. ~~Discerning between both possibilities is a critical issue for assessing seismic~~
101 ~~hazard in the region.~~

102 This paper presents the paleoseismological characterization of the Teruel Fault based
103 on the results obtained in three trenches, together with a comprehensive structural study.
104 The paleoseismic data will contribute both to evaluate seismic hazard and to discern the
105 kinematic and kinematic relationships between the Concud and Teruel faults on short
106 (~~'infinitesimal' from a geological perspective~~) time scales. Our specific objectives are:

107 (1) Characterizing the structure and kinematics of the Teruel Fault, estimating its slip
108 rates for different time intervals.

109 (2) Reconstructing the paleoseismological record of the Teruel Fault, and comparing it
110 with that of the nearby Concud Fault. Additionally, analysing the representativeness of such
111 paleoseismic record taking into account the morpho-sedimentary framework.

112 (3) Understanding the geometric, kinematic and dynamic interactions between the
113 Concud and Teruel faults. In particular, examining their hypothetical structural linkage (and
114 hence their potential joint activity as a single seismogenic structure) vs. hypothetical strain
115 partitioning through independent, commonly alternating slip events on both of them.

116 (4) Discussing the implications for seismic hazard assessment.

117

118 2. Methodology

119 In order to evaluate Quaternary activity of the Teruel Fault, three explorative trenches
120 were excavated across the fault. Ideal trench locations are those where recent sediments are
121 affected by the fault, so that a geological record is present at least in the hanging-wall block
122 enabling us to identify the sequence and timing of seismic events. Following a general

123 survey of the fault, a study area (Pitraque-Valdelobos area; Fig. 2a) was selected in the
124 central-southern sector, where the main fault splits into distinct branches. This area contains
125 the only remnants of Quaternary sediments extending across the fault zone.

126 A detailed geological map of this area was made, based on field survey and
127 orthoimage analysis, complemented with low-height aerial photographs taken from a drone.
128 We also acquired topographic data: GPS coordinates (using a Garmin Oregon 450 device);
129 height measurements for controlling the position of critical markers (Nikon hypsometer
130 Forestry 550 pro); a laser-level (Leica Sprinter 100) profile along the Rambla de Valdelobos
131 talweg across the Teruel fault zone, in order to check the hypothesis of a **topographic drop**.

132 Once selected the location of the trenches, we applied the classical methodology
133 (e.g., McCalpin, 1996), which includes: excavating the trench; cleaning and gridding the
134 selected walls; identifying, interpreting and marking sedimentary units and structures; taking
135 a photograph and drawing a detailed log of each cell; analysing the relationship between
136 units and faults to identify individual events; and collecting samples for absolute dating,
137 especially those that pre- and post-date seismic events. Owing to clastic lithology of
138 sediments, the dating method was that based on Optically Stimulated Luminescence (OSL);
139 the samples were analysed in the Laboratorio de Datación y Radioquímica of Universidad
140 Autónoma de Madrid (Spain).

141
142

143 **3. Geological setting**

144 The Neogene-Quaternary, NNW-SSE to NNE-SSW trending extensional basins of
145 the eastern Iberian Chain (Fig. 1) cut in an oblique direction, and postdate the Alpine
146 contractional structures (Vegas et al., 1979). The extensional faults represent the onshore
147 deformation linked to rifting of the Valencia Trough, which is accommodated by a listric
148 extensional fault system detached at a depth of 11-14 km (Roca and Guimerà, 1992).

149 ~~Extension developed through two distinct rift episodes (Simón, 1982, 1983): the first one~~
150 ~~(Miocene) gave rise to the main NNE-SSW trending grabens (Teruel and Maestrazgo), and~~
151 ~~the second one (Late Pliocene-Quaternary) originated the NNW-SSE trending Jiloca Graben~~
152 ~~and reactivated the Teruel and Maestrazgo grabens.~~

153 The Teruel Basin, where the Teruel Fault is located, is a N-S to NNE-SSW trending
154 half graben (Fig. 1). Its active, eastern boundary shows prominent mountain fronts
155 separating the floor of the graben (usually at 800-1000 m a.s.l.) from El Pobo and

156 Javalambre massifs (around 1700 and 2000 m, respectively). The graben is filled with
157 Neogene alluvial deposits that grade basinwards into lacustrine carbonates and evaporites.
158 Several units based on either lithostratigraphy (Weerd, 1976; Godoy et al., 1983) or changes
159 in allocyclic factors (Alcalá et al., 2000; Ezquerro et al., 2014) have been defined, their ages
160 being constrained by mammal ages and magnetostratigraphy (Alcalá et al., 2000). The
161 informal units proposed by Godoy et al. (1983) are commonly used in maps of the Neogene
162 Teruel Basin: Rojo 1 (red clastics; Vallesian); Páramo 1 (white carbonates, Turolian); Rojo 2
163 (red lutites, Upper Turolian-Ruscinian); Páramo 2 (white carbonates, Ruscinian); and Rojo 3
164 (red lutites, Ruscinian-Villafranchian).

165 During the Late Pliocene-Quaternary the graben infill was excavated by the Alfambra
166 and Turia rivers and their tributaries. ~~Quaternary sediments are linked to the fluvial network,
167 in the form of stepped fluvial terraces and alluvial pediments.~~ Four main fluvial terrace
168 levels developed (Peña, 1981; Godoy et al., 1983), some of them locally splitting into
169 several sublevels (Sánchez Fabre, 1989; Moissenet, 1993; Simón et al., 2016.) Table 1
170 compiles the available information on the height and age of these terrace levels.

171 During graben development, ~~Teruel and Jiloca grabens developed under a the~~ tectonic
172 stress field ~~that, through Neogene-Quaternary times,~~ evolved from: (i) triaxial extension with
173 minimum stress (σ_3) trajectories oriented WNW-ESE, prevailing during the first, Late
174 Miocene rift episode, to (ii) almost radial extension (σ_1 vertical, $\sigma_2 \approx \sigma_3$) with nearly WSW-
175 ENE trending σ_3 , prevailing during the second, Pliocene to Quaternary rift episode (Simón,
176 1982, 1989; ~~Cortés, 1999;~~ Capote et al., 2002; Arlegui et al., 2005). The latter has remained
177 active up to the present-day (Herraiz et al., 2000), although both WSW-ENE and WNW-ESE
178 σ_3 directions are recorded by fracture systems formed during the Pliocene and Quaternary. In
179 summary, this regional 'multidirectional' extensional stress field has been partitioned (in the
180 sense of Simón et al., 2008) into two stress systems, with S_{Hmax} (maximum horizontal stress
181 axis) nearly parallel to trends of the Jiloca and Teruel grabens, respectively, and directly
182 linked to the main tectonic stress sources during the Neogene-Quaternary in eastern Spain:
183 the intraplate NNW-SSE compression produced by Africa-Iberia convergence, and the
184 WNW-ESE extension induced by rifting at the Valencia trough (Simón, 1989; Herraiz et al.,
185 2000; Capote et al., 2002; Arlegui et al., 2005). A similar 'time dissociation' of the overall
186 stress field into distinct genetic stress systems (although in a compressional setting) has been
187 described in the Italian Alps as *Twist Tectonics* by Caputo et al. (2010). Moreover, minor-
188 order stress heterogeneities (deflection of stress trajectories, veering to become either

189 parallel or perpendicular to major faults; **swapping between** σ_2 and σ_3 axes) are also frequent
190 within this complex stress field (Simón, 1989; Arlegui et al., 2005, 2006).

191 The Concué Fault is a NW-SE trending, west-dipping fault, which shows an average
192 transport direction N220°E, has been active since the mid Pliocene, and totalizes a net slip of
193 255-300 m. Paleoseismological studies have been carried out on the Concué Fault based on
194 analysis of five trenches **where a wide paleoseismic succession has been reconstructed**
195 (Lafuente, 2011; Lafuente et al., 2011a, 2014; Simón et al., 2016). The results indicate that
196 the fault underwent eleven events since ca. 74 ka BP, with an average recurrence period of
197 7.1 to 8.0 ka (according to different hypotheses on the age of the youngest recorded event;
198 Simón et al., 2016). **Timing of paleoearthquakes on the fault has been constrained by a total**
199 **of 37 OSL ages.** The net accumulated slip during this time **interval was** 20.5 m, with average
200 coseismic slip of 1.9 m. The displacement pattern shows alternating ‘fast periods’ (up to 0.53
201 mm/a) and ‘slow periods’ (0.13 mm/a), resulting in an average slip rate of 0.29 mm/a. A
202 potential moment magnitude up to $M_w = 6.8$ has been estimated by Lafuente et al. (2011a)
203 based on the empirical correlation proposed by Wells and Coppersmith (1994), Stirling et al.
204 (2002) and Pavlides and Caputo (2004). Recent calculations made by Ezquerro et al. (2015)
205 using the equation by Hanks and Kanamori (1979), considering (i) a hypothetical rupture of
206 the total length (14.2 km) up to a 14 km-deep detachment level with an assumed dip angle of
207 60°, and (ii) the average coseismic slip inferred from paleoseismological studies, renders M_w
208 = 6.6.

209 Historic and instrumental seismicity of the Teruel Graben and the surrounding region
210 is low to moderate. **Epicentres are concentrated in several areas (see e.g. Simón et al., 2016,**
211 **fig. 2): Albarraeín Massif, western margin of the Jiloca Graben, relay zone between the**
212 **Concué and Sierra Palomera faults, northern Javalambre Massif, and southern sector of the**
213 **Teruel Graben.** There exists a moderate epicentre clustering along the Teruel Fault (see e.g.
214 **Simón et al., 2016, fig. 2).** Measured magnitudes (M_b) usually range from 1.5 to 3.5, with
215 maximum $M_b = 4.4$ in the Teruel Graben (data from Instituto Geográfico Nacional, 2010).
216 Before the instrumental period, intensities up to VIII were recorded in the Teruel Basin, **VI**
217 **VII in the Albarraeín Massif,** and IV-V in the Jiloca Graben. Focal depths typically range
218 from 5 to 15 km, at the brittle layer above the basal detachment level identified by Roca and
219 Guimerà (1992). Most of the available focal mechanisms correspond to normal faults, and
220 are consistent with the regional recent stress field (Herraiz et al., 2000).

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224

4. Structure and kinematics

4.1. The Teruel Fault

226 The Teruel Fault is a N-S striking, 9.0 km-long normal fault that extends from the
227 north of Teruel city to the south of Villaspesa village, offsets the Neogene infill of the Teruel
228 basin (Fig. 2a). In detail, it shows a single, N170°E trending trace in its northern sector,
229 while southwards it branches into two main fault traces trending N-S and NNW-SSE,
230 respectively. The latter, together with additional minor faults, progressively die out in the red
231 lutites of Rojo 2 unit and the coeval Castralvo gypsum succession.

232 The hanging-wall block shows a rollover structure reflected by tilting of the Páramo
233 2 unit (Figs. 2b, 3a). This unit exhibits an average dip of 2°E, its base decreasing in height
234 from 1010 m a.s.l. at the highest point to less than 880 m a.s.l. west of Teruel city. In the
235 footwall block, the base of the Páramo 2 unit lies at about 1130 m a.s.l., from which a
236 cumulative throw of ca. 250 m can be estimated. This displacement has been partially
237 accommodated by bending (perhaps, a monocline above a blind fault in a previous
238 evolutionary stage), with dips up to 17° at the east of the Teruel city and 30° at the southern
239 tip of the fault. The combination of rollover and monocline gives rise to a synformal sag
240 parallel to the fault (Figs. 2b, 3a,b).

241 Field measurements of rupture surfaces within the Teruel Fault show average strike
242 close to N-S and dip ranging from 60° to 80° W (average: 68°; Fig. 2c,d). Striations observed
243 on the main fault surfaces indicate an almost-pure normal movement with average transport
244 direction towards N275°E.

245 Considering (i) the above calculated throw, (ii) the average fault dip, and (iii) a pure
246 normal movement, a net slip of ca. 270 m can be inferred for the base of the Páramo 2 unit.
247 Given an age of ~ 3.6 Ma (latest Ruscinian, Godoy et al., 1983; Opdyke et al., 1997; Alcalá
248 et al., 2000) for this stratigraphic marker, the long-term slip rate is ca. 0.075 mm/a.

249 On the other hand, remnants of the Upper Terrace of the Turia River have been
250 mapped at an altitude of 970–980 m a.s.l. on the hanging wall west of the Teruel Fault (La
251 Muela site; Peña, 1981; Godoy et al., 1983). Moissenet (1983) identified the same level at a
252 small outcrop east of Teruel city at 1017 m a.s.l., interpreting a vertical offset of the T3
253 terrace close to 40 m. Nevertheless, the age of this terrace remains unknown, so that no slip

254 rate could be calculated from these data. An independent estimation of the overall rate since
255 the Late Pleistocene will be achieved at Puntal del Pitraque site, as explained below.

256 4.2. The relay zone between Teruel and Conclud faults

257 Surface structural information, together with results of geophysical (magnetic,
258 electromagnetic and georadar) surveys, suggest that the Teruel and Conclud faults are
259 geometrically and kinematically independent structures (Lafuente et al., 2011b). These faults
260 do not show any evidence of a physical link: the northern tip of the Teruel Fault is located at a
261 distance of 1.3 km from the Conclud Fault (Fig. 2a), and both have distinct hanging-wall
262 transport directions (N275°E and N220°E, respectively). They exhibit a right-stepping relay
263 geometry, their displacement being transferred by means of a relay ramp dipping towards N or
264 NNW, which can be clearly identified in Fig. 3a,b. Their displacement-length (D-L) profiles
265 show high displacement gradients approaching the relay zone (Fig. 3c), indicating sharp slip
266 transference between the faults. Further structural complexity at the relay zone occurs due to
267 the presence of a transverse faulted syncline (Mansuetos-Valdecebro syncline; Fig. 2a, 3a,b).

268 Although the northern tip of the fault is apparently located to the north of Teruel city,
269 there exist two sites aligned with the main trace where deformation structures affecting the
270 fluvial terrace T2b are exposed. These could hypothetically reveal a prolongation of the
271 Teruel Fault to the north, either at surface or as a blind fault (Figs. 2a, 3a). At Las Ramblillas
272 site, T2b is offset by two synthetic faults (one of them with decametre-scale throw), and
273 separated into two tilted blocks where bedding dips up to 10° E and 18° E, respectively (Fig.
274 4). The western synthetic fault has an average orientation 157, 48 W and striations that pitch
275 70°S. The measured fault plane is nearly parallel to that of the southern Conclud Fault, as
276 well as to the northern Teruel Fault (Fig. 2a). Cuesta de la Bajada site shows two main
277 rupture surfaces striking NNW-SSE, with minimum offsets of 7 m and 2.5 m, and associated
278 rollover monoclines that tilt T2b beds up to 28° E and 10° E, respectively (Peiro, 2016). If
279 the described deformation features actually represent the northwards propagation of the
280 Teruel Fault parallel to the adjacent Conclud Fault after the Middle Pleistocene, its total
281 length would be more than 11 km.

282 The only misfit concerns the kinematics of Las Ramblillas faults. The transport
283 direction (N 218°E, inferred from a single striation measure) closely approaches the average
284 calculated for the Conclud Fault (N220°E; Lafuente et al., 2011a,b), and clearly differs from
285 that recorded for the entire Teruel Fault (N275°E; Fig. 2e). Nevertheless, the possibility of

286 occasional slip of one of these faults following the typical transport direction of the other
287 fault cannot be ruled out. Indeed, Lafuente et al. (2014) describe striations recording two
288 distinct movements along transport directions SW and WNW superposed on a single rupture
289 plane of the Concué fault zone. This issue will be examined later when discussing strain
290 partitioning between these structures.

291

292

293 **5. Preliminary paleoseismological characterization of the Teruel Fault**

294

295 Several empirical relationships allow the expected maximum moment magnitude
296 (M_w) of a fault and its associated coseismic displacement to be estimated. Those proposed by
297 Wells and Coppersmith (1994), Stirling et al. (2002), Pavlides and Caputo (2004), and
298 Mohammadioun and Serva (2001) have been applied in this study. Considering a length of
299 9.0 km for the Teruel Fault and applying the mentioned relationships, values of M_w ranging
300 from 6.1 to 6.6 are obtained (Table 2). For the coseismic displacement, there is some
301 disagreement between the results obtained from the different correlations. Wells and
302 Coppersmith (1994) and Pavlides and Caputo (2004) correlations yield values of 0.40 m and
303 0.65 m, respectively, while that by Stirling et al. (2002) attains 1.32 m (Table 2). These
304 estimates will be later compared with real offsets measured in trenches. As mentioned above,
305 there exists the possibility of a prolongation of the Teruel Fault to the north, reaching a total
306 length of at least 11 km. If this length was considered, the inferred M_w values and coseismic
307 displacements would be a little higher (Table 2).

308 Combining the potential coseismic displacement based on empirical relationships
309 (0.37 m to 1.28 m, considering a 9 km-length fault) with the long-term slip rate calculated
310 since mid Pliocene times (0.075 mm/a; only reliable rate available for the fault prior to the
311 present research), a recurrence interval between 4.9 ka and 17.1 ka is tentatively approached.
312 If the fault were 11 km long, the recurrence periods would slightly increase (5.3-17.6 ka).

313

314 **6. Detailed structure of the Pitraque-Valdelobos area**

315 In the Pitraque-Valdelobos area the Teruel Fault cuts Quaternary deposits, so it has
316 been selected for trenching study. Puntal del Pitraque is a conical hill located 1.2 km south of
317 Teruel city, in the area where the Teruel Fault splits southwards into several synthetic fault
318 branches (M, N, P, Q, R, S in Fig. 5a; see location in Fig. 2a). A remnant of the lower
319 sublevel of the Middle Terrace (T2a) occupies the top of the hill. A larger remnant of the

320 same terrace appears on a horizontal platform some 100 m westwards. T2a unconformably
321 overlies Neogene units (Rojo 2 and Páramo 2), and had previously provided an OSL age of
322 76.0 ± 5.0 ka (Simón et al., 2012). The Rambla de Valdelobos is a gully oriented transverse
323 to the Teruel Fault that drains westwards into the Turia River, south of Puntal de Pitraque
324 and shows a relatively wide bottom filled with Holocene clastic sediments, where the gully
325 is slightly incised.

326 The main Teruel Fault branch (M) crops out north of Puntal del Pitraque site (Fig.
327 5b), where it has an average strike N033°E and juxtaposes the Páramo 2 (hanging-wall
328 block) and Rojo 2 (footwall block) units. The other macro-scale faults are also clustered
329 around NNE-SSW (N024°E in average from outcrop measures) and show westwards dip
330 ranging from 52° to 84° (68°W in average) (Fig. 5c,d). Each individual fault offsets several
331 metres to several tens of metres the Neogene beds. Together with the main fault and the
332 monocline visible at the footwall block, the total displacement accommodated across this
333 transect is estimated at 190 m (Figs. 2b, 3a).

334 The top of Middle Terrace (T2a) at Puntal del Pitraque lies 8.2 m higher than that at
335 the western, horizontal platform (Fig. 5e). Such a height difference can be attributed to
336 displacement on fault branches M and N. The corresponding net slip, assuming the average
337 dip of the rupture surface (68°) and the inferred transport direction (N275°E), is ca. 8.8 m.
338 Using the previously available OSL age at the base of the terrace deposits (76.0 ± 5.0 ka),
339 Simón et al. (2012) calculated a minimum slip rate of 0.12 ± 0.01 mm/a since ca. 76 ka.
340 Taking into account that the marker where that offset was measured is the terrace top, and
341 hence If the younger OSL age provided in the present work (46.5 ± 3.2 ka; Table 3) is
342 assigned to the terrace top, a more realistic slip rate of 0.19 ± 0.01 mm/a is obtained for the
343 Late Pleistocene-Holocene. Moreover, Since the displacement is only recorded at two
344 (among five) synthetic branches within the fault zone, the total slip rate for the overall
345 structure should exceed this value. The absence of Quaternary deposits displaced by the
346 eastern branches of the fault makes impossible to test such hypothesis.

347 The primary target for our paleoseismological study was the M fault branch west of
348 Puntal del Pitraque, where the initial field survey revealed small, decimetre-scale offset of
349 the fluvial terrace T2a. Two paleoseismological trenches (Pitraqe 1 and Pitraqe 2) were
350 excavated at this site, exposing Neogene lacustrine limestones and lutites unconformably
351 overlain by the Pleistocene materials. Detailed inspection after trench digging showed that,
352 within the M branch, the main observed fault surface (F_{μ}), locally striking N020°E to

353 N030°E, is cut by a second fault ($F\alpha$) striking N050°E, which is exposed in Pitraque 2 trench
354 and apparently extends below Pitraque 1 (Fig. 6a). In addition, a third fault striking N019°E
355 is exposed in Pitraque 2 ($F\beta$) as well as at the natural terrace scarp. $F\beta$ constitutes the
356 prolongation of $F\mu$, but their physical linkage could not be observed in the field. The
357 described structural relationships suggest local segmentation of the main NNE-SSW fault
358 surfaces, these being articulated with (and their displacement being locally transferred to)
359 NE-SW striking faults. Fracture patterns observed at a mesostructural scale, both in trenches
360 and on natural outcrops (Fig. 6b,c,d,e), are consistent with the general structure of the
361 Pitraque-Valdelobos area, although the range of strike values (from NNE-SSW to ENE-
362 WSW) is wider than that expressed at macroscale (Fig. 5d), owing to juxtaposition of that
363 second fracture set around N050°E to the main, N020°E to N030°E striking set. Further
364 geometric description and kinematic interpretation of the fracture systems will be provided
365 while analysing each individual trench.

366

367 7. Trench study at the Pitraque-Valdelobos area

368

369 7.1. Pitraque 1 trench

370 The Pitraque 1 trench was excavated for studying deformation associated to the main
371 branch of the Teruel fault zone (M in Fig. 5a,c). This trench trends N148°E, is 12.5 m long
372 and 4.5 m deep; its western wall was selected for detailed logging and analysis (Fig. 7a).
373 Neogene sedimentary units (Rojo 2 and Páramo 2) crop out in the lower part of the trench,
374 overlain by Pleistocene coarse clastic, generally well cemented materials that have been
375 subdivided into six units (1 to 6 in Fig. 7a; see detailed description in Appendix 1).

376 The largest deformation structure exposed in this trench is a gentle bending fold that
377 occupies most of the logged section shown in Fig. 7a. The geometry of the fold is continuous
378 along both the Pliocene and Pleistocene beds (units 2 to 5), which suggests that most of
379 folding essentially occurred after sedimentation of unit 5. Perhaps this fold had already
380 deformed the Pliocene units before Pleistocene sedimentation, but The boundary between
381 both lithological successions essentially represents an erosional discontinuity, not an
382 unconformity.

383 The Páramo 2 unit is also deformed by a number of normal, NE-SW striking faults
384 (domain 4 in Fig. 7a) that make a rough conjugate system with a dominant strike close to
385 NE-SW (Fig. 7e). The overlying Pleistocene units in the northwestern sector are affected by

386 numerous fractures also with an average NE-SW strike (domain 2; Fig. 7a,c). These fractures
387 include a few small faults with centimetre-scale offsets, small closed joints, and a large
388 tensile crack filled with carbonate (C1 in Fig. 7a) that attains about 2 m in length and 20 cm
389 in thickness. The fracture systems affecting domains 2 and 4 are disconnected from each
390 other; indeed, the only Pleistocene fracture that could be rooted in a Neogene fault does not
391 clearly show any physical linkage with it (see cell 10c in Fig. 7a). Domain 1 shows the same
392 types of faults and fractures as in domain 2 (although in domain 1 these are mostly close to
393 vertical; Fig. 7b), as well as a second large open crack filled with carbonate appears within
394 this domain (C2 in Fig. 7a), showing even more walls than C1. Finally, domain 3 contains a
395 number of small faults close to the Neogene-Pleistocene boundary. One of them (F γ), is
396 oriented NE-SW, produces an offset of about 0.1 m on it and propagates within the lower
397 part of Unit 2. The others are oriented NNW-SSE (Fig. 7d) and do not produce any visible
398 displacement.

399 Most fractures in the lower structural domains (3 and 4) express the prevailing
400 extensional fracture pattern in the region, represented by sets oriented NNW-SSE and NNE-
401 SSW, i.e. parallel to macroscale faults of the Jiloca and Teruel grabens, respectively. In
402 contrast, most fractures within domains 1 and 2 seem to be induced by local deformation
403 conditions, i.e. the bending fold. This interpretation is based on two pieces of evidence: (i)
404 most of the fractures are concentrated within the outer arc at the hinge zone (cells 9d and 10d
405 in Fig. 7a); (ii) the movement plane of the bending fold, as defined by poles of bedding (Fig.
406 7f), is nearly orthogonal to NE-SW fractures of domains 1 and 2 (including cracks C1 and
407 C2, which accommodate an important part of stretching affecting units 3, 4 and 5 in the outer
408 arc). Although at present most of these fractures dip towards SE, they probably originated as
409 nearly vertical fractures, as can be inferred by restoring bed tilting. The genetic dependence
410 of these fractures with respect to local bending, as well as the rheological contrast between
411 Pleistocene cemented clastic deposits and Neogene carbonates, could explain why the
412 fracture systems affecting domains 2 and 4 appear to be independent from each other.
413 Bending, and hence the associated tensional fractures, could be related to movement on
414 either an adjacent fault cutting Pliocene units (tentatively, F δ in Fig. 7a, striking N 030° E) or
415 an underlying blind fault.

416 Considering the structural relationships between faults and sedimentary units, as well
417 as their OSL ages (Fig. 7a; Table 3), three paleoseismic events have been identified:

418 - **Event(s) X_{P1}**. Interpreted by the rupture and displacement (not quantified) of
419 Neogene materials along fault F_α, and maybe other faults in domain 4, prior to local
420 sedimentation of the Pleistocene terrace. More than one paleoearthquake could have resulted
421 in such faulting, but they cannot be distinguished. This event (or events) occurred before
422 70.7 ± 5.3 ka BP (earliest OSL age obtained in the lower part of Unit 1). From the geologic
423 record in the trench, it is not possible to estimate the associated displacement.

424 - **Event Y_{P1}**. Interpreted by the rupture along a small fault (F_γ), which produces a
425 throw of 0.1 m at the base of the Pleistocene Unit 2. Predated by the upper part of Unit 1
426 (OSL age of 70.7 ± 5.3 ka BP) and postdated by overlying materials of Unit 2 (OSL age of
427 71.8 ± 5.1 ka BP).

428 - **Event Z_{P1}**. Represented by bending of Neogene (R2, P2) and Pleistocene (2, 3, 4, 5)
429 units and development of associated tensional fractures, including opening of cracks (C1 and
430 C2) subsequently filled with carbonate. All fractures would be hypothetically related to
431 movement of either fault F_δ or an underlying blind fault. This event is predated by the
432 youngest available OSL age (48.5 ± 3.8 ka BP; middle-upper part of Unit 5), and postdated
433 by the regolith (Unit 4, probably Holocene in age). Considering the amplitude of the
434 bending fold, a minimum coseismic throw of 1.0 m is estimated on a hypothetical
435 underlying, blind fault (coseismic net slip >1.1 m for a 70° dipping plane).

436

437 7.2. Pitraque 2 trench

438 Pitraque 2 trench also exposes the main branch of the Teruel fault zone (M in Fig.
439 5a,c). It trends N133°E, is 7.5 m long and 2.5 m deep, the southwest wall being selected for
440 study (Fig. 8a). Neogene sediments similar to those described As in Pitraque 1 trench, Rojo 2
441 and Páramo 2 Pliocene units underlie Pleistocene conglomerates and sandstones, which have
442 been subdivided into four units (1 to 4 in Fig. 8a); see detailed description in Appendix 1).

443 Two main normal faults are exposed in Pitraque 2 trench. To the northwest, fault F_α
444 (domain 2; Fig. 8a,d), locally striking N035°E, offsets the Neogene units sinking its NW
445 block and being responsible for erosion of Páramo 2 unit at the SE one; then F_α is overlain
446 by non-affected Pleistocene deposits. To the southeast, F_β (N019°E) offsets Pleistocene units
447 1, 2 and 3, producing the same throw (0,5 m) on each of them, and splits upwards into
448 several splay faults (domain 1, Fig. 8a,b,c). The association of splay faults to the main fault
449 makes a *horse tail* structure (as defined by Granier, 1985), which is interpreted to be the

450 product of local stretching close to the fault tip while fault $F\beta$ was activated and propagated
451 through the overlying Pleistocene deposits. This fracture system is also exposed on the
452 opposite trench wall, with the same NNE-SSW to NE-SW strike and exhibiting pure-normal
453 striations on the main fault $F\beta$ (Fig. 8e). Finally, a tensile crack filled with carbonate (C3),
454 similar to C1 and C2 of Pitraque 1 trench, overprints this system of splay faults. Although
455 included within the main fault zone, C3 represents a kinematically distinct deformation
456 pattern. Its opening vectors, with homogeneous length about 2-3 cm, are nearly orthogonal to
457 the crack walls (Fig. 8a,b). Such a displacement pattern does not fit slip parallel to fault $F\beta$,
458 and instead is consistent with tangential stretching at the outer arc of an accommodation
459 monocline.

460 Three paleoseismic events have been interpreted (Fig. 8a; Table 3):

461 **Event(s) X_{P2} .** As in the case of Event X_{P1} , deformation previous to deposition of the
462 observed Pleistocene units is attributed to a first local event, although it may represent more
463 than one paleoearthquake. Two inferred fault movements can be assigned to such a
464 ‘composite’ X_{P2} event: (i) movement of $F\beta$ that cut the Neogene Rojo 2 unit previously to
465 deposition of Unit 1, therefore before 78.3 ± 5.2 ka BP; its associated *horse tail* structure (a
466 fracture pattern typically found at extensional fault tips) involves activation of a blind, pre-
467 existent fault through the overlying Pleistocene deposits; (ii) rupture and displacement of
468 Rojo 2 and Páramo 2 units along fault $F\alpha$, as well as northwards tilting, previous to $50.0 \pm$
469 3.4 ka BP (age of the base of Unit 2, not affected). Since $F\alpha$ is also exposed in Pitraque 1
470 trench, where it is postdated by OSL 70.7 ± 5.3 ka BP, we can assume this time constrain for
471 it. These two fault movements cannot be chronologically distinguished and their associated
472 displacements remain unknown.

473 **Event Y_{P2} .** Rupture and displacement of Pleistocene units 1, 2, and 3 along fault $F\beta$
474 and its associated splay faults. Predated by the youngest OSL age available in the trench, at
475 the base of Unit 3 (46.5 ± 3.1 ka). The associated coseismic slip along fault $F\beta$ can be
476 estimated at 0.5 m.

477 **Event Z_{P2} .** Represented by opening of tensile crack C3, which was subsequently
478 filled with carbonate. As with the previous event, this one is predated by the youngest
479 available OSL age (46.5 ± 3.1 ka), and postdated by the regolith (Unit 4, probably Holocene
480 in age). We infer that the Z_{P2} event is distinct from the former event based on the kinematic

481 differences between the tensile crack and the structures linked to Event Y_{P2} . The geometry of
482 deformation does not permit measurement of coseismic slip.

483

484 7.3. Valdelobos trench

485 This N100°E trending trench was excavated in the T0 terrace of Rambla de
486 Valdelobos some 0.4 km south of Puntal del Pitraque, where the gully apparently crosses the
487 fault branch P (Fig. 5a), and its talweg exhibits a discrete gradient anomaly inferred from the
488 laser-levelling profile (Fig. 5f). An exposure of around 5 m long and 2.5 m deep along the
489 southern wall of the trench shows massive red Neogene
490 lutites (Rojo 2) at its base, which are covered by Quaternary clastic deposits subdivided into
491 five units (1 to 5 in Fig. 9; see detailed description in Appendix 1).

492 The Neogene materials exposed at the trench bottom are displaced by a normal fault
493 (Fε) striking N155°E (Fig. 9). This fault also affects the lowermost Quaternary deposits
494 (Units 1 and 2), and is covered by Unit 3. The minimum fault throw is 0.3 m, but it could be
495 much larger since the fault scarp was eroded below the base of Unit 2. A single event has
496 been interpreted in this case, referred to as Event Z_{VL} , this event occurred between $26.7 \pm$
497 1.9 ka BP (age of Unit 2) and 9.9 ± 0.7 ka BP (age of Unit 3).

498

499 8. Interpretation and discussion

500

501 8.1. Paleoseismic record of the Teruel Fault: correlation of events

502 Correlation of events between the Pitraque and Rambla de Valdelobos trenches
503 (Table 4; Fig. 10) has been accomplished on the basis of geological judgement and OSL
504 ages. It can be conventionally assumed that Event(s) X is common to both Pitraque 1 and
505 Pitraque 2 trenches and inferred to be the same event (now renamed as Event 0): this event
506 only affects Neogene materials, exhibiting upper time limits 70.7 ± 5.3 and 78.3 ± 5.2 ka BP,
507 respectively, for each trench. We are aware that this event could actually represent a
508 succession of several seismic episodes, either Pleistocene or even Pliocene in age.
509 Considering the OSL ages that constrain their timing, Y_{P1} and Y_{P2} are interpreted as being
510 two independent events: Event 1, with absolute time brackets 76.0 and 66.7 ka BP (central,
511 most probable age: 70-71 ka BP), and Event 2, younger than 49.6 ka BP. Z_{P1} and Z_{P2} are
512 interpreted as a single event (renamed Event 3, younger than 49.6 ka BP), taking into

513 account their postdating OSL ages, the style of deformation (crack opening, subsequent
514 carbonate filling) and the orientation of coseismic fractures (around NE-SW in both cases).
515 Finally, Event Z_{VL}, only recorded at the Rambla de Valdelobos trench and therefore at a
516 different fault branch, represents the youngest event (renamed Event 4, with absolute time
517 brackets 28.6 and 9.2 ka BP).

518 In summary, the trench study has yielded ~~at least five independent events~~: one (or
519 several) ~~uncertain event~~ prior to 73.1 ka BP, and four ~~events~~ occurred between 76.0-66.7 ka
520 and 28.6-9.2 ka BP. This four-event-succession yields an average recurrence period ~~in the~~
521 ~~range of 9.5-16.7 ka~~. Nevertheless, the individual interseismic periods remain unknown, ~~as~~
522 ~~only the timing~~ of events 1 and 4 are ~~constrained~~ (quite widely in the case of the second
523 one), ~~while the timing of Events 2 and 3 is unconstrained (only with a single, shared~~
524 ~~predatum).~~

525 8.2. Representativeness of the paleoseismic record of the Teruel Fault

526 Events 1, 2 and 3 occurred on the western, main branch (M) of the Teruel Fault, while
527 Event 4 occurred on a minor branch (P; see map in Fig. 5a). Events 1, 2 and 3 represent a
528 minimum accumulated net slip of 1.7 m on branch M. The average coseismic slip for these
529 three events (0.57 m) lies close to the estimates ~~made from~~ the empirical correlations of
530 Wells and Coppersmith (1994) and Pavlides and Caputo (2004): ~~0.40 m and 0.65 m,~~
531 ~~respectively~~ (see section 5 and Table 2). This suggests that (i) these correlation models ~~better~~
532 ~~describes our data~~ than that ~~of~~ Stirling et al. (2002), ~~which yields a value of 1.32 m,~~ and (ii)
533 the recorded paleoseismic ~~single event displacements~~ approach the *characteristic earthquake*
534 of the Teruel Fault (in the sense of Schwartz and Coppersmith, 1984). If Event 4 is
535 incorporated, the results do not ~~change substantially~~: minimum net slip on branches M+P (as
536 recorded in trenches) will attain 2.0 m, with average coseismic slip of 0.50 m, and local slip
537 rate of 0.04 ± 0.01 mm/a (~~estimate from hypothetical ages of the four events within their~~
538 ~~respective time constraints~~; Fig. 11d).

539 ~~This~~ paleoseismic succession only represents a fraction of the total ~~activity~~ on the
540 western branches ~~of the fault system~~ during the ~~sampled time interval~~. It should be reminded
541 that the total offset of the fluvial terrace T2a represents a net slip of 8.8 m, with slip rate =
542 0.19 ± 0.01 mm/a for the last 46.5 ± 3.2 ka (Fig. 11d; see Section 6 and Table 5). Therefore,
543 only a small part of the paleoseismic history of the Teruel Fault during the studied time
544 window has been recorded in the studied trenches, and the calculated average recurrence
545 period (~~9.5 to 16.7 ka~~) has little meaning. Assuming the average coseismic slip of 0.57 m

546 and the accumulated net slip of 8.8 m, the total number of paleoseismic events on branches
547 M+N since 76.0 ± 5.0 ka BP could attain fifteen, with a shorter average recurrence period of
548 5.1 ± 0.3 ka (close to the minimum estimated from empirical correlation, 4.9 ka).

549 ~~Unfortunately, no other site apart from Pitraque and Rambla de Villalobos is available for~~
550 ~~trenching syntectonic Quaternary sediments across the fault, so improving the present~~
551 ~~paleoseismic record will be difficult.~~

552 8.3. Comparison with the paleoseismic record of the Concul Fault

553 The paleoseismic results for the Teruel Fault can be compared with those previously
554 obtained on the neighbouring Concul Fault (Lafuente, 2011; Lafuente et al., 2011a, 2014;
555 Simón et al., 2016) in order to analyse the seismogenic dependence or independence
556 between them. At first glance, the recorded paleoseismic activity of the Teruel Fault seems
557 significantly lower than that of the Concul Fault during a similar time period (76 ka vs. 74
558 ka BP; Fig. 10; Table 5): four events with average coseismic slip of ca. 0.6 m vs. eleven
559 events with average coseismic slip of 1.9 m. Nevertheless, we should remind that the
560 paleoseismic record obtained for the Teruel fault zone should be considered: it only includes
561 the seismic events occurred on two fault branches (M and P), which represent just a fraction
562 of the total activity at the Teruel Fault zone. With this respect, it would be more realistic a
563 comparison with the paleoseismic record obtained at a single fault branch in the the central
564 sector of the Concul Fault (Fig. 11b,d; Table 5). Two trenches excavated across its southern
565 branch (El Hocino site) could be studied, provided a sequence of five events occurred since
566 74 ka BP, with an accumulated net displacement of 3.9 m, average coseismic slip close to 0.8
567 m, and slip rate of 0.05 mm/a (Fig. 11b) (Lafuente et al., 2014). These results are closer to
568 those obtained for the Teruel Fault in the present work, which allows us to estimate that the
569 likely degree of activity of both faults has been similar. Unfortunately, due to the poor time
570 constraint on individual events interpreted for the Teruel Fault, comparing and correlating
571 events recorded on the Teruel and Concul faults is impractical (Fig. 10).

572 8.4. Structural and seismotectonic relationships between the Teruel and Concul faults

573 As stated above, surface and shallow subsoil information does not support the
574 hypothesis of full structural link between the Teruel and Concul faults (hard linkage in the
575 sense of Walsh and Watterson, 1991). Moreover, their distinct transport directions (N275°E
576 vs. N220°E) indicate that they behave as two independent structures from the kinematic
577 point of view. Their separate displacement-length profiles at the relay zone (Fig. 3c) are also
578 consistent with such independence, although the sharp gradients of these profiles close to the

579 fault tips suggest some dynamic interaction between them.

580 Our paleoseismological study provides further evidence for autonomous activity on
581 each fault. Time constraints of events in the Teruel Fault do not allow us to either confirm or
582 disprove that some events ruptured both faults (Fig. 10). Nevertheless, coseismic
583 displacements observed at the Teruel Fault helps us to suggest that the Teruel and Concu
584 faults behave as two independent seismogenic sources instead of as a single seismogenic
585 structure. Displacement values of the Teruel Fault (0.1 to 1.1 m; average = 0.5-0.57 m): (i)
586 are consistent with those expected for a 9.0 km-long fault according to empirical correlation;
587 (ii) are significantly smaller than those actually recorded on the 14.2 km-long Concu
588 (1.9 m, in average); and (iii) are less consistent with a hypothetically joint Concu-Teruel, 23
589 km-long fault (expected coseismic slip ranging from 0.7 m to 2.4 m, according to empirical
590 correlation; see section 5 and Table 2). Moreover, the difference between their prevailing
591 transport directions, previously noticed from overall kinematic data at both faults, has been
592 confirmed from faults exposed in paleoseismological trenches (Fig. 11a,c).

593 Another different issue concerns the location of the true northern tip, and hence the
594 true length of the Teruel Fault and its distance to the Concu Fault. Faults and associated
595 tilted beds observed in Middle Pleistocene deposits at two sites (Cuesta de la Bajada and Las
596 Ramblillas; see location in Fig. 2a) suggest a prolongation of the Teruel Fault some 2 km
597 northwards from the mapped tip point located north of Teruel city. As in the case of the
598 Concu Fault, no trace can be identified through the flood plain of the Alfambra River
599 (Holocene, T0 terrace), but the Teruel Fault could cut the underlying Neogene and
600 Pleistocene units. Future research in this area, including geophysical surveys of the Alfambra
601 flood plain, may clarify this issue.

602 The transport direction inferred at Las Ramblillas (N218°E) differs from that of the
603 Teruel Fault (N275°E) and is approximately parallel to that of the Concu Fault (N220°E).
604 This anomalous observation plays somehow against the full connection of the Las
605 Ramblillas structure to the Teruel Fault, and points to two alternative hypothesis: (i) the
606 outcropping Las Ramblillas fault is a smaller, recent synthetic rupture kinematically
607 associated with the Concu Fault, although it could play a role within an eventual linkage
608 process with the Teruel Fault; (ii) the striation measured on the Las Ramblillas fault is not
609 representative of its prevailing transport direction: in the same way that a second striation
610 exists on the Concu Fault surface at El Hocino site, oriented towards NW and overprinting
611 the SW-oriented prevailing striation (Fig. 11a; Lafuente et al., 2014), an ‘anomalous’

612 movement towards SW could have been recorded on the Teruel Fault.

613 In any case, the tentative propagation **and linkage** of the Teruel Fault **with the** Las
614 Ramblillas structure would represent a recent, incipient process, as suggested by the
615 pronounced bell-shape of its D-L profile. In this profile a high D-L gradient at the relay zone
616 (around **the** abscise 14 km in Fig. 3c) is followed by a sharp reduction of the gradient near
617 the northern tip (frictional breakdown zone; Cowie and Sholz, 1992; Cowie and Shipton,
618 1998).

619 *8.5. Dynamic interaction and future linkage?*

620 Although the Teruel and Concud faults **remain two** independent structures, future
621 linkage **is possible**, as proposed by Ezquerro et al. (2012) and Lafuente et al. (2012). **Linkage**
622 **would be** consistent with the mechanical state inferred for the relay zone. **In spite of their**
623 **geometric and kinematic independence,** The steep gradients of their displacement-length (D-
624 L) profiles **in the relay** zone **indicate** that both faults undergo dynamic interaction, according
625 to theoretical models. The elastic strain fields of two adjacent faults interfere close to their
626 tip lines, which tends to hinder propagation while displacement increases, resulting in
627 anomalously high displacement gradients (Huggins et al., 1995; Nicol et al., 1996;
628 Cartwright and Mansfield, 1998; Gupta y Scholz, 2000; Peacock, 2002).

629 According to this hypothesis, the relay zone between the Teruel and Concud faults is
630 in a transient stage from independence to linkage. **It cannot be anticipated how such full**
631 **connection would happen.** The coalescence of Las Ramblillas fault with both the Teruel and
632 Concud faults could be the most probable one, the southernmost, NNW-SSE trending
633 segment of the Concud Fault **probably** remaining as an inactive splay fault (Childs et al.,
634 1995). **Alternatively,** transverse faults of the Mansuetos-Valdecebro structure could cut the
635 relay ramp, **resulting in a transfer fault zone** (hard linkage. **Walsh and Watterson, 1991).**

636 *8.6. A scenario of strain and stress partitioning at the scale of the seismic cycle*

637 Owing to their dynamic interaction, it is expected that displacement on one fault
638 results in stress perturbation **of** the rock volume surrounding the other fault, and vice versa.
639 At the scale of individual earthquakes, static Coulomb stress changes could trigger seismic
640 events **on** segments of the other fault that were approaching critical conditions for rupture
641 (Freed, 2005; King et al., 1994).

642 This suggests a scenario of slip on both structures taking place in a broadly
643 alternating **manner**: stress release on one fault after a seismic event, and stress instability

644 induced in the surrounding volume, will favour the next event to occur in the other fault (Fig.
645 12). Indeed, the average recurrence period may be similar for both structures during the Late
646 Pleistocene times, with 7.1 ± 3.5 to 8.0 ± 3.3 ka on the Conclud fault (Simón et al., 2016),
647 and 10-15 ka on the Teruel Fault, as estimated from empirical correlation proposed by
648 Villamor and Berryman (1999) using the average slip rate. This scenario involves local strain
649 partitioning between the Teruel and Conclud faults at the scale of the seismic cycle,
650 representing a small incremental deformation episode within overall strain partitioning
651 between NNW-SSE and NNE-SSW normal faults.

652 It is known that conjugate fault systems formed according to Mohr-Coulomb's failure
653 criterium only accommodate plane strain ($\lambda_2 = 1$). In order to accommodate 3D finite strain,
654 movement on multiple-set fault patterns (such as those typically made of four sets with
655 orthorhombic symmetry) is necessary (Reches, 1978; Krantz, 1989; Nieto-Samaniego,
656 1999). Therefore, the biaxial extensional deformation that characterizes the recent tectonic
657 setting of eastern Iberian Chain (Simón, 1982, 1989; Capote et al., 2002) could not be
658 accommodated by a single fault set, or by a single conjugate normal fault system;
659 progressive slip on diversely orientated fault planes and along diverse transport directions is
660 needed.

661 However, this does not occur as a linear, steady process, but as a non-linear sequence
662 of rupture episodes, during discontinuous deformation. The bulk 3D deformation is
663 partitioned into a number of slip events on individual faults, which in their turn involve a
664 sequence of episodic, systematic (not chaotic) stress changes that Simón et al. (2008) define
665 as *stress partitioning*. Each failure event is compatible with stress-based models, while the
666 finite 3-D strain fits kinematic boundary conditions.

667 The described process can occur at any spatial scale between e.g. tensile joints up to
668 intraplate regions, and also at a wide range of time scales. In our study region, the long-term,
669 Neogene-Quaternary tectonic evolution of eastern Iberia is characterized by both spatial
670 transition and time shifting between regional stress systems with NNW-SSE and NNE-SSW
671 S_{Hmax} trajectories, coexisting with local switching to orthogonal, either ENE-WSW or ESE-
672 WNW trending ones (Simón, 1989; Cortés et al., 1996; Herraiz et al., 2000; Arlegui et al.,
673 2005). At a much shorter time scale, it is known that earthquake focal mechanisms
674 frequently reveal stress instabilities during aftershock sequences, some fault mechanisms
675 being representative of the regional stress field while others represent second-order stresses
676 including episodes of stress axis swapping (Mercier et al., 1989; Bowman et al., 2003;

677 Caputo, 2005). Similar outcomes arise from laboratory experiments carried out by Reches
678 and Dieterich (1983), which describe how fracture patterns made of four sets with
679 orthorhombic symmetry (needed for accommodating 3D finite strain) developed through two
680 yielding events with swapping of the two major stress axes between them.

681 Our hypothesis is that strain/stress partitioning also occurs at an intermediate time
682 scale, i.e. the scale of seismic cycle (as postulated as well for the notion of *Twist Tectonics* by
683 Caputo et al., 2010) giving rise to the above postulated scenario of broadly alternating slip
684 on the Teruel and Concud faults. Dynamic interaction between neighbouring faults
685 (described in the previous section) provides the way for that process to come about. In this
686 way, our scenario: (i) is consistent with the structural and dynamic relationships between
687 faults, (ii) is consistent with the intrinsic stress changes in the complex regional stress field,
688 and (iii) allows accommodation of bulk biaxial extension in the Teruel region.

689 8.7. Implications for seismic hazard assessment

690 The type of relationship interpreted for the Teruel and Concud faults has undeniable
691 implications for seismic hazard assessment of the Teruel region. In general, an intermediate,
692 transient stage (structural decoupling but dynamic interaction) implies a different seismic
693 hazard level than that involved by the alternative, extreme options: (i) full independence, or
694 (ii) linkage.

695 A hypothetically linked Concud-Teruel fault, with a total length of 23 km, would
696 represent a seismogenic structure able to produce larger earthquakes than those generated by
697 each separate structure. Their characteristic earthquake would show maximum moment
698 magnitude $M_w \approx 6.6-7.0$, while $M_w \approx 6.1-6.6$ and $M_w \approx 6.6-6.8$ for the single Teruel and
699 Concud faults, respectively (Table 2). In the case of two independent seismic sources, with
700 each having a similar recurrence period to that of the hypothetical linked structure, the
701 probability of occurrence of such characteristic earthquakes in a given term would be
702 significantly increased.

703 On the other hand, dynamic interaction between both faults involves shortening of
704 the seismic cycle. Local stress perturbations induced by movement on one fault can trigger
705 movement on the other one, which is found to be most evident within short distances (up to
706 ≈ 5 km), although only for events that are relatively late in their respective earthquake cycle
707 (Chen et al., 2010).

708

709 9. Conclusions

710 (1) Surface and shallow subsoil information indicates that the Teruel and Conclud faults
711 are not structurally linked. They also behave as kinematically independent structures, with
712 distinct transport directions: N275°E and N220°E, respectively.

713 (2) The Pleistocene paleoseismic record of the Teruel Fault includes four events. ~~One~~
714 ~~of them (Event 0, probably representing a succession of several seismic episodes indeed) is~~
715 ~~prior to 73.1 ka BP, and the other four~~ (Events 1, 2, 3, and 4) occurred between 76.0 and 9.2
716 ka BP (Table 4, Fig. 10). Since timing of individual events is poorly constrained, the duration
717 of interseismic periods remains unknown. The recorded paleoseismic activity only represents
718 a limited succession of slip events in two fault branches (therefore far from embodying the
719 total activity of the Teruel fault zone).

720 (3) This paleoseismic record is significantly lower than that of the overall Conclud
721 Fault during a similar studied time lapse (76 ka BP vs. 74 ka), but comparable to that
722 obtained in the southern branch of the Conclud Fault at its central sector (Fig. 11). Hence we
723 estimate that the overall degree of activity of both faults could be similar. The most
724 representative slip rates obtained from morpho-sedimentary markers (see Table 5) are \approx
725 0.075 mm/a for the last \sim 3.6 Ma on the overall Teruel fault zone, and 0.19 ± 0.01 mm/a for
726 the last 46.5 ± 3.2 ka on two branches at Pitraque site. Strictly considering the events
727 recorded at trenches, such slip rate is reduced to 0.04 ± 0.01 mm/a. These values are
728 comparable to those previously obtained at the Conclud Fault: 0.07-0.08 mm/a for the last \sim
729 3.6 Ma, and 0.29 mm/a since \sim 74 ka BP on the entire fault zone; 0.05 mm/a since \sim 74 ka BP
730 on a single branch (Lafuente, 2011; Lafuente et al., 2011a, 2014; Simón et al., 2016).

731 (4) Owing to the poorly constrained timing of events identified at the Teruel Fault,
732 comparing and correlating them with those on the Conclud Fault is not feasible, neither
733 ~~Therefore, our results are not conclusive in order~~ discerning whether some rupture event
734 have simultaneously occurred on both faults. Nevertheless, the observed coseismic
735 displacements on the 9.0 km-long Teruel Fault (average = 0.5-0.57 m) are consistently
736 smaller than those previously measured on the 14.2 km-long Conclud Fault (average = 1.9
737 m), and unsuitable for a hypothetically joint Conclud-Teruel, 23 km-long fault. We therefore
738 interpret that the Teruel and Conclud faults behave as two independent seismogenic sources.

739 (5) In spite of their geometric and kinematic independence, both structures undergo
740 dynamic interaction (i.e. stress perturbation at the rock volume surrounding one fault
741 subsequent to activation of the other one). This could have induced broadly alternating slip

742 on both faults along their distinctive transport directions, which would involve a certain type
743 of strain partitioning at the scale of the seismic cycle (Fig. 12): combining multiple slip
744 events on both fault surfaces would allow accommodation of bulk 3D deformation in the
745 Teruel region, within the framework of a biaxial extensional stress regime. The described
746 scenario represents a transient stage from independence to linkage; future connection
747 (probably through coalescence with an intermediate fault, Las Ramblillas fault) is a potential
748 process.

749 (6) Structural relationships between the Teruel and Conclud faults clearly influences
750 seismic hazard of the studied region. Two independent seismic sources will produce smaller,
751 although more frequent earthquakes than those generated by a hypothetically linked Conclud-
752 Teruel fault. Dynamic interaction between both faults probably involves shortening of the
753 seismic cycle, therefore increasing the probability of seism occurrence, but distributing the
754 total released energy into smaller events.

755

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764

765

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956

957 **FIGURE CAPTIONS**

958

959 Fig. 1. Location of the Teruel Fault within the Teruel Graben system, eastern Spain. Inset:
960 sketch of the main Alpine chains within the Iberian Peninsula.

961

962 Fig. 2. Structure of the Teruel Fault. (a) Geological map. MVS: Mansuetos-Valdecebro
963 syncline. (b) Cross section (see location in a). (c) Partial outcrop view of the main fault zone
964 cutting the Rojo 2 unit within the Teruel urban area (see location in a). (d) Equal-area plot
965 (lower hemisphere) showing orientations of measured planes and striations along the main
966 fault. Black: data from central and southern sectors, showing an overall transport direction
967 (red dot) towards N275°E. Grey: Las Ramblillas fault.

968

969 Fig. 3. (a) Structural contour map of the base of Páramo 2 (youngest pre-rift unit relative to
970 the Late Pliocene-Quaternary extensional period) at the relay zone between the Teruel and
971 Concud faults. (b) 3D scheme of the relay structure reconstructed from the previous map. (c)
972 Distribution of vertical displacement (throw) along fault length (D-L profiles) for the
973 Concud and Teruel faults, obtained from the structural contour map. Modified from Lafuente
974 et al. (2011b).

975

976 Fig. 4. Deformation at Las Ramblillas site, revealing hypothetical prolongation of the Teruel
977 Fault. (a) Panoramic view. (b) Interpretation sketch. V: Villafranchian pediment; T2b:
978 Middle Terrace of Alfambra River; T0: Holocene terrace; **Qa**: Quaternary alluvial pediment.

979

980 Fig. 5. Aspects of local geology of the Pitraque-Valdelobos area. (a) Detailed geological map
981 (see location in Fig. 2a). (b) Outcrop view of the main Teruel Fault branch (M) north of
982 Puntal del Pitraque (see location in Fig. 2a). (c) Overall field view. (d) Equal-area plot (lower
983 hemisphere) of the main macroscale fault planes, and one observed striation. (e) Schematic
984 cross section showing offset of the Middle Terrace T2a (see location on Fig. 5a). (f) Laser-

985 levelling profile along the talweg of Valdelobos gully (sector shown in map a), showing the
986 location chosen for the Valdelobos trench. M, N, P, Q, R, S: fault branches referred to in the
987 text; R1, R2, and P2: Rojo 1, Rojo 2, and Páramo 2 units, respectively; T2a: Middle Terrace
988 of the Turia River; T0: Holocene terrace; QA: Holocene alluvium and colluvium.

989

990 Fig. 6. Meso-scale fracturing at the Pitraque 1 and Pitraque 2 site (equal-area plots, lower
991 hemisphere). (a) Vertical, low height aerial photograph with structural sketch. (b) Fault
992 planes and striations observed on the natural terrace scarp. (c) Idem in Pitraque 1 trench. (d)
993 Idem in Pitraque 2 trench. (e) Synthetic rose diagram of fault strikes measured in the whole
994 site. $F\mu$, $F\delta$, $F\alpha$, $F\beta$: faults referred to in the text; R2: Rojo 2 unit; P2: Páramo 2 unit; T2a:
995 Middle Terrace of the Turia River.

996

997 Fig. 7. (a) Detailed cross section of Pitraque 1 trench. R2: Rojo 2 unit; P2: Páramo 2 unit; 1,
998 2, 3, 4, 5, 6: Pleistocene units described in the text; light-grey stripes: carbonate; $F\gamma$, $F\alpha$, $F\delta$:
999 faults referred to in the text; location (asterisks) and age of samples dated by OSL is
1000 indicated. (b) (c) (d) (e) Stereoplots (equal-area, lower hemisphere; symbols as in Fig. 6) of
1001 meso-scale fractures measured in domains 1, 2, 3 and 4, respectively. (f) Poles to bedding
1002 measured in all sedimentary units, and inferred movement plane (M).

1003

1004 Fig. 8. (a) Detailed cross section of trench Pitraque 2. R2: Rojo 2 unit; P2: Páramo 2 unit; 1,
1005 2, 3, 4: Pleistocene units described in the text; light-grey stripes: carbonate; $F\beta$, $F\alpha$: faults
1006 referred to in the text; location (asterisks) and age of samples dated by OSL is indicated. (b)
1007 Detail photograph of domain 1 in (a). (c) (d) Stereoplots (equal-area, lower hemisphere;
1008 symbols as in Fig. 6) of meso-scale fractures measured in domains 1 and 2, respectively. (e)
1009 Idem in the opposite, not logged trench wall.

1010

1011 Fig. 9. Detailed cross section of Valdelobos trench. R2: Rojo 2 unit; 1, 2, 3, 4, 5: Quaternary
1012 units described in the text; $F\epsilon$: active fault; location (asterisks) and age of samples dated by
1013 OSL is indicated.

1014

1015 Fig. 10. Chronological sketch of paleoseismic events recorded at the overall Concul Fault
1016 (complete paleoseismic succession reconstructed by Simón et al., 2016), its southern branch
1017 (El Hocino trenches; Lafuente et al., 2104), and the Teruel Fault (this work).

1018

1019 Fig. 11. Comparison between seismic **succession** reconstructed for the southern branch of the
1020 Concul Fault (Lafuente et al., 2014) and for the Teruel Fault (M and P branches, present
1021 work). (a) Kinematic data for the southern branch of the Concul Fault at El Hocino site:
1022 equal-area, lower hemisphere stereoplot of fault planes and striations, and prevailing
1023 transport direction. (b) Slip history of the southern branch of the Concul Fault, as inferred
1024 from the palaeoseismic succession at El Hocino trenches; slip rates inferred from that
1025 succession and from offset of a morpho-sedimentary marker (pediment cover) are expressed
1026 as dotted lines. (c) and (d): Idem as a and b, respectively, for the western branches of the
1027 Teruel Fault at Pitraque-Valdelobos site (offset marker in this case: top of fluvial terrace
1028 T2a).

1029

1030 Fig. 12. Proposed model of stress/strain partitioning at the scale of seismic cycle for the
1031 activity of the Teruel and Concul faults. (a) (b) (c) (d) Sketches of successive, alternating slip
1032 on both faults favoured by stress release on each fault after a seismic event (see explanation
1033 in text); large arrows: transport directions; stereoplots: active fault (plane and prevailing
1034 striation) for each seismic event, and orientation of stress axes (σ_1 , σ_2 and σ_3) of the most
1035 representative stress systems **responsible for such movements** (according to palaeostress
1036 analysis by Lafuente, 2011). (e) Simplified model for the overall fracture systems in the
1037 Teruel area, and kinematic interpretation according to the model proposed by Reches (1978);
1038 X, Y, Z: virtual strain axes representing the bulk finite deformation. **achieved by**
1039 **accumulating the variety of incremental fault slips.**

1040

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1042 **TABLE 1:**

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Level	Age	Sublevel	Height above talweg (m)	Numerical age	Dating method	References
Upper	Early Pleistocene (?)	T3	85-90	Unknown		
Middle	Middle Pleistocene	T2b	45-65	250 (\pm 32) to 116 (\pm 4) ka	U/Th	Arlegui et al. (2005); Gutiérrez et al. (2008)
		T2a	40-45	90.5 (\pm 5.3) to 76.0 (\pm 5.0) ka	OSL	Lafuente et al. (2008); Simón et al. (2012)
Lower	Late Pleistocene	T1c	20-30	22.0 (\pm 1.6) ka	OSL	Lafuente (2011)
		T1b	15-20	14.9 (\pm 1.0) to 15.6 (\pm 1.3) ka	OSL	Lafuente et al. (2008); Gutiérrez et al. (2008)
		T1a	10-15	Unknown		
Subactual	Holocene	T0	3-5	3.4 (\pm 0.7) ka	OSL	Lafuente (2011)

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1045 **Table 1.** Levels of fluvial terraces defined in the Teruel area (Alfambra and Turia rivers).

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1051 **TABLE 2:**

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Scenario	Paleoseismic parameters		Wells & Coppersmith (1994)	Stirling <i>et al.</i> (2002)	Pavlidis & Caputo (2004) (*) (**)	Mohammadioun & Serva (2001) (*) (***)	
<i>Length of 9 km</i>						100 bar	30 bar
Moment magnitude (M_w)			6.12	6.64	6.35	6.26	5.73
Coseismic slip (m)	Vertical		-	-	0.55	-	-
	Net		0.37	1.28	0.59	-	-
<i>Length of 11 km</i>							
Moment magnitude (M_w)			6.23	6.71	6.41	6.39	5.87
Coseismic slip (m)	Vertical		-	-	0.60	-	-
	Net		0.40	1.32	0.65	-	-
<i>Length of 23 km (linked Concud and Teruel faults)</i>							
Moment magnitude (M_w)			6.66	6.96	6.62	6.88	6.36
Coseismic slip (m)	Vertical		-	-	0.66	-	-
	Net		1.19	2.43	0.71	-	-

1053

1054 **Table 2.** Moment magnitude and coseismic slip for the Teruel Fault estimated from empirical relationships for three different1055 scenarios. (a) Obtained M_s values have been transformed to M_w by applying the relationship of Konstantinou *et al.* (2005):1056 $M_w = 0.76 M_s + 1.53$. (b) Vertical displacement initially yielded by this correlation has been translated into net displacement1057 considering an average dip of 68° and a pure normal movement of the Teruel Fault. (c) Moment magnitudes according to

1058 Mohammadioun and Serva (2001) have been calculated for stress drop scenarios of 100 and 30 bar.

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1065 **TABLE 3:**
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Sample	Laboratory reference	Lithological unit	Equivalent dose (Gy)	Annual dose (mGy/yr)	Supralinearity (Gy)	K factor	OSL age (ka B.P.)
<i>Trench: Pitraque 1</i>							
P1-4	MAD-6076SDA	Fluvial terrace (Unit 1)	170.46	2.41	0	0.19	70.730 ± 5.259
P1-5	MAD-6077SDA	Fluvial terrace (Unit 2)	124.93	1.74	0	0.12	71.798 ± 5.059
P1-6	MAD-6078BIN	Fluvial terrace (Unit 5)	77.57	1.60	0	0.11	48.481 ± 3.801
<i>Trench: Pitraque 2</i>							
P2-1	MAD-6079SDA	Fluvial terrace (Unit 1)	130.05	1.66	0	0.14	78.343 ± 5.189
P2-7	MAD-6081BIN	Fluvial terrace (Unit 2)	91.95	1.84	0	0.11	49.972 ± 3.365
P2-5	MAD-6080SDA	Fluvial terrace (Unit 3)	127.80	2.75	0	0.14	46.472 ± 3.147
<i>Trench: Valdelobos</i>							
VL-C1	MAD-6073SDA	Fluvial terrace (Unit 2)	112.82	4.23	0	0.16	26.671 ± 1.912
VL-B2	MAD-6074SDA	Fluvial terrace (Unit 3)	16.97	1.71	0	0.23	9.923 ± 0.690

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 1068 **Table 3.** OSL dating of samples collected from trenches at the Teruel fault.
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1072 **TABLE 4:**

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Teruel Fault event (renamed)	Original event at individual trench	Predating OSL age (ka B.P.)	Postdating OSL age (ka B.P.)	Absolute age constraints (ka)	Coseismic net slip (m)
Event 0	XP1		70.7 ± 5.3	Pre-73.1	?
	XP2		78.3 ± 5.2		
Event 1	YP1	70.7 ± 5.3	71.8 ± 5.1	76.0 – 66.7	0.1
Event 2	YP2	46.5 ± 3.1		Post-49.6	0.5
Event 3	ZP1	48.5 ± 3.8		Post-49.6	> 1.1
	ZP2	46.5 ± 3.1			
Event 4	ZVL	26.7 ± 1.9	9.9 ± 0.7	28.6 – 9.2	> 0.3

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 1075
 1076 **Table 4.** Summary of paleoseismic events of the Teruel Fault interpreted and correlated from the studied trenches: Pitraque
 1077 1 (P1), Pitraque 2 (P2) and Valdelobos (VL). Absolute age constraints take into account the error bar for each OSL age.
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1088 **TABLE 5:**
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Marker / data source	Age / time window	Teruel Fault (this work)		Concud Fault (*)			
		Net slip (m)	Slip rate (mm/a)		Net slip (m) (**)	Slip rate (mm/a)	
			Overall	Partial (In 1-2 branches among 4-5)		Overall	Partial (In 1 branches among 2-3)
<i>Trenching information</i>							
Compilation of coseismic slip values	since 76.0 to 9.9 ka BP	1.7 - 2.0	0.03 - 0.05				
	since ca. 74 to 3.4 ka BP			20.5 (3.9)	0.29	0.05	
<i>Stratigraphic marker</i>							
T2b terrace top	46.5 ± 3.2 ka	8.8	0.18 - 0.20				
T2a terrace top	282 - 112 ka			39	0.14 - 0.35		
Páramo 2 unit (Latest Ruscinian)	3.6 Ma	270	0.075	255 - 290	0.07 - 0.08		

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Table 5. Summary of slip rates calculated for the Teruel and Concud faults from different markers and for different time windows. (*) Data for the Concud Fault are compiled from Gutiérrez et al. (2008), Lafuente (2011), Lafuente et al. (2011a, 2014), and Simón et al. (2016). (**) In parentheses, partial net displacement measured on one fault branch.

1096 **APPENDIX 1:**

1097 **Description and age of sedimentary units exposed in trenches**

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1099 *Pitraqe 1 trench*

1100 Neogene sediments comprise: (i) pedogenized massive brown lutites with pedogenic features
1101 (top of the Rojo 2 elastic unit); (ii) brecciated and karstified grey and white limestones (mudstone or
1102 wackestone) interbedding black and green marls with remains of gastropods and charophytes,
1103 representing the Páramo 2 carbonate unit. These materials correspond to the Genetic Unit 4
1104 Megasequence 3 of Ezquerro et al. (2014,2017).

1105 The Pleistocene succession has been subdivided into six units (1 to 6 in Fig. 7a):

1106 Unit 1. Gravel made of white with Neogene limestone angular to subrounded pebbles to
1107 boulders and brown and green rip up clasts. It Gravel is grain-supported and crops out
1108 discontinuously below the erosive base of the overlying unit 2. Sample A sample collected in this
1109 unit (P1-4; see location in Fig. 7a) yielded an OSL age of 70.7 ± 5.3 ka (Table 2).

1110 Unit 2. Greyish and yellowish gravel with interbedded brown, fine- to coarse-grained sand
1111 levels. Gravel is grain-supported and composed by made of angular to subangular carbonate and
1112 siliceous pebbles and cobbles up to 14 cm in diameter; internal erosive surfaces individualise it
1113 shows trough cross-bedding sets indicating paleocurrent towards SW. Sand forms appears in
1114 decimetre-scale, tabular levels with parallel and cross-lamination, and ripples. Sample P1-5 (see
1115 location in Fig. 7a) yielded an OSL age of 71.8 ± 5.1 ka (Table 2).

1116 Unit 3. Grey gravel with encased brown medium-grained sand lenses with floating clasts up
1117 to 3 cm in diameter. Gravel is grain-supported and made of angular to subrounded limestone and
1118 siliceous pebbles and cobbles up to 24 cm in diameter; it shows pebble-granule cycles and trough
1119 cross-bedding in decametre thick sets. Sand is massive and contains floating clasts up to 3 cm in
1120 diameter.

1121 Unit 4. Grey gravel with interbedded medium to coarse-grained brown sand. Gravel is grain-
1122 supported with homometric, subangular to subrounded limestone clasts up to 8 cm in diameter and
1123 trough. Trough cross-bedding can be recognised indicating SW directed paleocurrents. Sand makes
1124 laminated lensoid or tabular bodies with horizontal lamination.

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1129 Unit 5. Grey gravel with encased coarse-grained brown sand. Gravel, grain-supported, is
1130 composed of **homometric**, angular **to** subangular clasts up to 6 cm in diameter. Horizontal bedding
1131 (pebble-granule cycles) **is evident and** merges **laterally into towards the SE into** trough cross-bedding
1132 sets. Sand makes tabular levels with parallel lamination; and **contains** floating grey limestone clasts
1133 up to 1 cm in diameter. Sample P1-6 (see location in Fig. 7a) yielded an OSL age of 48.5 ± 3.8 ka
1134 (Table 2).

1135 Unit 6. Regolith, **consisting of** brown lutite with scattered centimetre-scale limestone clasts,
1136 carbonate nodules, and root traces.
1137

1138 *Pitraqe 2 trench*

1139 Neogene sediments are similar to those described in Pitraqe 1 trench (Rojo 2 and Páramo 2
1140 units). The overlying Pleistocene materials have been subdivided into four units (1 to 4 in Fig. 8a):

1141 Unit 1. Grey and brown, grain-supported gravel with rare sand. Gravel is made of angular **to**
1142 subangular limestone and siliceous pebbles and cobbles up to 18 cm in diameter; **it** shows planar
1143 cross-stratification and interbedded **coarse** sand levels in the lower part. Sample P2-1 **from this unit**
1144 (see location in Fig. 8a) has an OSL age of 78.3 ± 5.2 ka BP (Table 2).

1145 Unit 2. Grey and brown gravel with intercalated brown very coarse-grained sand towards the
1146 top **of the unit**. Gravel, **consists of angular limestone and siliceous pebbles and cobbles up to 16 cm**
1147 **in diameter, being** matrix-supported at the base and **turning into** grain-supported towards, **consists of**
1148 **angular limestone and siliceous pebbles and cobbles up to 16 cm in diameter and shows c-** Cross-
1149 bedding **indicates SW directed paleocurrents**. Sand forms a slightly channelled body with angular,
1150 grey limestone floating clasts (up to 2 cm **in diameter**), and armoured clay balls (up to 16 cm).
1151 Sample P2-7 **at the base of this unit** (Fig. 8a) yielded an OSL age of 50.0 ± 3.4 ka (Table 2).

1152 Unit 3. Gravel with interbedded centimetre-**thick scale** levels of fine- to coarse-grained sand.
1153 Gravel, **commonly mainly** grain-supported, is made of **homometric** angular limestone pebbles and
1154 cobbles, **and forms making** a tabular body in the lower part and a channel in the upper part. The
1155 channel is composed by larger clasts (up to 15 cm **in diameter**) and shows planar cross-bedding
1156 **indicating SW paleocurrents**. Sand makes irregular levels with horizontal and cross-lamination. Its
1157 base has an OSL age (sample P2-5) of 46.5 ± 3.1 ka (Table 2).

1158 Unit 4. Regolith, **consisting of** brown lutite with carbonate nodules, root traces and
1159 scattered centimetre-scale limestone clasts.

1160

1161 *Valdelobos trench*

1162 Massive red Neogene lutites (Rojo 2) are covered by a succession of Quaternary fluvial and
1163 alluvial deposits in which five units have been distinguished (1 to 5 in Fig. 9):

1164 Unit 1. Massive brown lutite with grey patches, carbonate nodules and interbedded fine- to
1165 medium-grained sand that grades laterally into brown silt and includes with carbonate granules elasts
1166 up to 5 mm in diameter. that grades laterally into brown silt and includes.

1167 Unit 2. Coarse-grained sand with white and grey carbonate and black quartzite granules; in It
1168 makes a coarsening upward channelled body with coarsening upwards evolution, preserved close to a
1169 fault plane in the middle part of the trench. A Sample (VL-C1); (Fig. 9) yielded an OSL age of 26.7
1170 \pm 1.9 ka BP (Table 2).

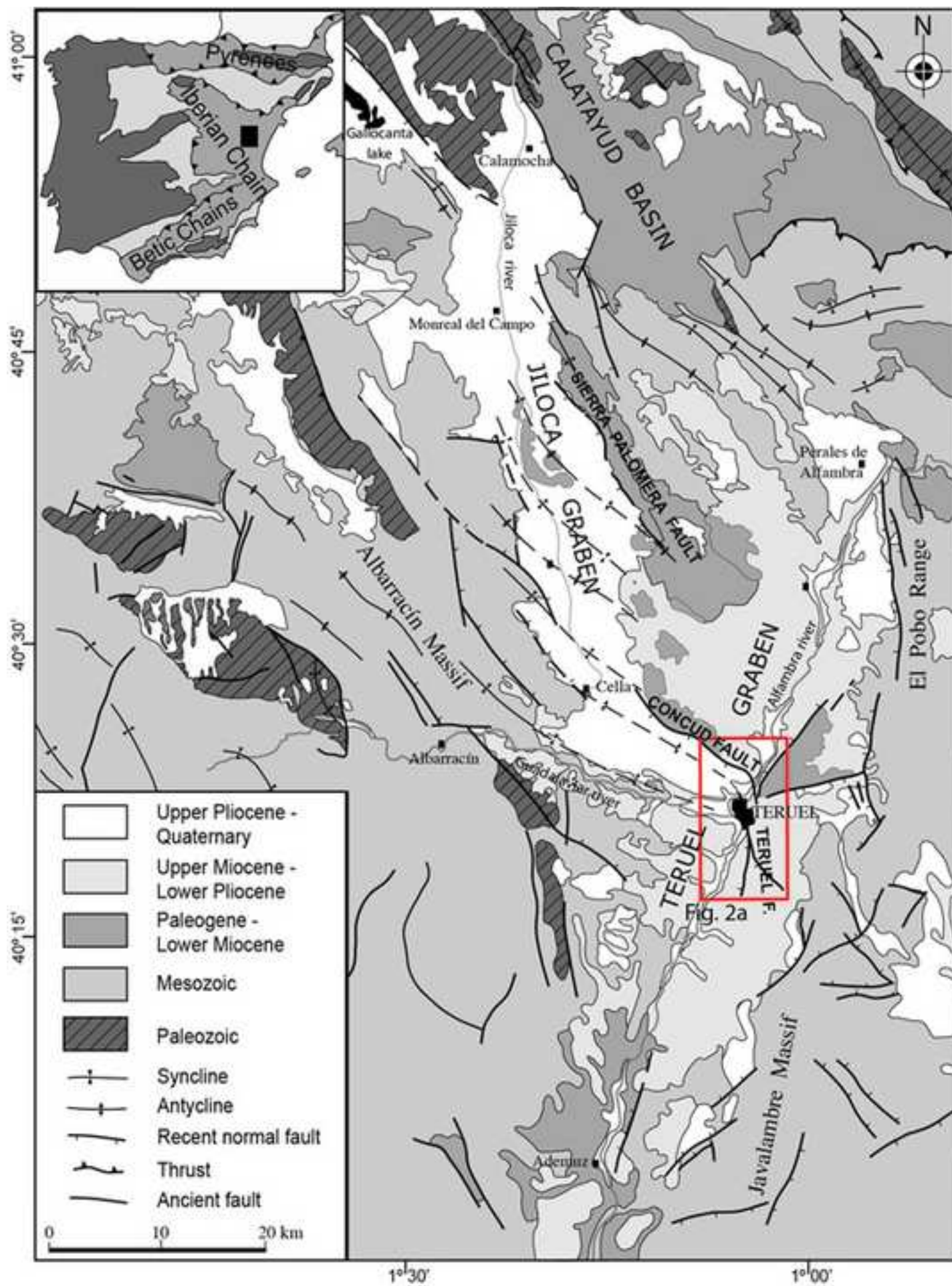
1171 Unit 3. Channelled body with highly erosive body base integrated by with brown gravel in the
1172 lower part and medium-grained sand and lutites in the upper part. Gravel is made of subangular to
1173 subrounded white carbonate (up to 8 cm in diameter) and brown and red siliceous clasts (up to 3 cm);
1174 it shows horizontal bedding and, as well as imbricated clasts broadly indicating a SW directed
1175 paleocurrent. Sand forms tabular levels with parallel lamination and low angle cross-stratification.
1176 Some mud boulders have been recognized, up to with a maximum diameter of 88 cm exist. Sample
1177 VL-B2 collected in this unit (Fig. 9) yielded an OSL age of 9.9 \pm 6.9 ka BP (Table 2).

1178 Unit 4. Gravel (lower part) and coarse-grained sand (upper part) arranged in a dominantly
1179 red, tabular and fining-upwards body with erosive body with, locally channelled, base. Gravel,
1180 matrix-supported, gravel is made of white, subangular to subrounded carbonate clasts, up to 15 cm
1181 in diameter. Sand shows parallel lamination, ripples, scattered clasts and rare mud boulders.

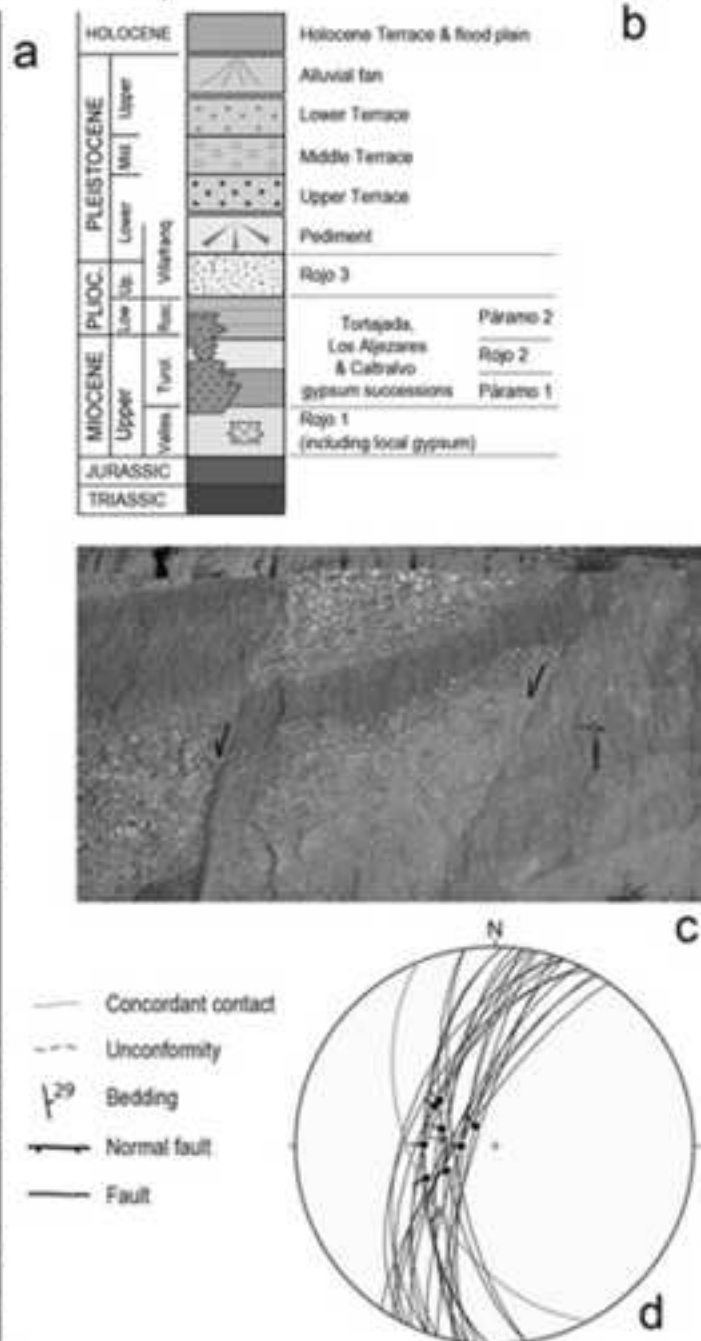
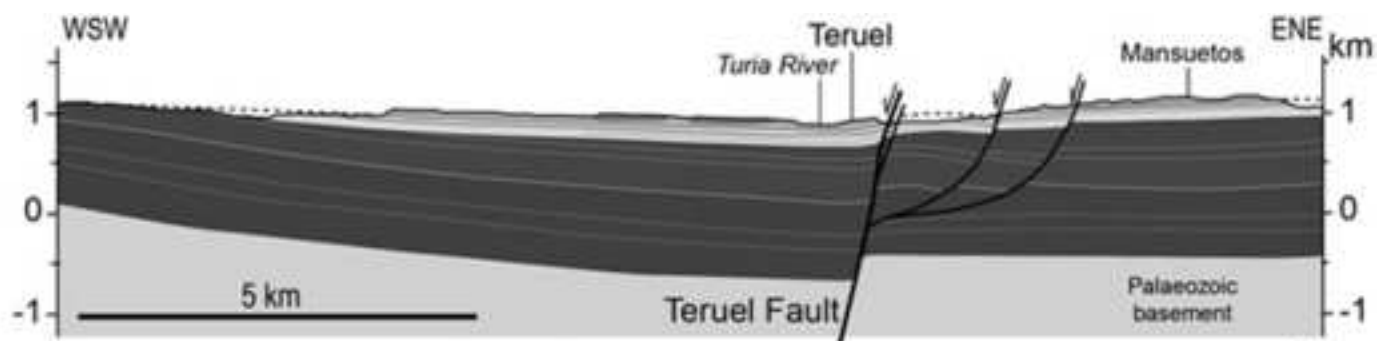
1182 Unit 5. Greyish grain-supported gravel in a tabular body with erosive base and horizontal
1183 stratification made of fining upwards sequences. It is grain-supported, composed by subangular to
1184 subrounded white carbonate clasts (up to 7 cm in diameter), subrounded orange siliceous clasts (up to
1185 4 cm), and locally rare some mud boulders broadly indicates paleocurrent towards SW. It supplied
1186 two fragments of clay teals (historical times, post-Middle Age). have been found within this unit
1187 which indicates that it belongs to

1188

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*Figure
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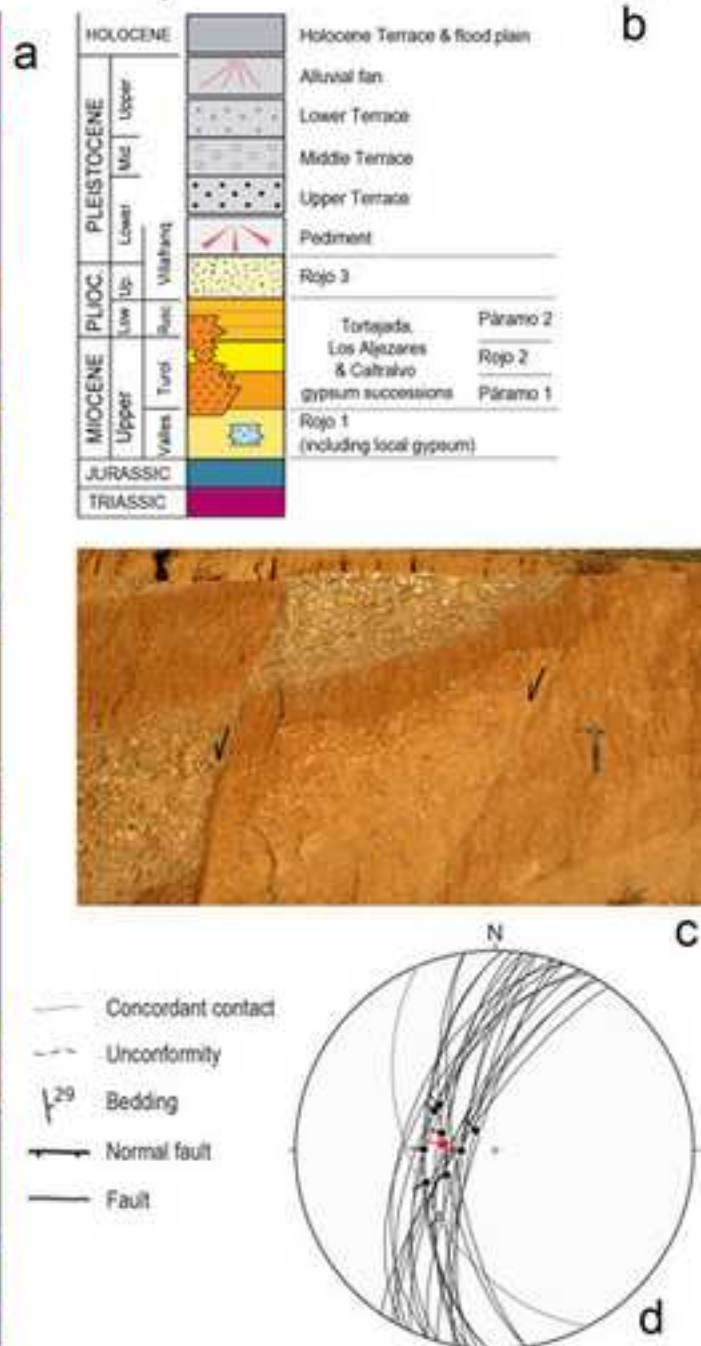
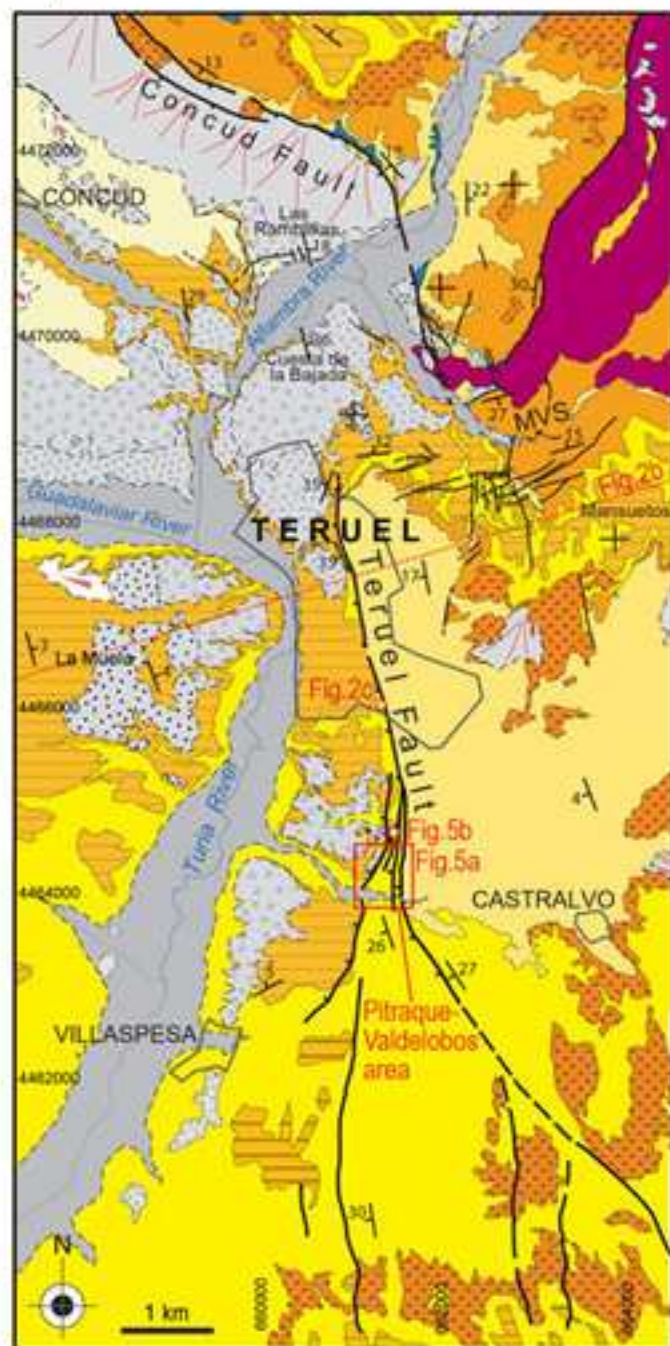
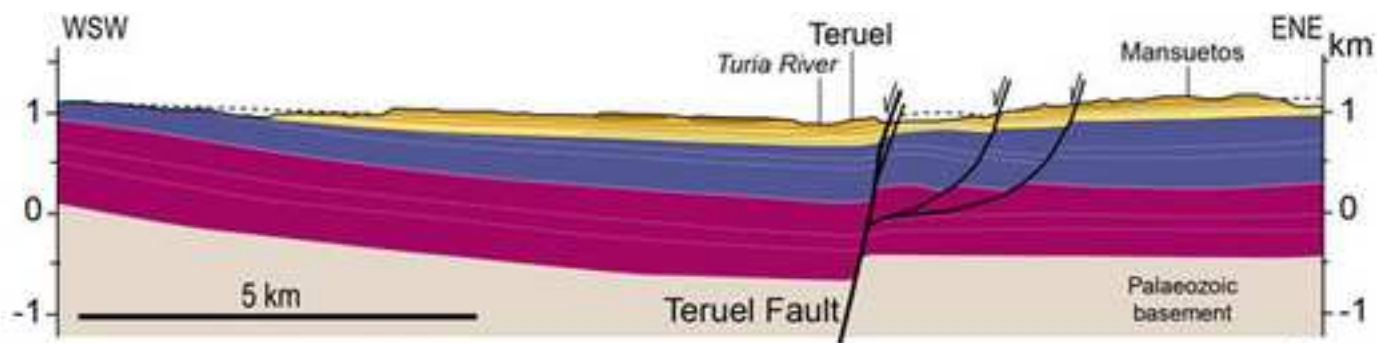


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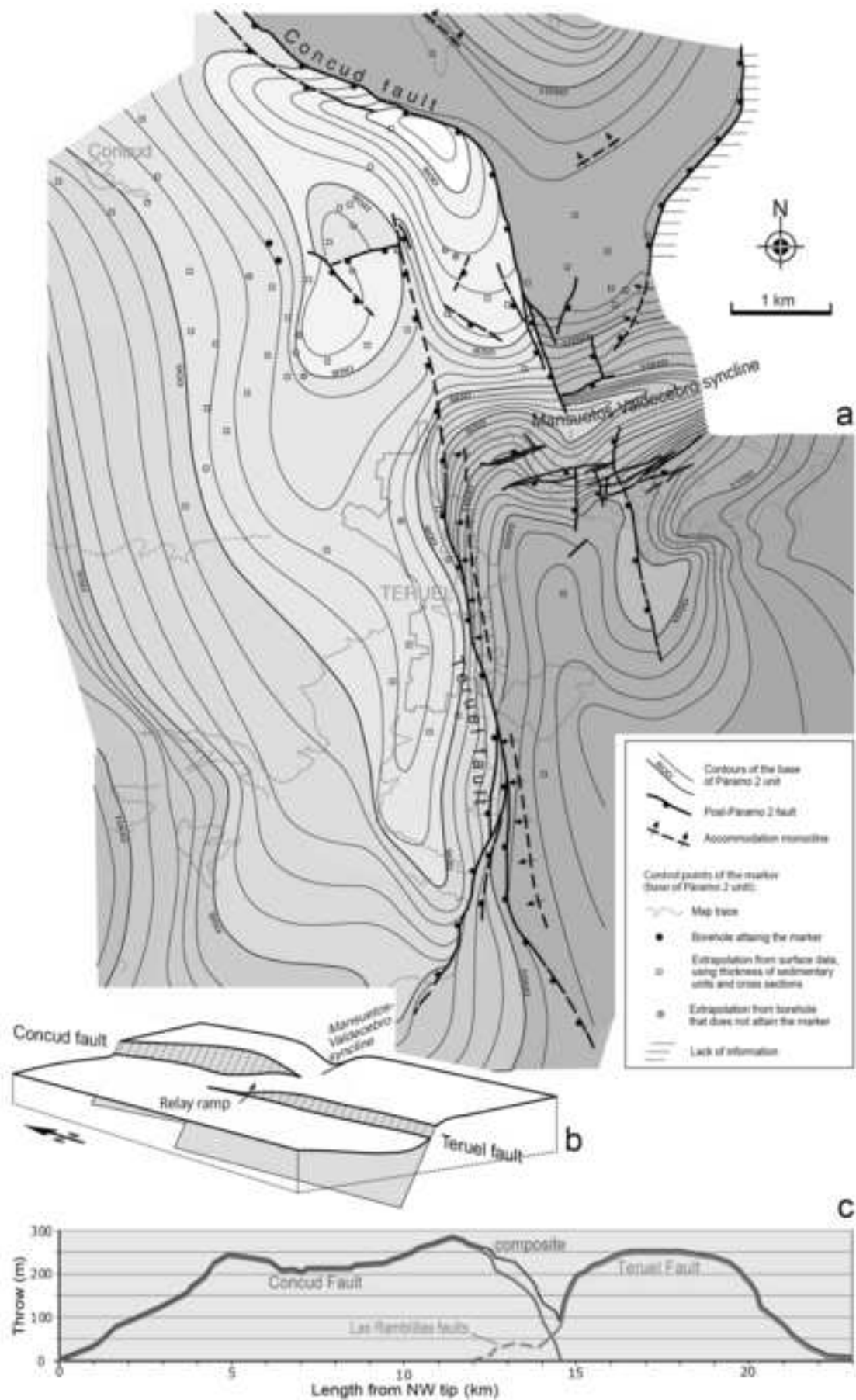


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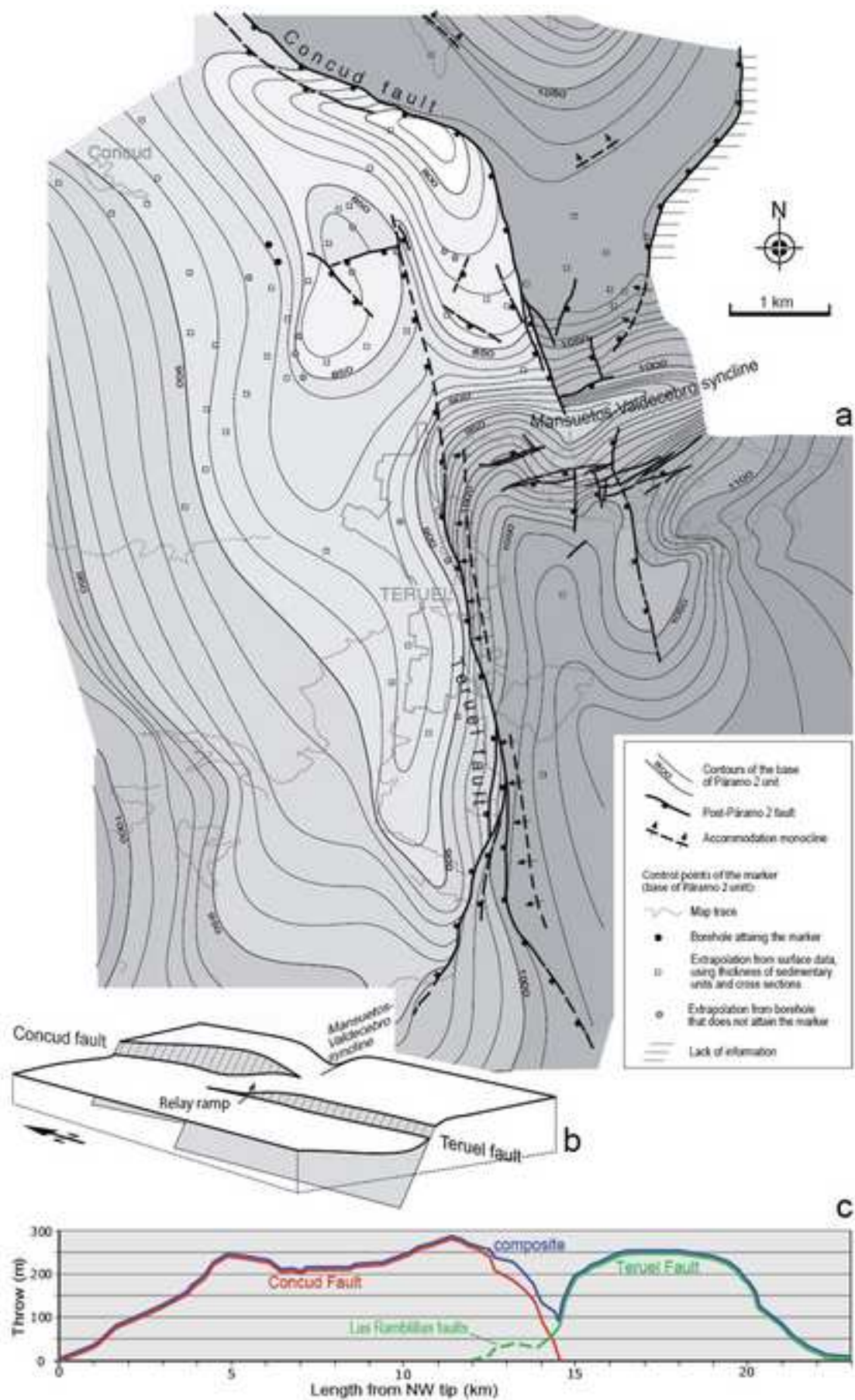


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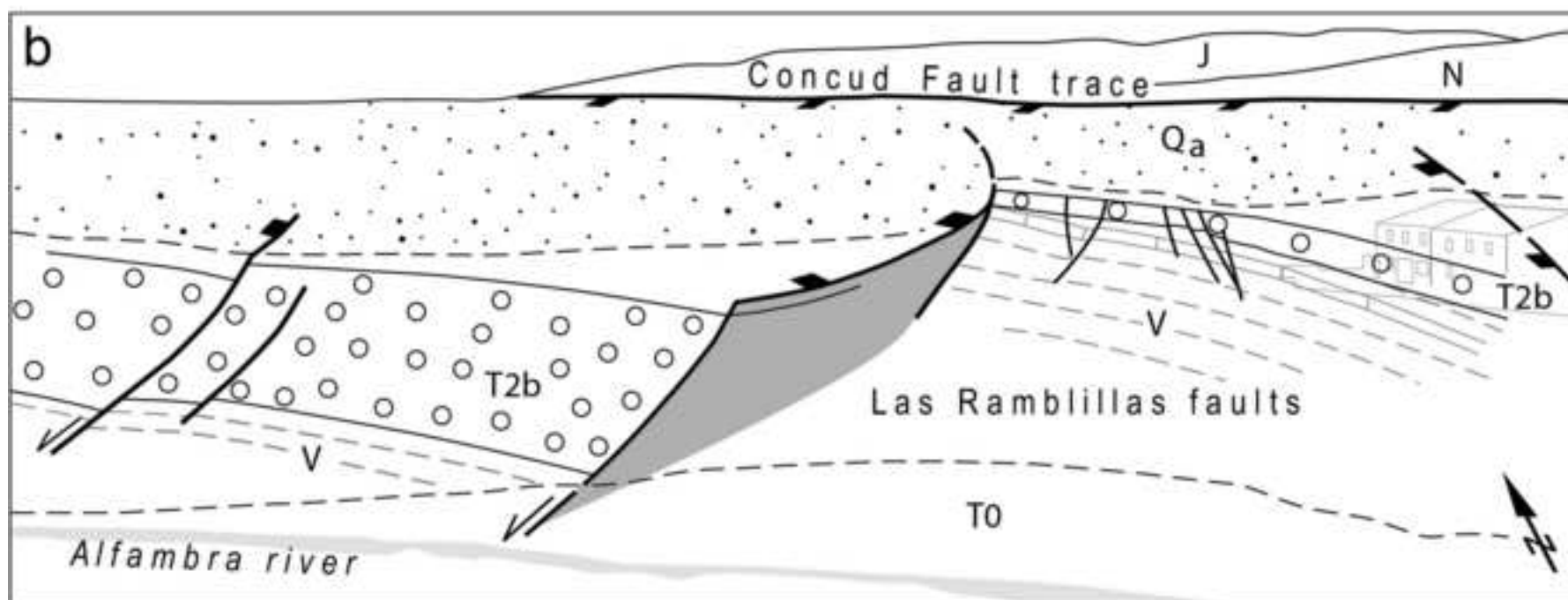
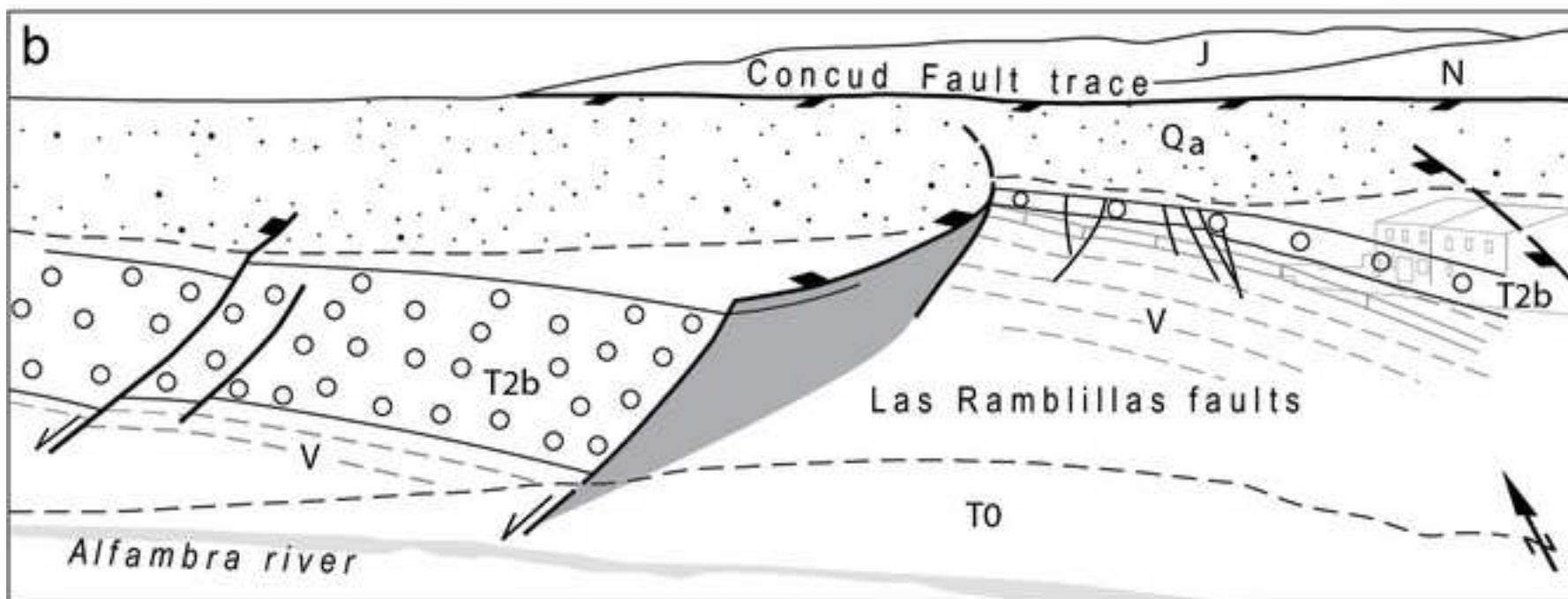
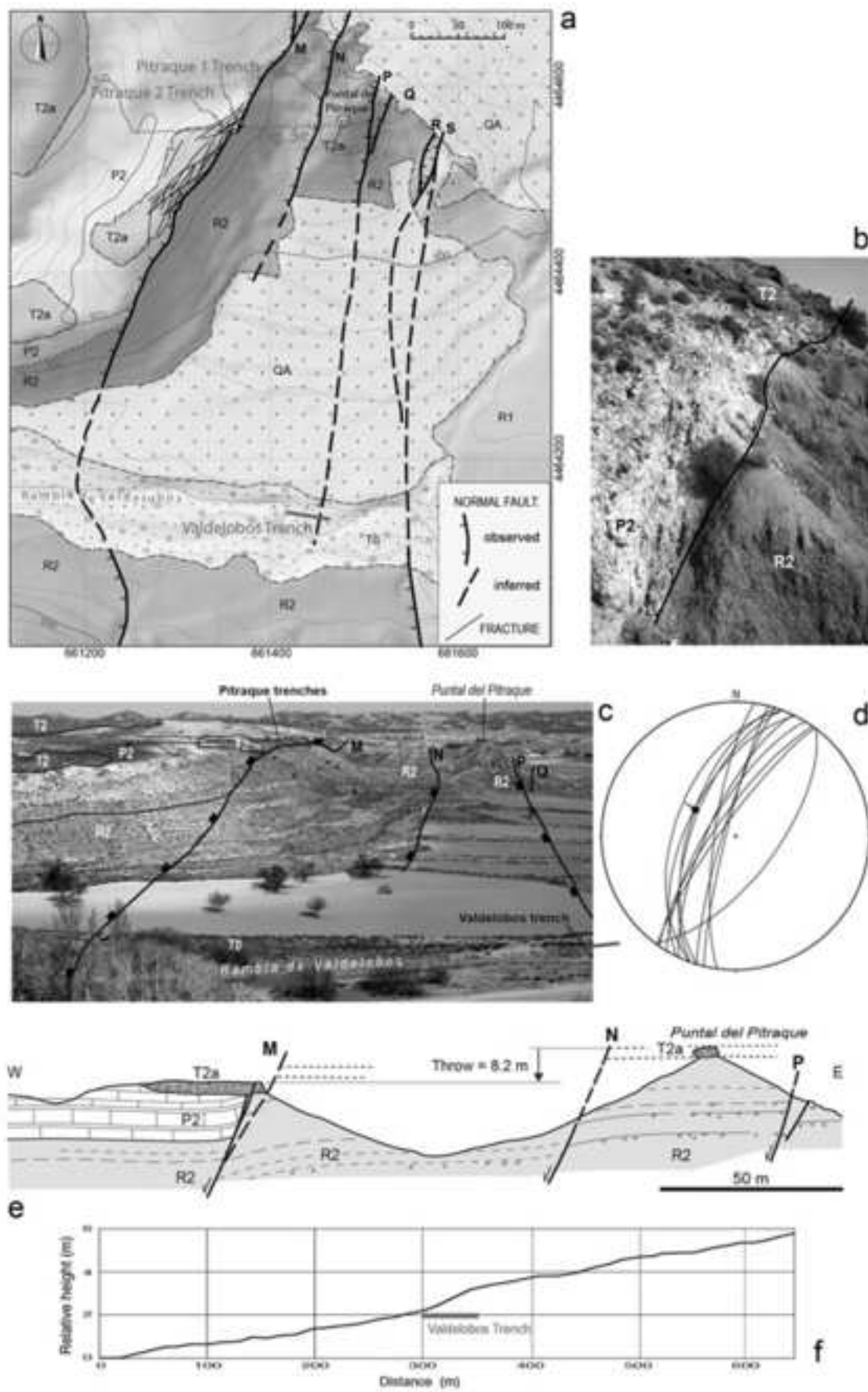


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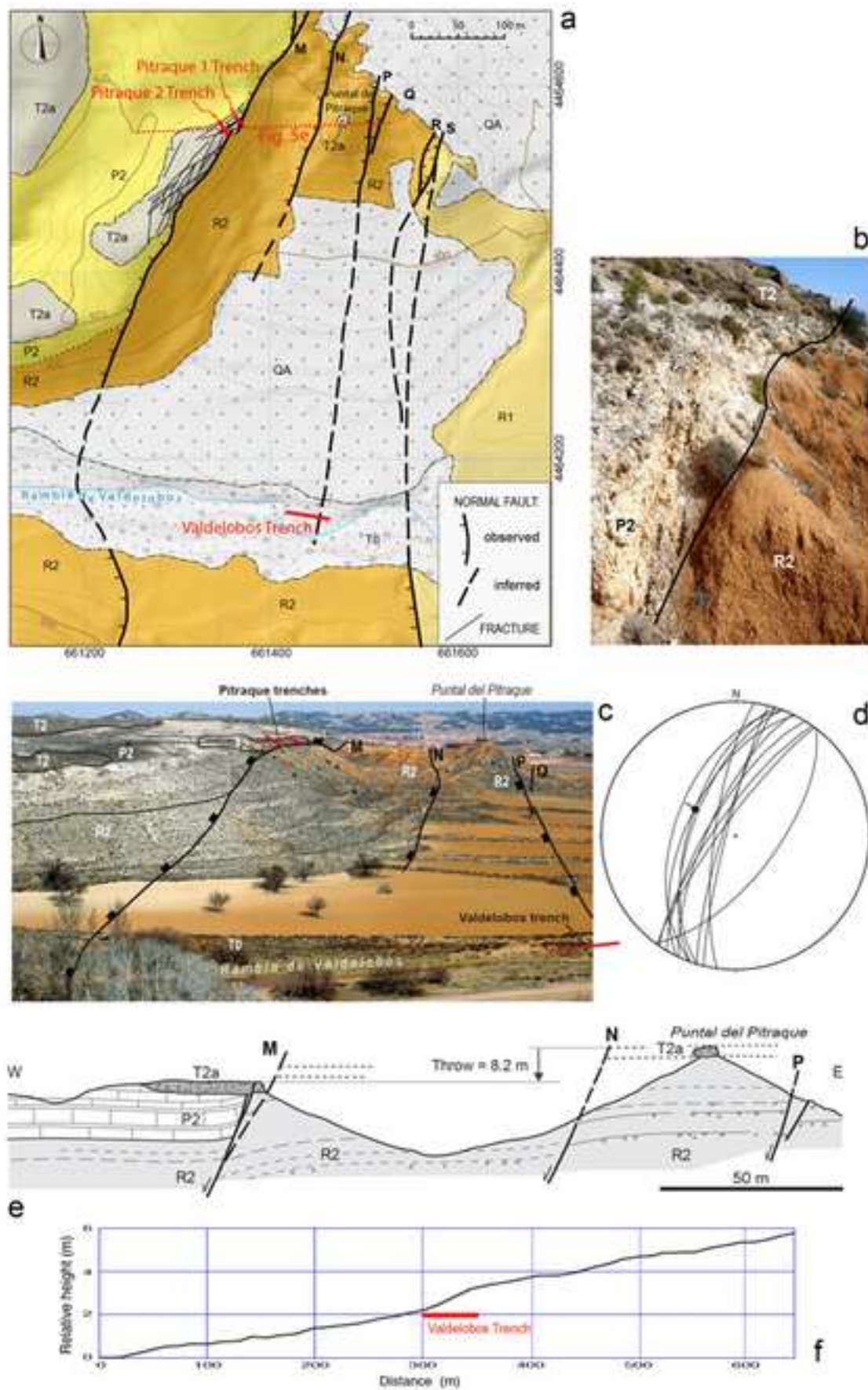


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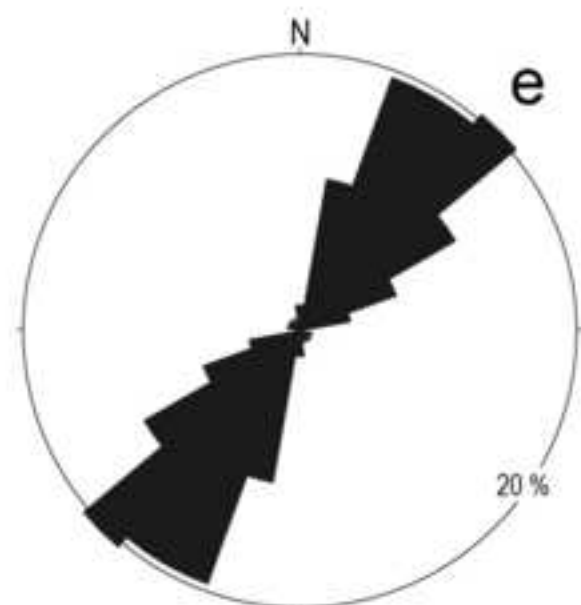
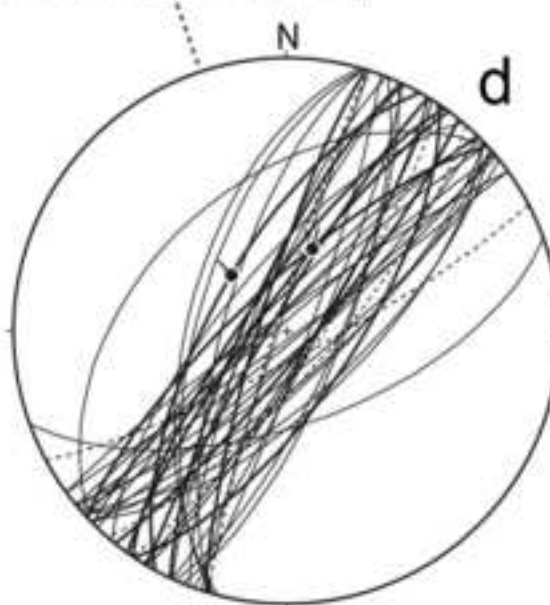
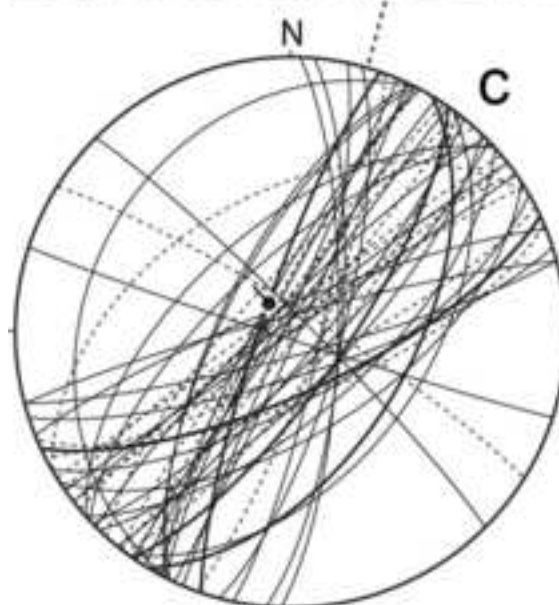
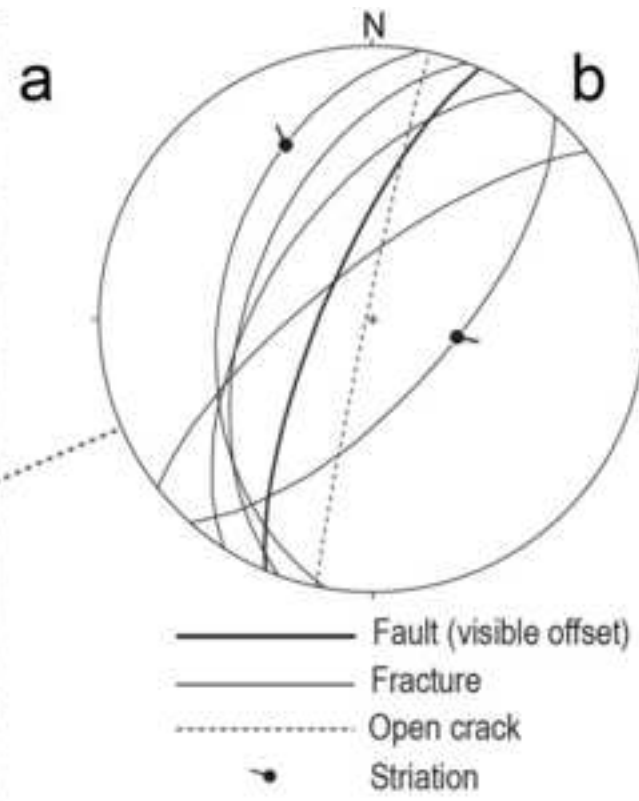
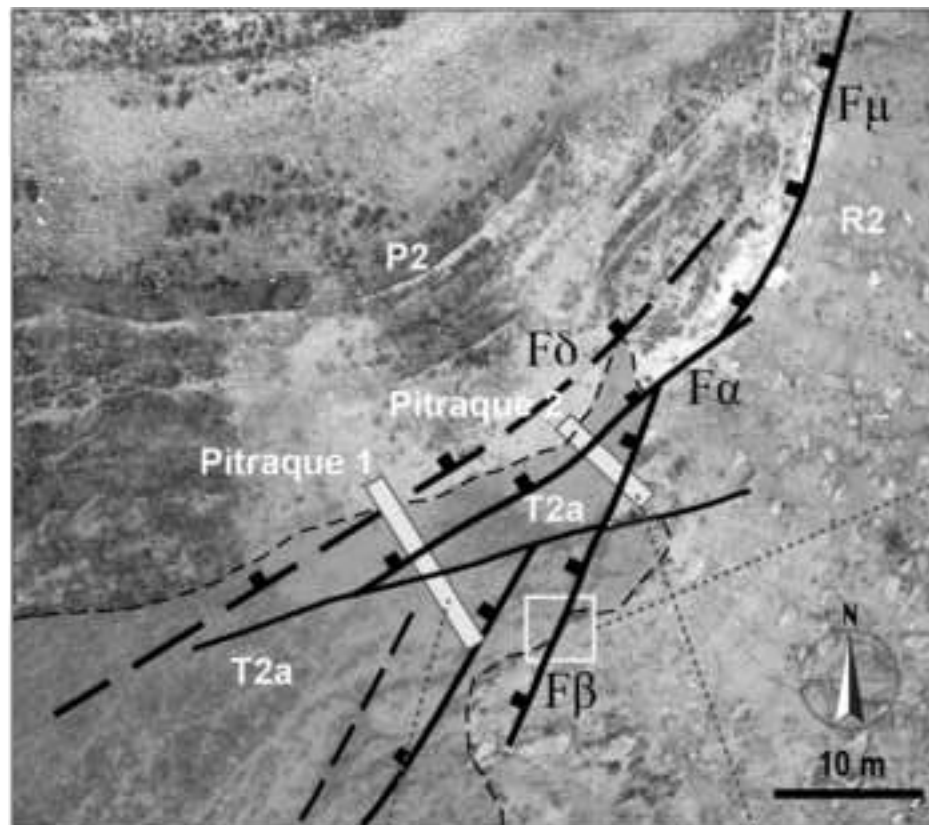


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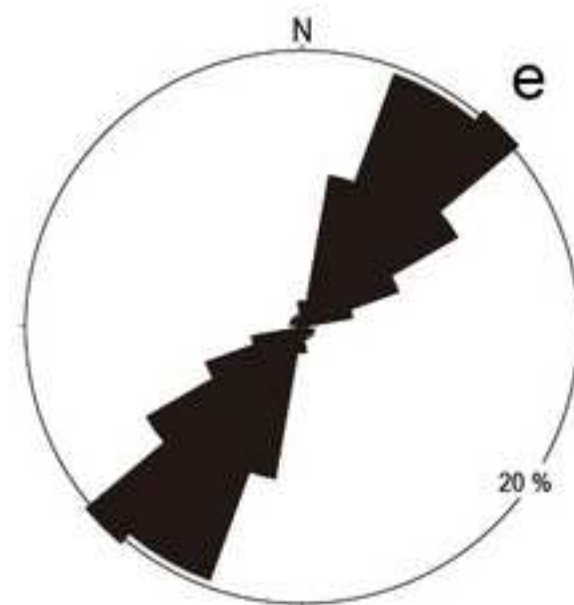
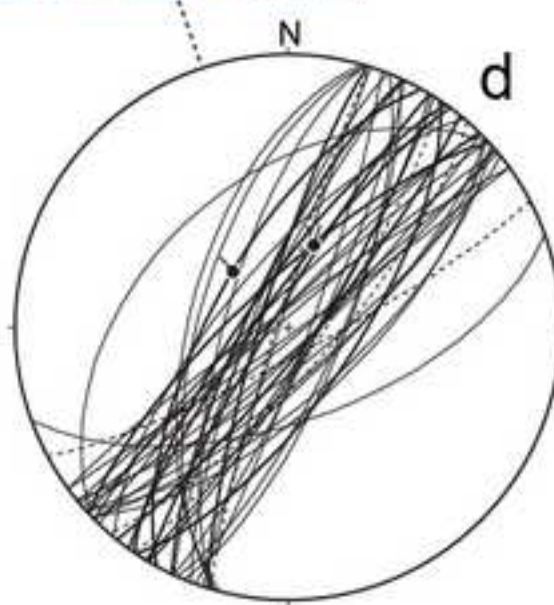
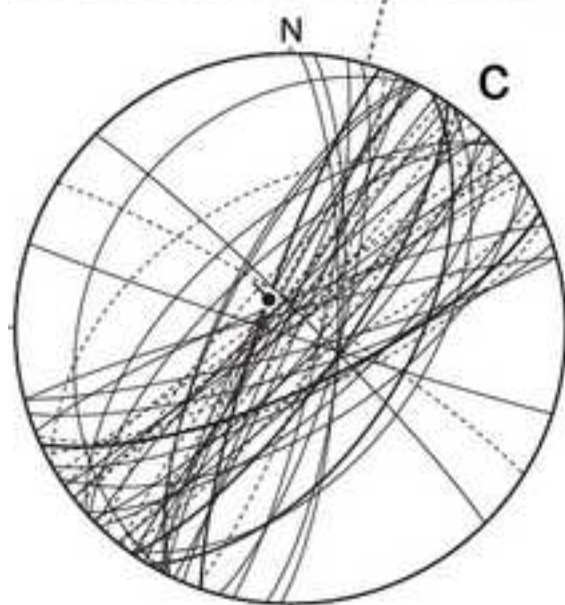
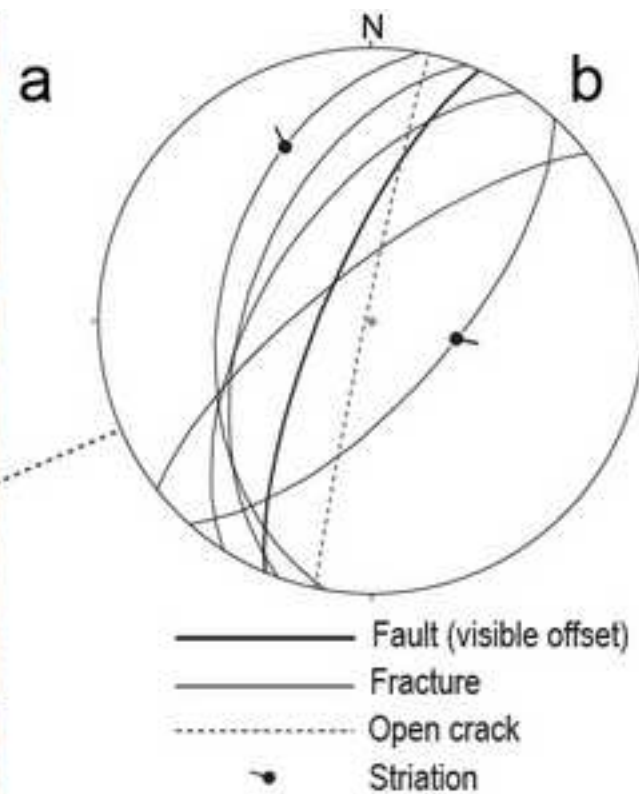
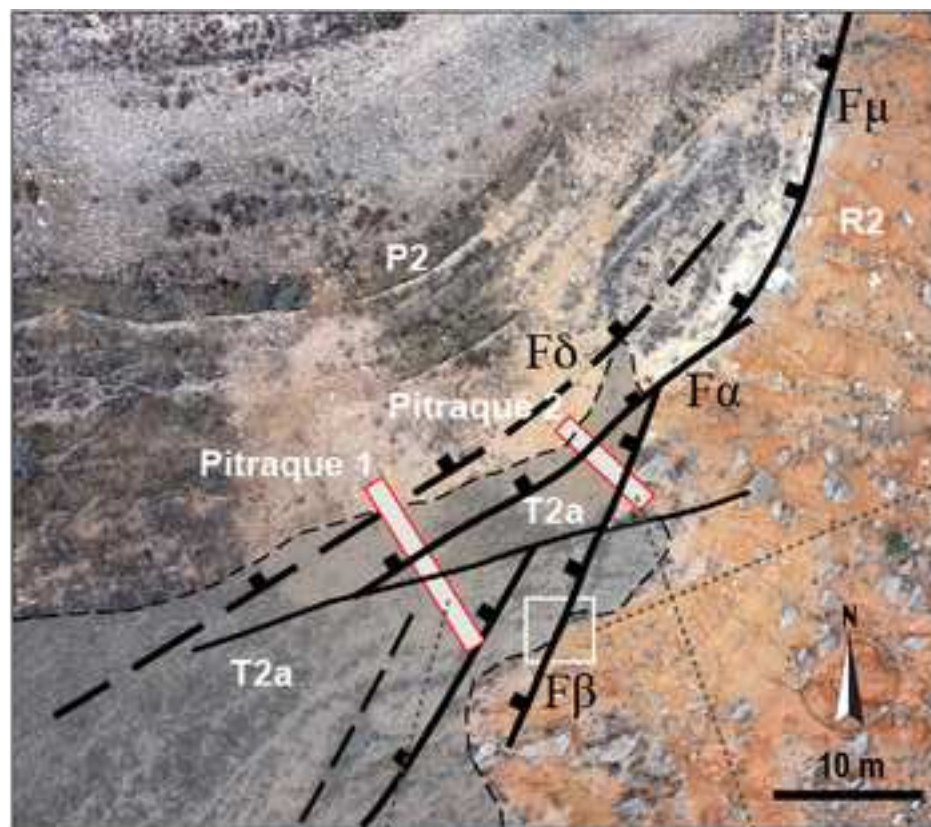


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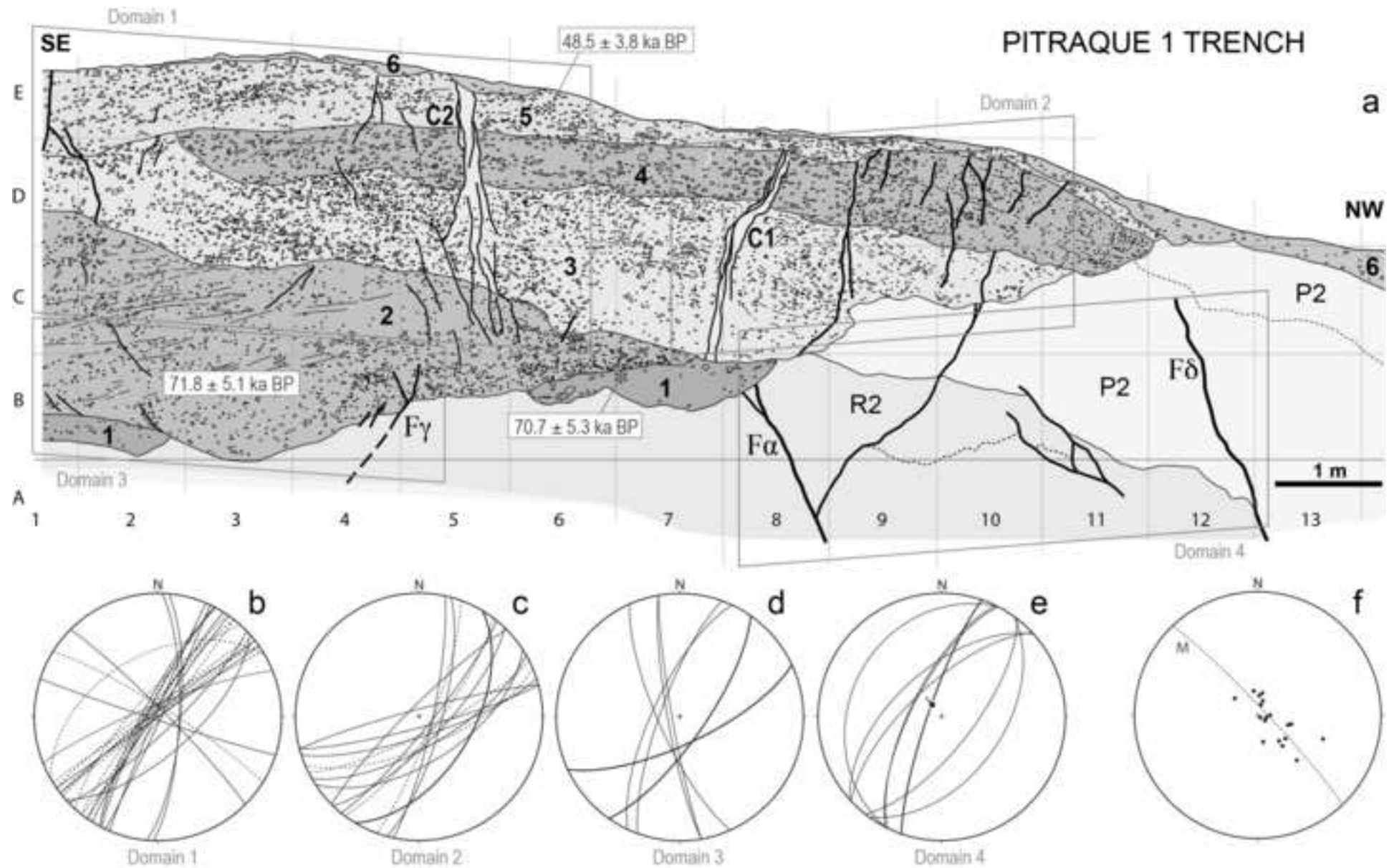


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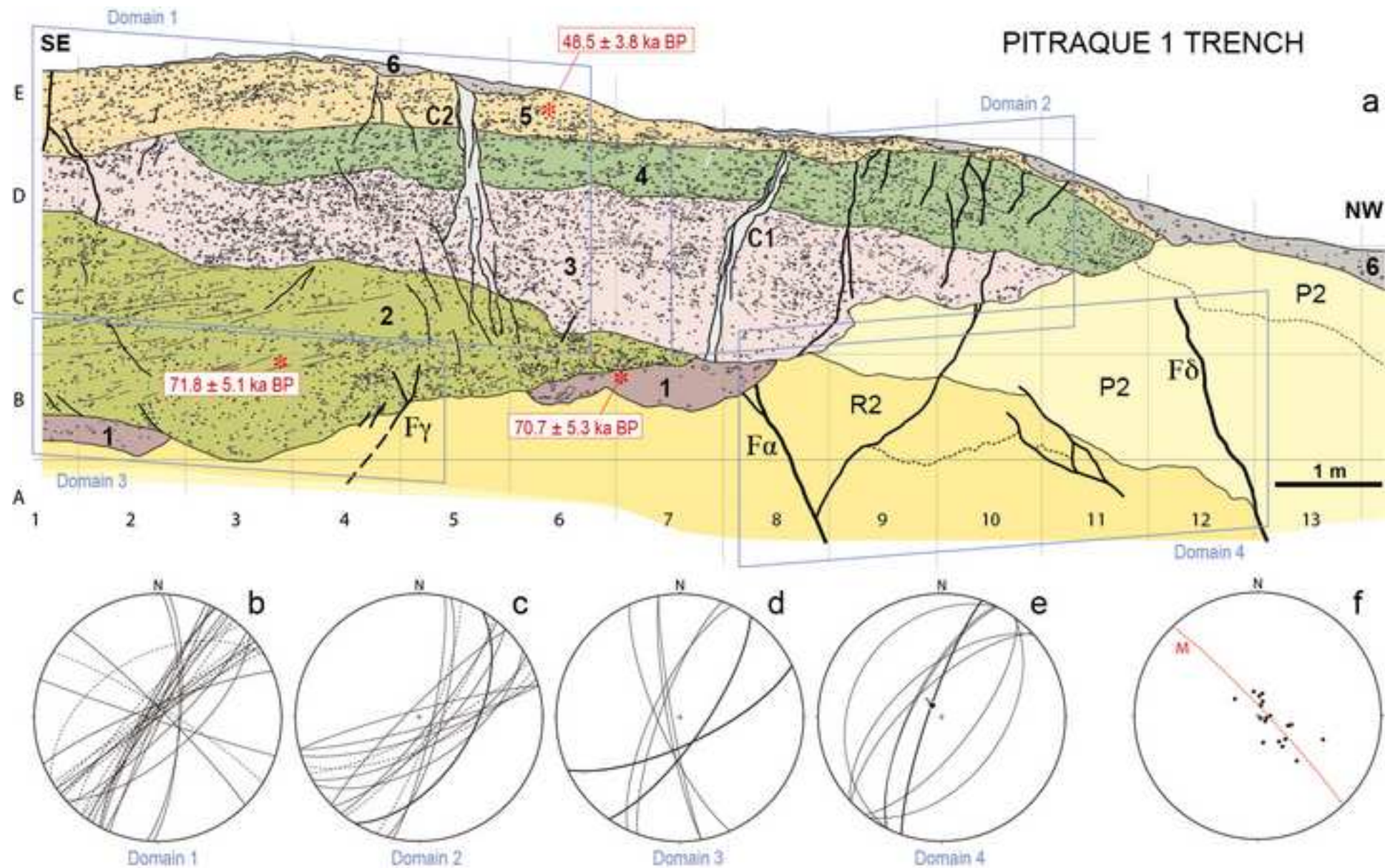


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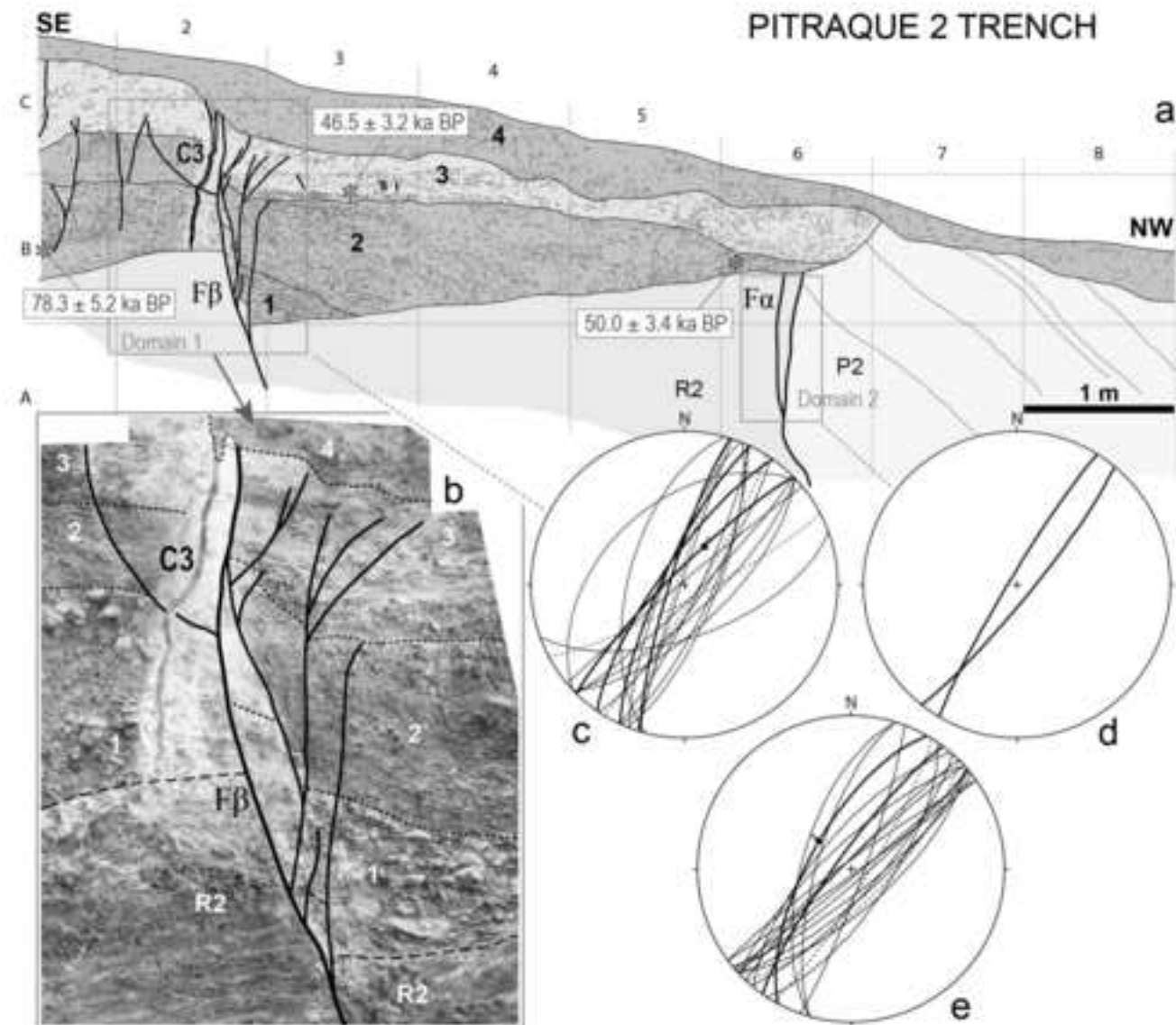


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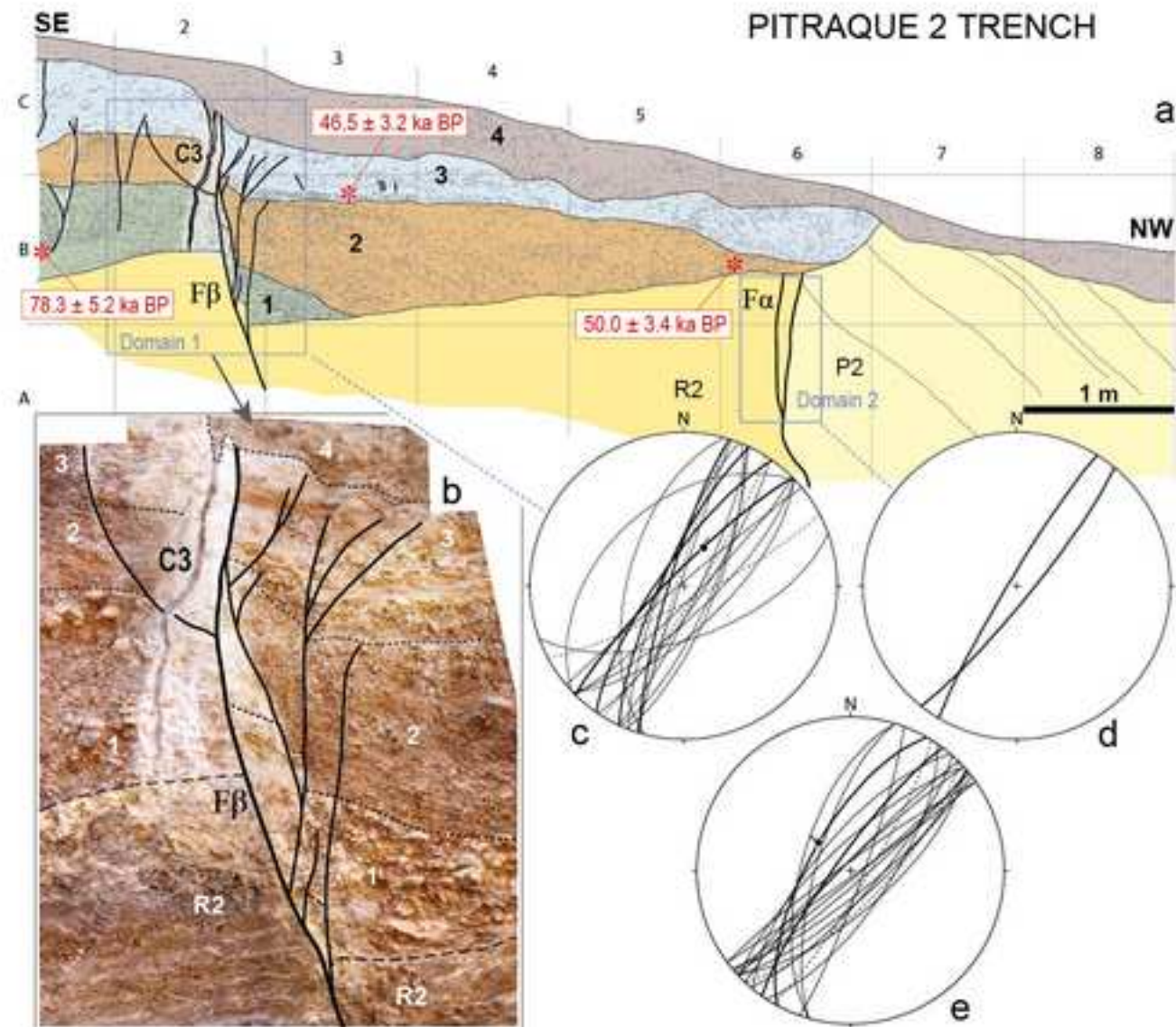


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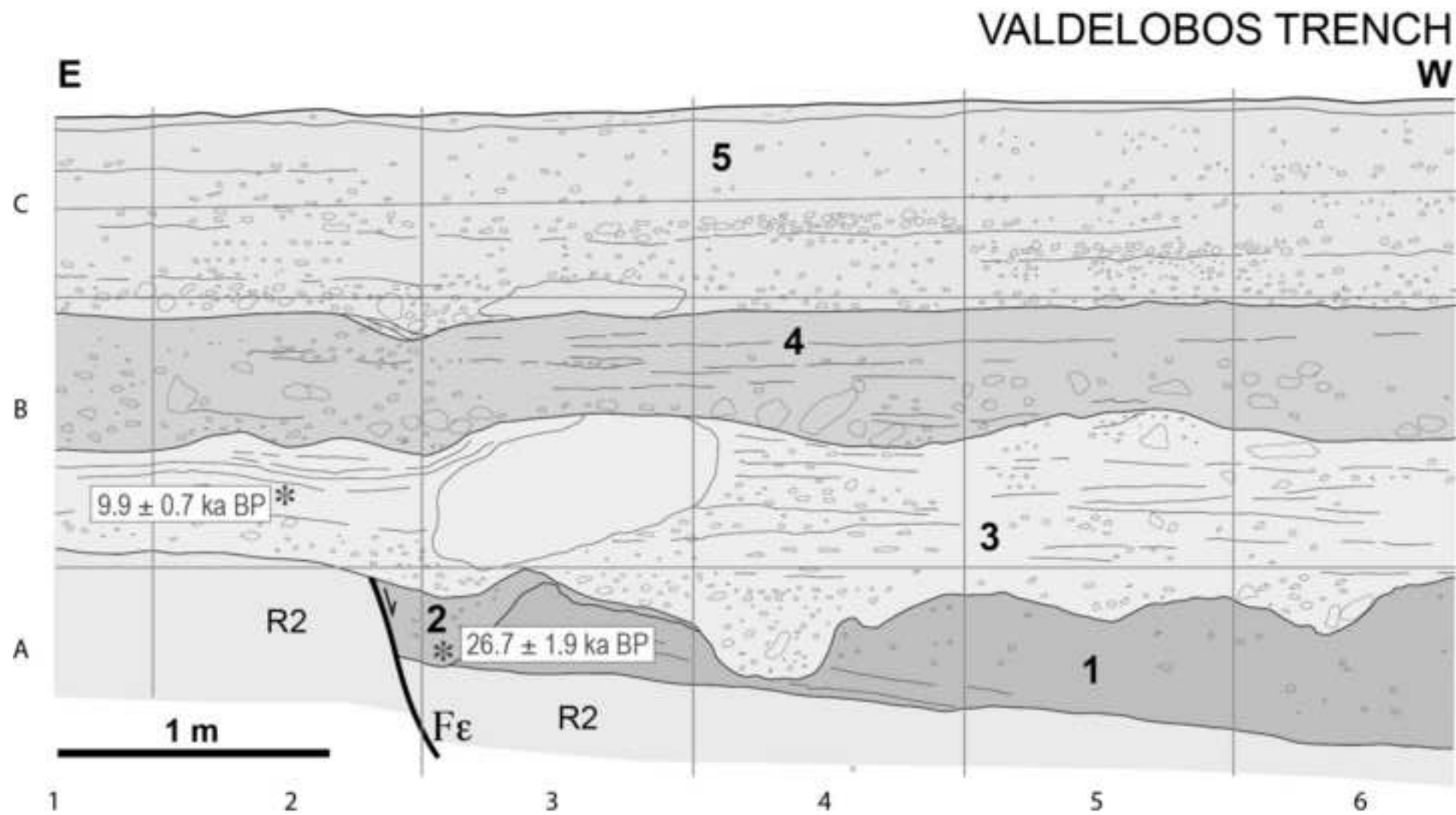


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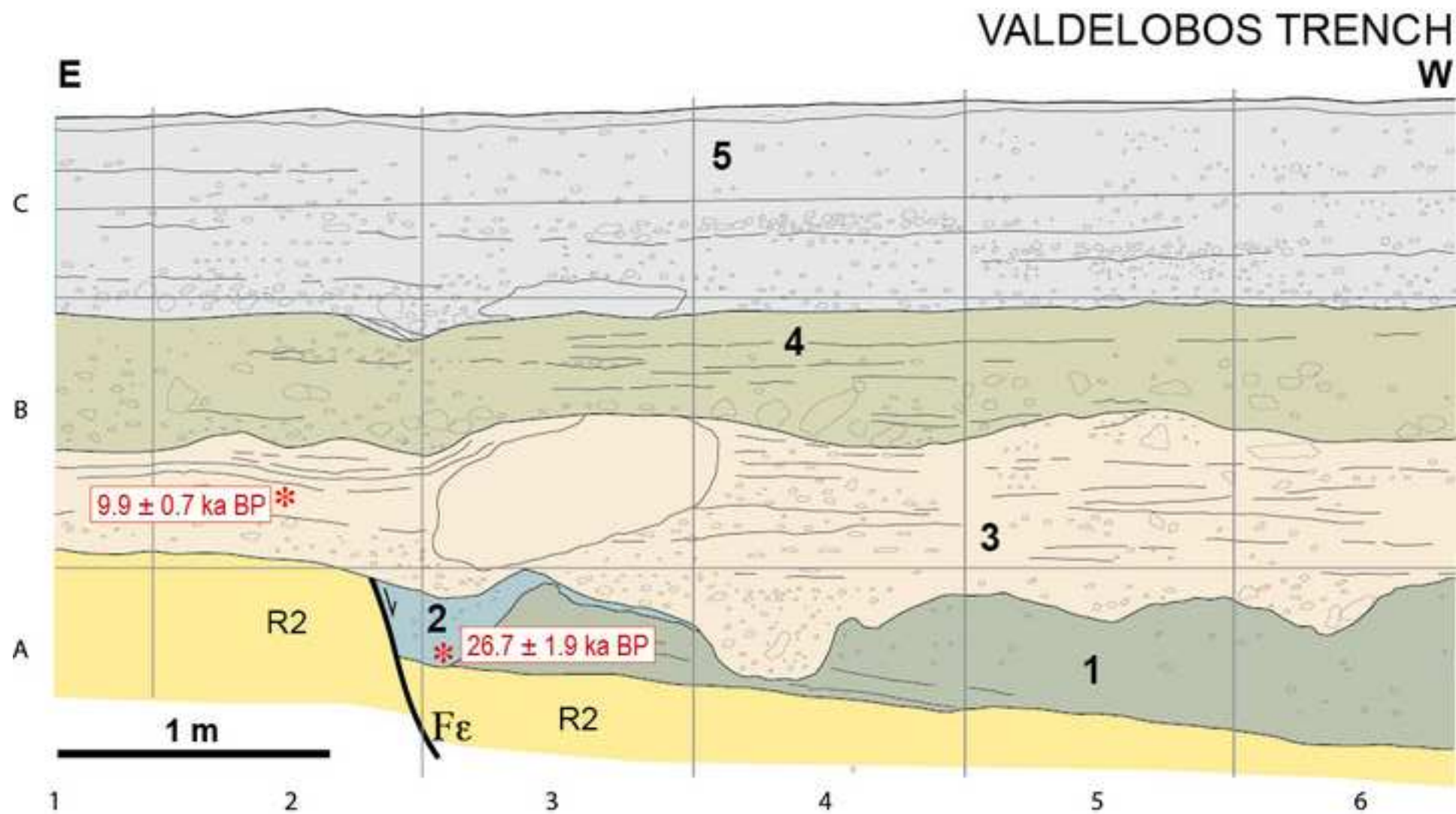


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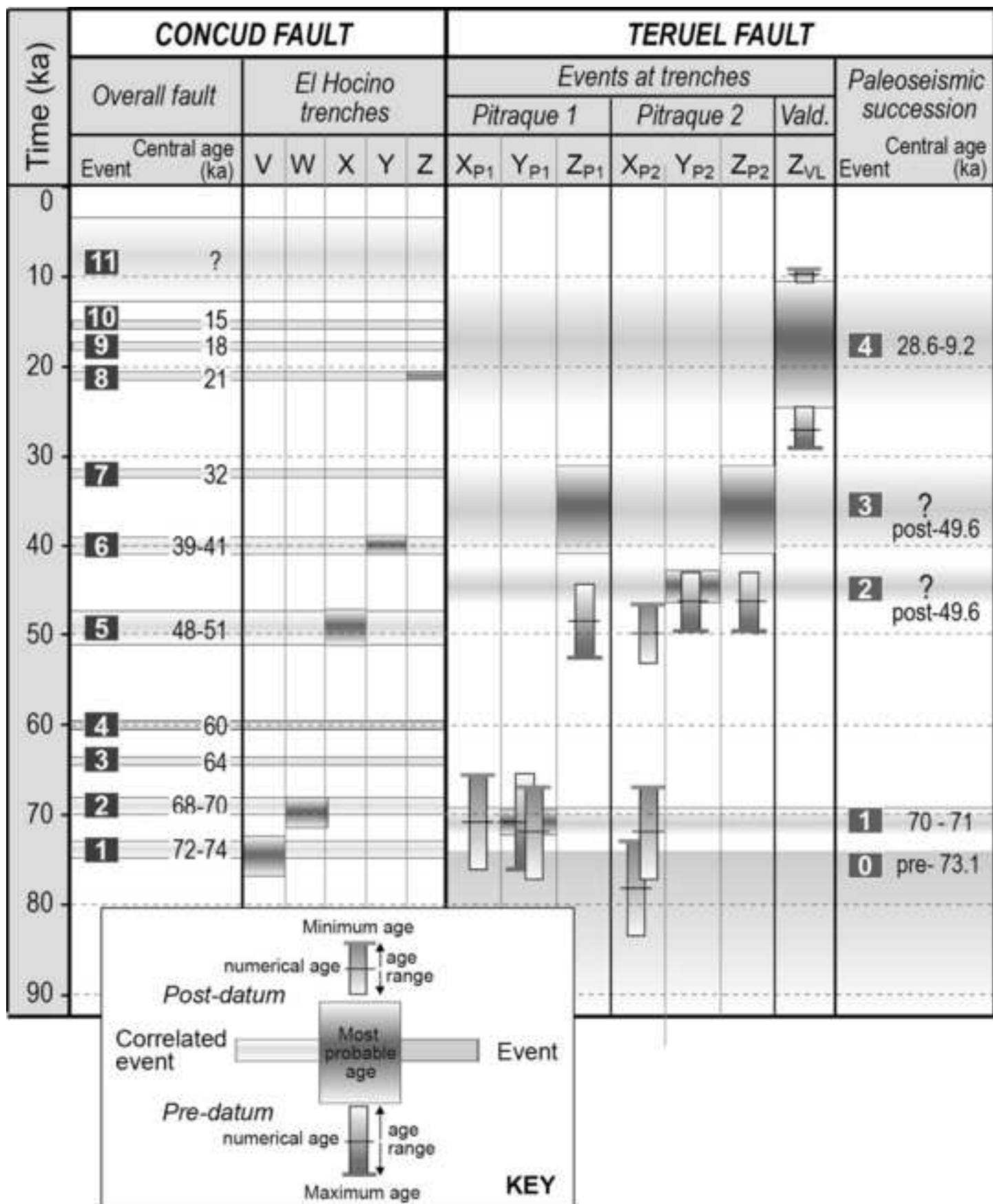


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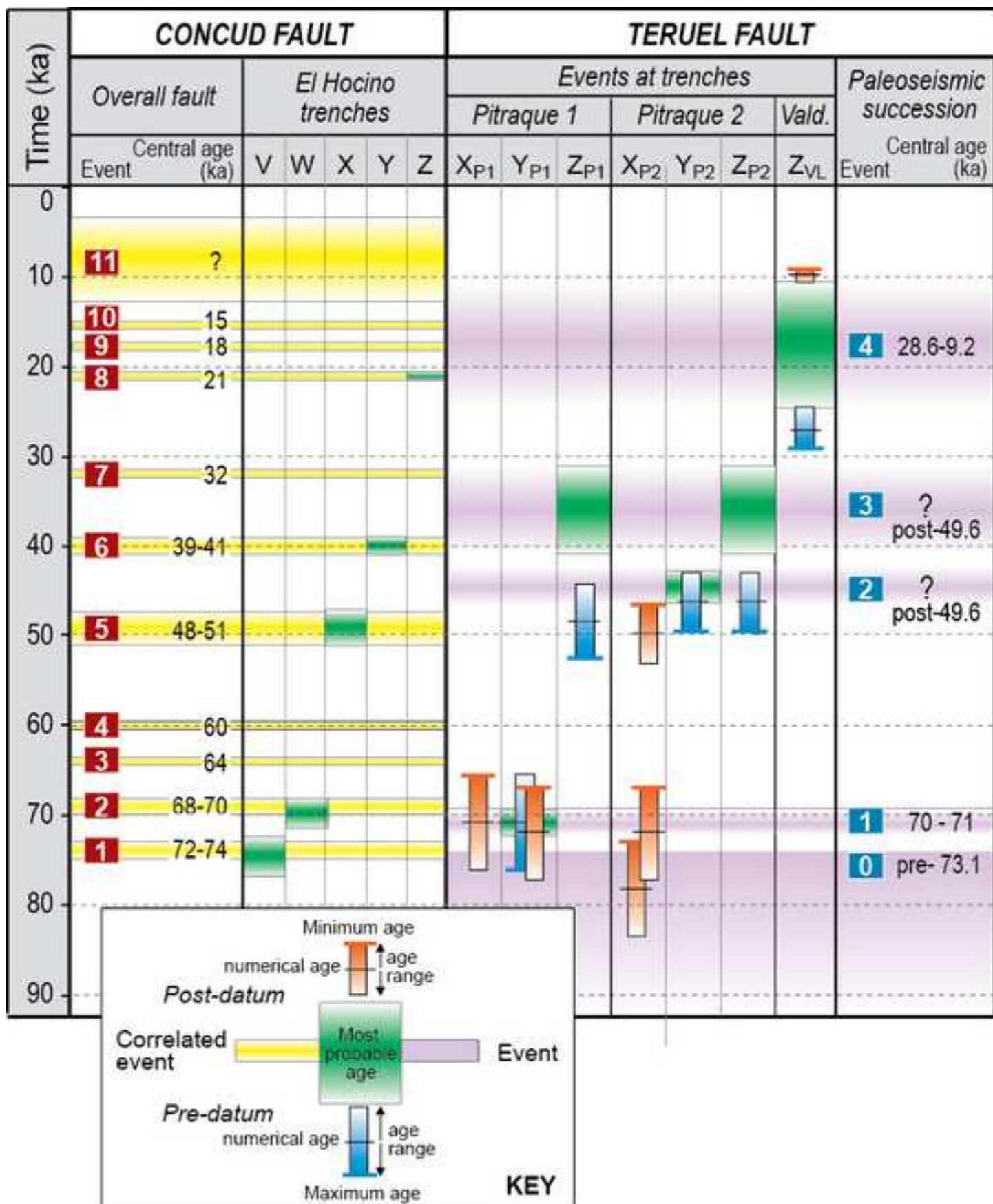


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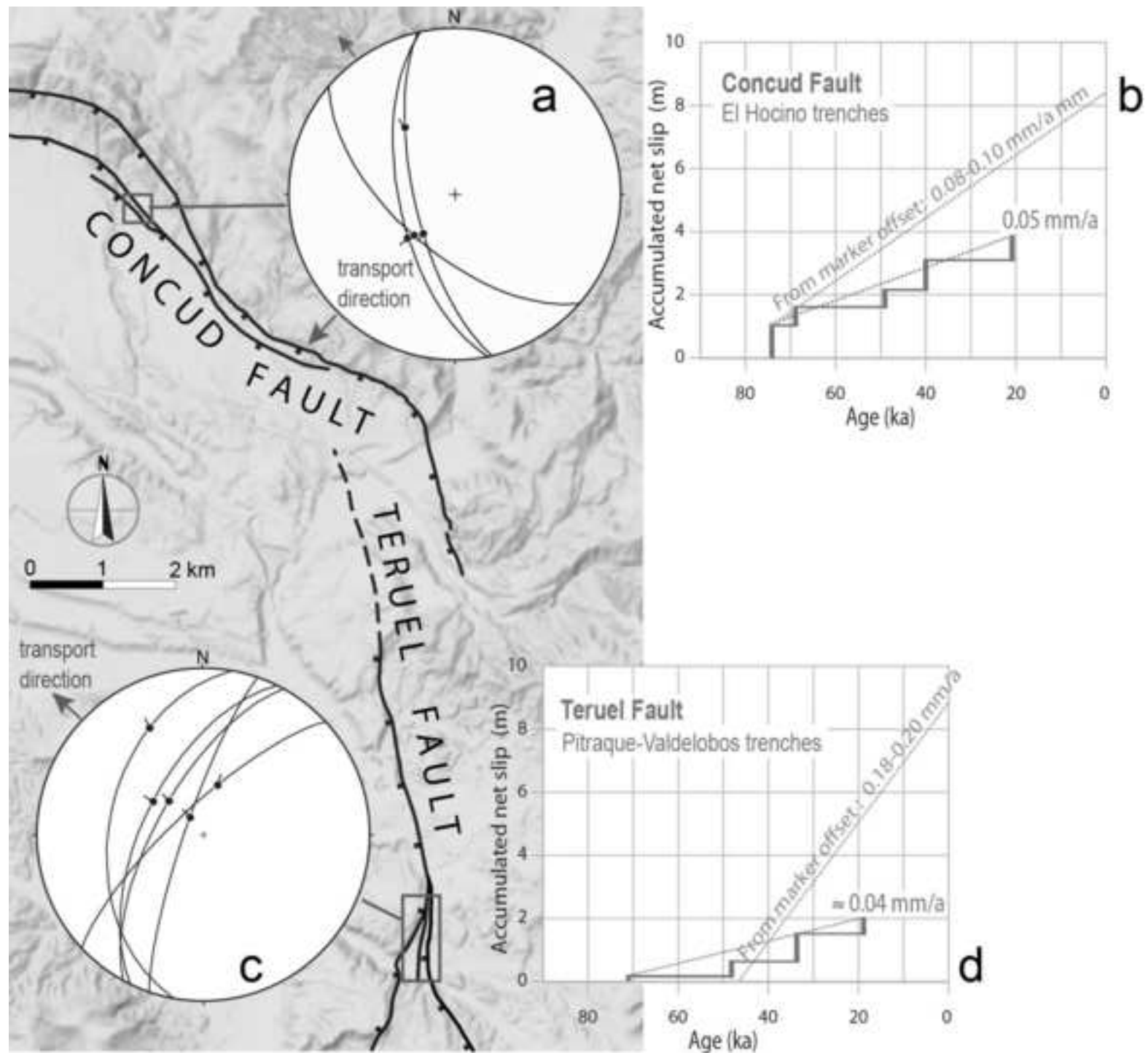


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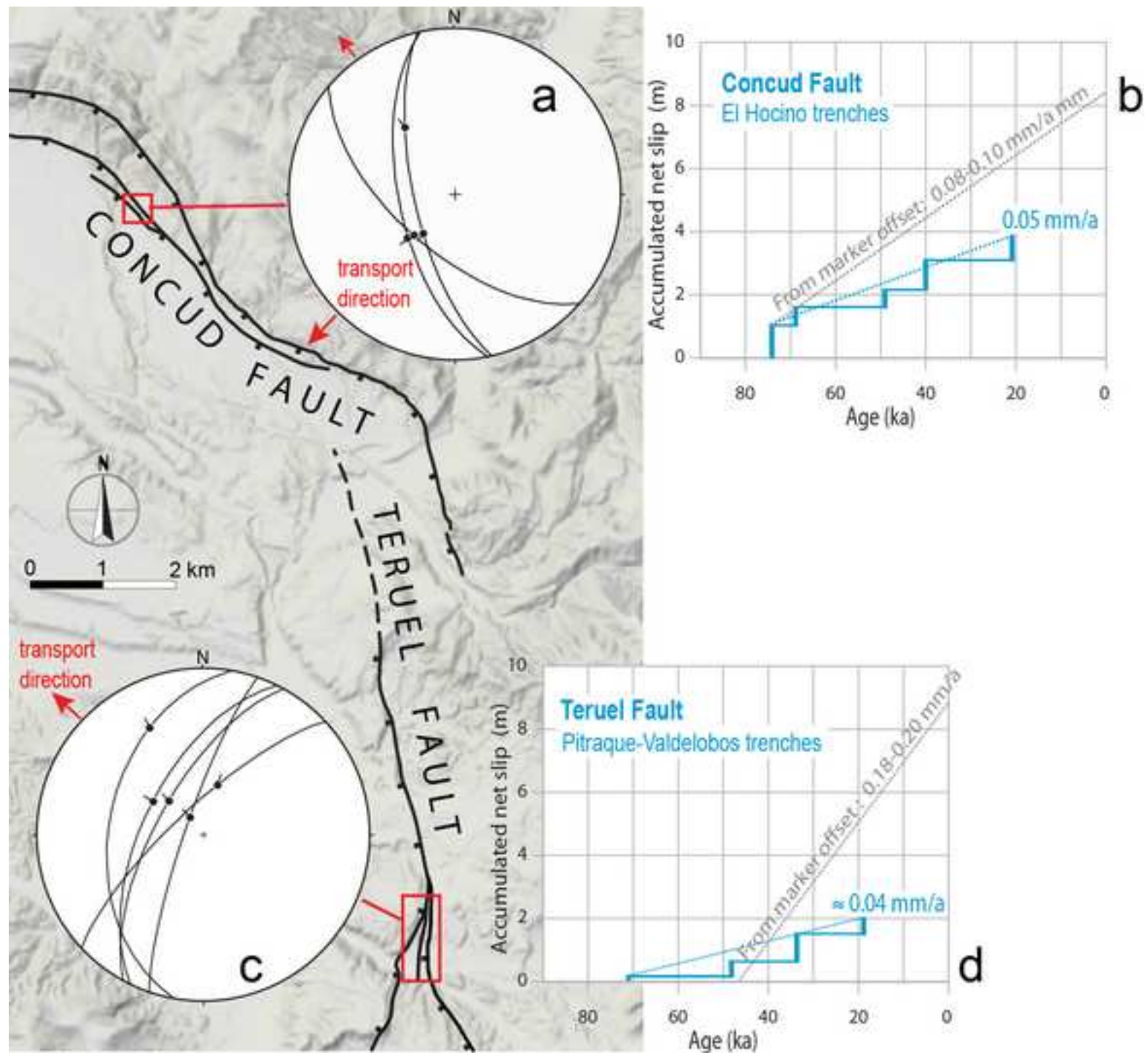


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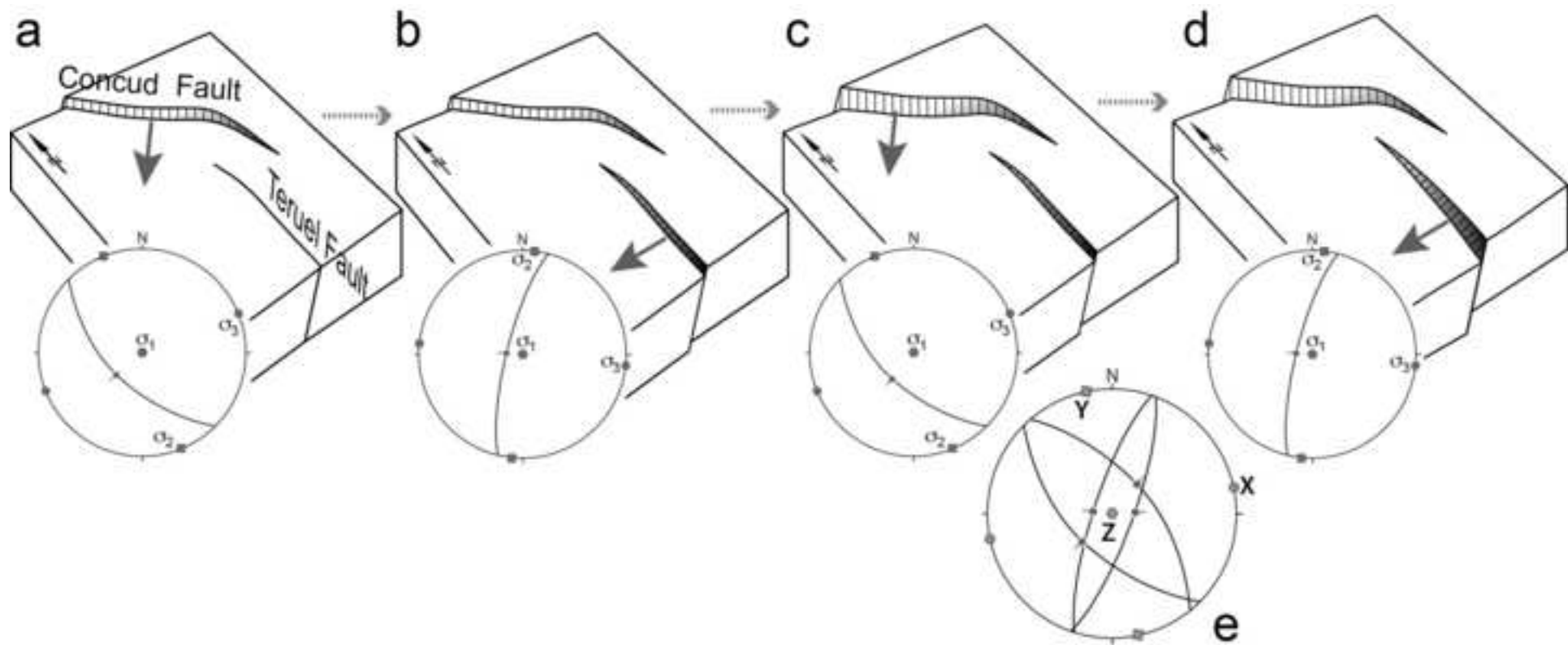
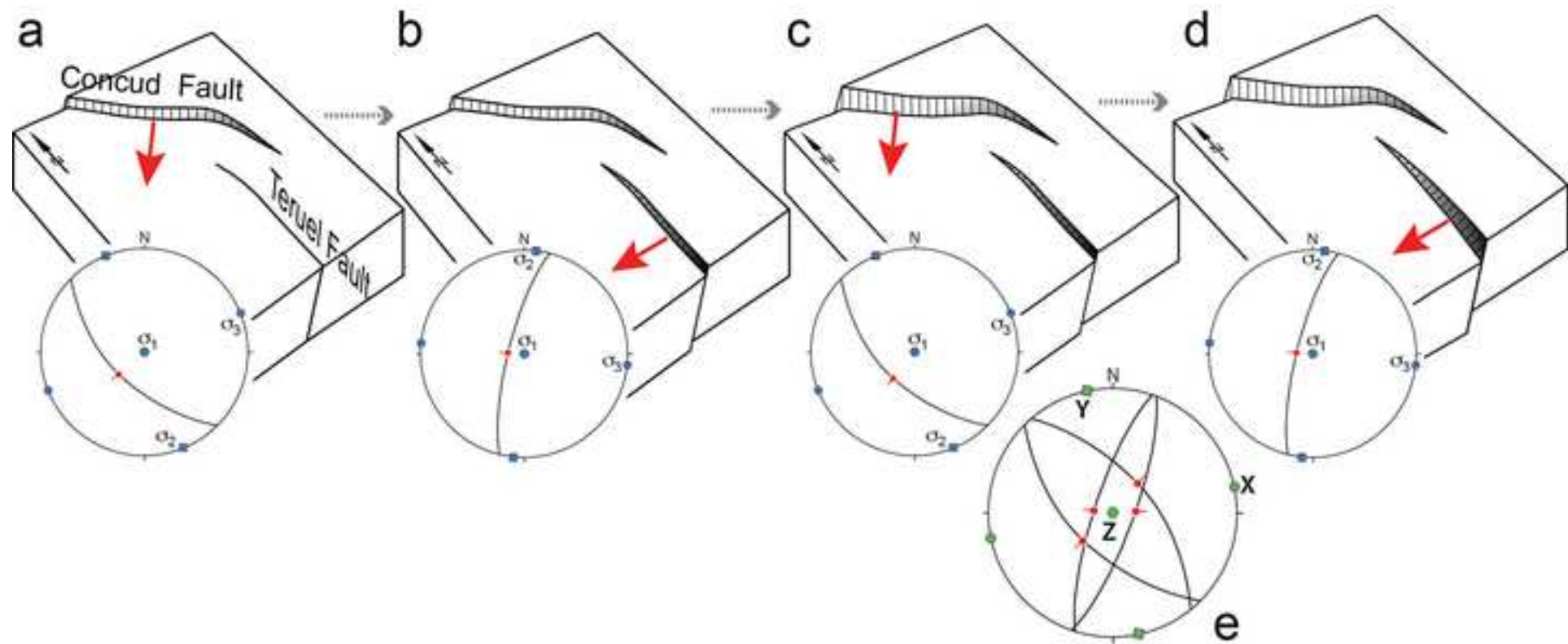


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Level	Age	Sublevel	Height above talweg (m)	Numerical age	Dating method	References
Upper	Early Pleistocene (?)	T3	85-90	Unknown		
Middel	Middle Pleistocene	T2b	45-65	250 (\pm 32) to 116 (\pm 4) ka	U/Th	Arlegui et al. (2005); Gutiérrez et al. (2008)
		T2a	40-45	90.5 (\pm 5.3) to 76.0 (\pm 5.0) ka	OSL	Lafuente et al. (2008); Simón et al. (2012)
Lower	Late Pleistocene	T1c	20-30	22.0 (\pm 1.6) ka	OSL	Lafuente (2011)
		T1b	15-20	14.9 (\pm 1.0) to 15.6 (\pm 1.3) ka	OSL	Lafuente et al. (2008); Gutiérrez et al. (2008)
		T1a	10-15	Unknown		
Subactual	Holocene	T0	3-5	3.4 (\pm 0.7) ka	OSL	Lafuente (2011)

Table 1. Levels of fluvial terraces defined in the Teruel area (Alfambra and Turia rivers).

Scenario	Paleoseismic parameters		Wells & Coppersmith (1994)	Stirling <i>et al.</i> (2002)	Pavlidis & Caputo (2004) (*) (**)	Mohammadioun & Serva (2001) (*) (***)	
<i>Length of 9 km</i>						100 bar	30 bar
Moment magnitude (M_w)			6.12	6.64	6.35	6.26	5.73
Coseismic slip (m)	Vertical		-	-	0.55	-	-
	Net		0.37	1.28	0.59	-	-
<i>Length of 11 km</i>							
Moment magnitude (M_w)			6.23	6.71	6.41	6.39	5.87
Coseismic slip (m)	Vertical		-	-	0.60	-	-
	Net		0.40	1.32	0.65	-	-
<i>Length of 23 km (linked Concud and Teruel faults)</i>							
Moment magnitude (M_w)			6.66	6.96	6.62	6.88	6.36
Coseismic slip (m)	Vertical		-	-	0.66	-	-
	Net		1.19	2.43	0.71	-	-

Table 1. Moment magnitude and vertical and net coseismic slip for the Teruel Fault estimated from empirical relationships for three different scenarios (fault length of 9, 11 and 23 km). (*) Obtained M_s values have been transformed to M_w by applying the relationship of Konstantinou *et al.* (2005): $M_w = 0.76 M_s + 1.53$. (**) Vertical displacement initially yielded by this correlation has been translated into net displacement considering an average dip of 68° and a pure normal movement of the Teruel Fault. (***) Moment magnitudes according to Mohammadioun and Serva (2001) have been calculated for stress drop scenarios of 100 and 30 bar.

Sample	Laboratory reference	Lithological unit	Equivalent dose (Gy)	Annual dose (mGy/yr)	Supralinearity (Gy)	K factor	OSL age (ka B.P.)
Trench: Pitraque 1							
P1-4	MAD-6076SDA	Fluvial terrace (Unit 1)	170.46	2.41	0	0.19	70.730 ± 5.259
P1-5	MAD-6077SDA	Fluvial terrace (Unit 2)	124.93	1.74	0	0.12	71.798 ± 5.059
P1-6	MAD-6078BIN	Fluvial terrace (Unit 5)	77.57	1.60	0	0.11	48.481 ± 3.801
Trench: Pitraque 2							
P2-1	MAD-6079SDA	Fluvial terrace (Unit 1)	130.05	1.66	0	0.14	78.343 ± 5.189
P2-7	MAD-6081BIN	Fluvial terrace (Unit 2)	91.95	1.84	0	0.11	49.972 ± 3.365
P2-5	MAD-6080SDA	Fluvial terrace (Unit 3)	127.80	2.75	0	0.14	46.472 ± 3.147
Trench: Valdelobos							
VL-C1	MAD-6073SDA	Fluvial terrace (Unit 2)	112.82	4.23	0	0.16	26.671 ± 1.912
VL-B2	MAD-6074SDA	Fluvial terrace (Unit 3)	16.97	1.71	0	0.23	9.923 ± 0.690

Table 3. OSL dating of samples collected from trenches at the Teruel fault.

Teruel Fault event (renamed)	Original event at individual trench	Predating OSL age (ka B.P.)	Postdating OSL age (ka B.P.)	Absolute age constraints (ka)	Coseismic net slip (m)
Event 0	XP1		70.7 ± 5.3	Pre-73.1	?
	XP2		78.3 ± 5.2		
Event 1	YP1	70.7 ± 5.3	71.8 ± 5.1	76.0 – 66.7	0.1
Event 2	YP2	46.5 ± 3.1		Post-49.6	0.5
Event 3	ZP1	48.5 ± 3.8		Post-49.6	> 1.1
	ZP2	46.5 ± 3.1			
Event 4	ZVL	26.7 ± 1.9	9.9 ± 0.7	28.6 – 9.2	> 0.3

Table 4. Summary of paleoseismic events of the Teruel Fault interpreted and correlated from the studied trenches: Pitraque 1 (P1), Pitraque 2 (P2) and Valdelobos (VL). Absolute age constraints take into account the error bar for each OSL age.

Marker / data source	Age / time window	Teruel Fault (this work)		Concud Fault (*)			
		Net slip (m)	Slip rate (mm/a)		Net slip (m) (**)	Slip rate (mm/a)	
			Overall	Partial (In 1-2 branches among 4-5)		Overall	Partial (In 1 branches among 2-3)
<i>Trenching information</i>							
Compilation of coseismic slip values	since 76.0 to 9.9 ka BP	1.7 - 2.0		0.03 – 0.05			
	since ca. 74 to 3.4 ka BP			20.5 (3.9)	0.29	0.05	
<i>Stratigraphic marker</i>							
T2b terrace top	46.5 ± 3.2 ka	8.8		0.18 – 0.20			
T2a terrace top	282 – 112 ka			39	0.14 – 0.35		
Páramo 2 unit (Latest Ruscinian)	3.6 Ma	270	0.075	255 – 290	0.07 – 0.08		

Table 5. Summary of slip rates calculated for the Teruel and Concud faults from different markers and for different time windows. (*) Data for the Concud Fault are compiled from Gutiérrez et al. (2008), Lafuente (2011), Lafuente et al. (2011a, 2014), and Simón et al. (2016). (**) In parentheses, partial net displacement measured on one fault branch.