

Structural inheritance, morphotectonics and Holocene activity of the Cucalón-Pancrudo extensional fault (Iberian Chain, Spain)

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ABSTRACT

A large active extensional fault is characterized, which will contribute to improve seismic hazard assessment in an intraplate region of the Mediterranean domain whose seismic potential until today has been underestimated. The Cucalón-Pancrudo fault (CPF) is a NNW-SSE striking extensional fault that represents the negative (extensional) inversion of a previous, Late Variscan and Paleogene, transpressional fault. It is part of the Río Grío-Pancrudo fault zone, the largest active structure in the intraplate central-eastern Iberian Chain. This study focuses on characterizing the CPF structure, morphotectonics and paleoseismology. The fault offsets a well-known regional planation surface (lower level of the Fundamental Erosion Surface, FES3, 3.5 Ma), providing a basis for calculating the maximum fault throw (c. 280–300 m, including the contribution of a minor synthetic fault and a gentle accommodation monocline), and hence estimating the net slip (c. 305–325 m) and the long-term slip rate (0.09 mm/a). A trench dug in a Holocene fluvial terrace reveals an ensemble of listric, domino-style ruptures synthetic to the main fault. They were activated during at least two paleoseismic events (X, Z), 14.9 ± 1.4 ka and 6.9 ± 0.4 ka in age. An intermediate event (Y), dated to 11.0 ± 1.0 ka, as an uncertainty because the attribution of their ruptures to event Z cannot be ruled out. The total net slip accumulated during these events (1.15–1.25 m) provides an apparent short-term slip rate of 0.07–0.09 mm/a, very similar to the long-term slip rate. Nevertheless, it is very likely that the faults exposed in the surveyed trench do not represent a complete paleoseismic record. Therefore, the actual slip rate during Late Pleistocene-Holocene times could be significantly higher, approaching that reported for most of the recent extensional faults in the central Iberian Chain. The inclusion of CPF in the map of Active Faults of Iberia (QAFI database) will result in improving seismic hazard assessment in Spain.

1. Introduction

The characterization of active normal faults in intraplate regions is poorly developed due to the greater relevance attributed to the active plate margins, which frequently results in underestimation of seismic hazard in the former. Intraplate seismotectonic activity has been frequently underestimated, since the globally released energy at plate interiors is very little compared to that associated with plate margins (Johnston and Kanter, 1990). It is true that strong intraplate

earthquakes have long recurrence periods (mostly on the order of 10^3 – 10^4 years), according to numerous paleoseismology studies carried out around the world, e.g. McCalpin and Nishenko (1996) and McCalpin (2005), in North America; Crone et al. (1997, 2003), in Australia; Liu-Zeng et al. (2007) and Fan et al. (2022), in China; Rockwell et al. (2009) and Simón et al. (2017), in Iberia. Nevertheless, they involve significant seismic hazard and sometimes cause a disproportionate amount of damage (Talwani, 2017), as demonstrated by, e.g., the New Madrid (Missouri) sequence of 1811–1812 ($M_w = 7.5$ – 8.3 ; Liu and

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Grío-Lanzuela fault, which is 55 km long). They have maximum net displacements of 120–620 m, and slip rates of 0.05–0.17 mm/a for the last 3.5–3.8 Ma (Peiro, 2023).

The Río Grío-Lanzuela fault, together with the Cucalón-Pancrudo fault (CPF), make the largest (about 95 km long) recent brittle structure within the central-eastern Iberian Chain: the Río Grío-Pancrudo fault zone (Fig. 1c; Peiro and Simón, 2022; Peiro, 2023). Its NNW-SSE trending trace bounds, or obliquely cuts, the Calatayud-Montalbán Variscan folded block and the Neogene Calatayud Basin, in which they have been locally referred with distinct names: Olalla fault (Gabaldón et al., 1991), Alpeñés fault (Tena and Casas, 1996), or Río Grío fault (Campos et al., 1996; Gutiérrez et al., 2013; Marcén and Román-Berdiel, 2015). Its complex geological history, addressed in a fragmented manner by the authors just cited, avoided identifying it as a single recent extensional fault zone until the work by Peiro and Simón (2022).

The Río Grío-Pancrudo fault zone represents a Late Variscan strike-slip structure, reactivated under Paleogene compression, and finally inverted during Neogene-Quaternary extension (Peiro, 2023). Morphotectonic methods have been crucial for mapping and characterizing the recent extensional structure, since extensively outcropping sedimentary levels are not always available to be used as regional deformation markers. In particular, Late Neogene planation surfaces have proved to be a very valuable tool for calculating fault throws and slip rates along the fault zone (Peiro and Simón, 2022), as was the case in the neighbouring Teruel Basin (Ezquerro et al., 2020). By using a Pliocene planation surface as a geomorphic marker (FES3, 3.5 Ma in age; Ezquerro et al., 2020), a total throw of about 240 m has been estimated for the normal movement along the Río Grío-Lanzuela fault, resulting in a net slip rate of 0.07 mm/a. At the Cucalón-Pancrudo fault, a maximum throw of about 300–350 m, and hence a long-term slip rate ~ 0.10 mm/a have been inferred (Peiro and Simón, 2022).

Quaternary activity at the Río Grío-Lanzuela fault has been evidenced from its imprint on the landforms and the drainage network, as well as from exposed surficial ruptures. Tilting of the hanging-wall block affecting a Villafranchian piedmont surface, and subsequent drainage reversal of a Pleistocene valley, allowed calculating a minimum throw in the range of 140–220 m for the last 2.0 Ma (slip rate of 0.07–0.11 mm/a). Besides, vertical displacement of c. 20 m of a sedimentary level dated to 66.6 ± 6.5 ka was reported from outcrop observations, yielding a slip rate of 0.30–0.36 mm/a (Peiro and Simón, 2022).

No comparable signs of Quaternary movement have been published for the Cucalón-Pancrudo fault, despite its long-term slip rate is higher than that of the Río Grío-Lanzuela fault. This is probably due to the scarcity of good outcrops of Quaternary sediments with evidence of deformation that could prove fault activity. In this paper we will address this issue, continuing the work of Peiro and Simón (2022) on the Río Grío-Lanzuela fault with a similar methodology, in order to assess the Quaternary activity of the Cucalón-Pancrudo fault, and hence its seismogenic potential. The lack of outcrops has been overcome by the excavation of research trenches allowing for a paleoseismological study.

Our specific objectives are: (1) characterizing the macrostructure and overall tectonic evolution of the Cucalón-Pancrudo fault from structural and morphotectonic data; (2) discriminating between the imprint of contractive and extensional stages from kinematic analysis at a mesostructural scale; (3) approaching the Quaternary activity and paleoseismology of the fault, and assessing its seismogenic potential; (4) obtaining the fault throw and slip rate for distinct time spans during Pliocene and-Quaternary times; (5) discussing the results in the context of the recent extensional tectonics of the central-eastern Iberian plate.

2. Geological setting

The Iberian Chain is a NW-SE intraplate range located in the eastern Iberian Peninsula (Fig. 1a and b). It developed during Paleogene to early Miocene times due to the convergence of African and European plates (Álvarez et al., 1979; Guimerà and Alvaro, 1990; Capote et al., 2002;

Liesa et al., 2018), as a result of the compressive episodes of the Alpine Orogeny (Liesa and Simón 2009). Such orogenic process mostly consisted in the positive inversion of several Mesozoic extensional basins, particularly in the eastern sector of the chain (Liesa et al., 2018).

At the central Iberian Chain, the so-called Aragonese Branch shows two large anticlines that span over 100 km in length, giving rise to the NW-SE trending reliefs (Algairén Range, Santa Cruz Range) that bound the Calatayud Basin (Fig. 1c). Paleozoic and Precambrian rocks are exposed at the anticline cores, and folded Mesozoic formations along their flanks (Cortés-Gracia and Casas-Sainz, 1996). These anticlines are constrained by thrust faults and steeply dipping faults, with notable examples including the Río Grío-Pancrudo and Cucalón-Pancrudo faults.

Since the beginning of the Late Miocene, the central-eastern Iberian Chain underwent an extensional tectonic regime linked to rifting of the Valencia Trough (Simón, 1982; Roca and Guimerà 1992; Maillard and Mauffret, 1999). This period was characterized by normal faults that bound large Neogene-Quaternary basins (Maestrat, Teruel, Jiloca, Gallocanta, Munébrega) and mostly represent the inversion of previous compressional faults (Álvarez et al., 1979; Capote et al., 2002). In this extensional period, two stages, Late Miocene to Early Pliocene and Late Pliocene to Quaternary have been distinguished. Both stages resulted in the formation of new faults, reactivation of existing ones, and development of intracontinental grabens and half-grabens with different orientations (Moissenet, 1980; Simón, 1982, 1983, 1989; Anadón and Moissenet, 1996; Gutiérrez et al., 2008, 2012; Ezquerro, 2017; Liesa et al., 2019; Ezquerro et al., 2020). The first stage was characterized by uniaxial tension with WNW-ESE trending trajectories, appearing in gradual transition from intraplate compression (decrease of the maximum horizontal stress σ_1 , until its permutation with the vertical stress axis, accompanied by clockwise rotation of the horizontal stress axes, S_{Hmax} and S_{Hmin}) (Simón, 1986; Ezquerro and Simón, 2017). It starts at the centre of the Valencia Trough and then propagates towards the interior of the Iberian Chain. The second stage was marked by nearly radial tension (induced by crustal doming at the eastern Iberian Chain; Simón, 1982) with prevalent WSW-ENE trending σ_3 trajectories, orthogonal to the prevailing intraplate compression direction (Simón, 1989; Arlegui et al., 2005; Liesa et al., 2019). This stress field has essentially continued until the present day (Herraiz et al., 2000).

During the first extensional stage, the 90-km-long, NNE-SSW to N-S trending Teruel half-graben (Fig. 1b) developed, being filled by a continental sedimentary succession up to 500 m thick (Simón, 1982, 1983; Moissenet, 1983; Anadón and Moissenet, 1996; Ezquerro, 2017; Ezquerro et al., 2019, 2020). The second extensional stage, which began by mid Pliocene time, produced a more widespread deformation in the central Iberian Chain. A large number of inherited structures were reactivated, producing new NNW-SSE trending grabens and half-grabens that are inset or cross-cut the pre-existent Teruel and Calatayud basins (Simón, 1983, 1989; Gutiérrez et al., 2008, 2020; Liesa et al., 2019). These include, among others (Fig. 1c), the 80-km-long Jiloca graben, which results from en-échelon, right releasing arrangement of the NW-SE striking Concud, Sierra Palomera, and Calamocha faults (Simón, 1983; Rubio and Simón 2007; Simón et al., 2012, 2017; Peiro et al., 2020).

The Calatayud Basin (Fig. 1c) evolved through a complex compressional-extensional setting, being filled by the most complete Neogene series in the Iberian Chain (Anadón et al., 2004). This is a continental sedimentary succession that includes clastic alluvial sediments sourced at the basin margins and lacustrine-palustrine evaporites and carbonates at the centre (Gabaldón et al., 1991; Sanz-Rubio, 1999; Sanz-Rubio et al., 2003). Several informal lithostratigraphic units were distinguished by Hernández et al. (1983) and Gabaldón et al. (1991), then adapted by Martín-Bello et al. (2014) and Peiro et al. (2023a). The Agenian and Aragonian are mostly represented by the Lower Clastic Unit (LCU), the Navarrete gypsum (NG), and the Nombrevilla limestone (NL). *Rojo 1* (R1, red clastics) and *Páramo 1* (P1, lacustrine carbonates) represent the Vallesian and Turolian. *Rojo 2* (R2, red clastics) and

Páramo 2 (P2, uppermost lacustrine carbonates) represent the Ruscinian. Younger, extensive clastic sediments (*Rojo 3* and Villafranchian pediments) overlapped the lacustrine sediments in large areas since the onset of the Late Pliocene–Quaternary extensional stage.

The mountains surrounding the Teruel and Jiloca basins exhibit extensive erosion surfaces and pediments that flattened the reliefs built during the orogeny (Peña et al., 1984). Two major planation surfaces have been identified. The *Intra-Miocene Erosion Surface* (IES), which dates back to the middle Miocene, is typically found in the upper part of the main reliefs. The *Fundamental Erosion Surface* (FES), which dates back to the middle Pliocene, is easily recognizable as a vast planation level at lower heights (Gutiérrez and Peña, 1976; Peña et al., 1984; Sánchez-Fabre et al., 2019). These surfaces correspond approximately to the Iberian Chain Surface and the Lower Pliocene Surface by Pailhé (1984), and the S1 and S2 by Gutiérrez and Gracia (1997), respectively. In recent studies (Simón-Porcar et al., 2019; Ezquerro et al., 2020), the original FES splits into three different surfaces: Upper Sublevel, FES s.s. (the most widely developed), and Lower Sublevel. Henceforth in this paper, these surfaces will be referred to as FES1, FES2, and FES3, respectively.

The *Intra-Miocene Erosion Surface* (IES) has been dated close to the Aragonian–Vallesian limit (~11.2 Ma; Alcalá et al., 2000; Ezquerro, 2017). The sublevels of the *Fundamental Erosion Surface* have been correlated with different coeval sedimentary horizons within the carbonate, lacustrine–palustrine infill in the central part of the endorheic Teruel basin. The ages of these horizons have been well constrained based on mammal sites and magnetostratigraphy: FES1 and FES2 have been dated to the Late Ruscinian, merging around ~3.8 Ma, and FES3 to the Early Villafranchian (~3.5 Ma) (Ezquerro et al., 2020). Subsequently, widespread pediments developed over the Teruel and Jiloca basins during the Villafranchian represent the transition to the Quaternary exorheic fluvial system.

According to the official seismic catalog of the Instituto Geográfico Nacional (IGN; <https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>), the historic and instrumental seismic activity of the region is generally low to moderate. The epicentres are primarily concentrated at the margins of the Jiloca graben (including a notable cluster between the Sierra Palomera and Concud faults, described by Peiro (2023), in the central-southern sector of the Teruel Basin, as well as in the Albarracín and Javalambre massifs. The magnitudes (Mb) typically range from 1.5 to 3.5, with a maximum Mb of 4.4 recorded in the Teruel Graben and Mb of 3.8 in the Albarracín massif (data from seismic database of Instituto Geográfico Nacional, IGN; <https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>). Nevertheless, the most recent and strong earthquakes have occurred further north: Cimballa, 1912 (intensity VI–VII) and Used, 1953 (intensity VII, magnitude 4.7), the latter being attributed to the Daroca Fault (Simón et al., 2022a).

3. Methods

3.1. Structural and morphotectonic study

In the present work, the structure of the Cucalón–Pancrudo fault is characterized by means of a multidisciplinary approach that includes geological mapping, structural analysis and morphotectonic reconstruction.

A comprehensive geological map, informed by the official 1:50,000-scale map from Instituto Geológico y Minero de España, IGME (Hernández et al., 1983; Gabaldón et al., 1989), has been elaborated for the northern sector of the Cucalón–Pancrudo fault. This map was further refined using 1:30,000-scale aerial photography, satellite orthoimagery, and hillshade maps generated in QGIS (QGIS.org, 2023). Detailed topography was sourced from Digital Elevation Models provided by the Instituto Geográfico Nacional (IGN), available at resolutions of 2, 5 and 25 m/pixel, or from LiDAR point cloud data. For the latter, raw LAZ files were processed using R Statistical Software (v4.1.2; R Core Team, 2021)

with the lidR package (Roussel et al., 2020; Roussel and Auty, 2024), to create a high-resolution digital terrain model (DTM). This DTM was constructed by spatial interpolation of the point cloud using a triangular irregular network (TIN) with linear interpolation, achieving resolutions finer than 1 m/pixel and effectively excluding the vegetation cover.

Geological cross-sections have been elaborated combining map and outcrop information. In addition, mesostructural data (fault planes and slickenlines, foliation) were collected in discrete outcrops, then submitted to geometrical and kinematical analysis using Stereonet software (Allmendinger et al., 2011).

The Cucalón–Pancrudo fault and other neighbouring recent structures have been represented on a morphotectonic map, focusing on the remnants of Late Neogene planation surfaces (more specifically, FES sublevels). The most extensively represented surface (FES3), together with its correlative deposits within the Calatayud Basin (uppermost lacustrine limestone, *Páramo 2* unit; Hernández et al., 1983; Gabaldón et al., 1991), have been used as the main morpho-sedimentary marker of recent deformation. Their topographical reconstruction has been achieved by means of height contours drawn on the morphotectonic map. A set of parallel topographical profiles have allowed calculating: (i) the distribution of total slip along the Cucalón–Pancrudo fault (throw vs. distance, T-D graph) and its maximum value; (ii) the long-term slip rate, by considering the age of FES3 (3.5 Ma).

The planation surfaces show gentle unevenness, and connect with residual reliefs via pediment slopes. The amplitude of the unevenness (usually in the range of 10–40 m) advises to use an adequate contour interval for FES3 for representing its present-day geometry with the suitable precision. We will therefore assume that: (i) the obtained fault throws include an error bar of ± 40 m, and (ii) a 50-m-spaced contour map can be considered as reasonable for calculations (as previously proposed by Ezquerro et al., 2020). Such level of uncertainty in the calculated fault throws results in errors for slip rates around 0.01 mm/a.

3.2. Geophysical study

In absence of exposures of the Cucalón–Pancrudo fault involving Quaternary sediments, and with the purpose of selecting the most adequate sites for trenching, a geophysical exploration of the subsoil was carried out. Magnetometry and Ground Penetration Radar (GPR) were used, following the research procedure proposed by Pueyo et al. (2015) and Peiro et al. (2022).

After field survey focused on the Valdelafuente gully (3 km to the SSE of Lagueruela village; see Fig. 2a) and an associated Pleistocene alluvial fan, an extensive magnetometric exploration was achieved. Magnetometric data (Earth magnetic field intensity and vertical magnetic gradient) were acquired by means of a GSM-19 equipment with built-in GPS (sensor separation = 0.5 m). Diurnal correction was made from a second, stationary, magnetometer (PMG-01). The regional trend was identified and subtracted to Earth magnetic data to obtain residual anomalies.

The distribution of geomagnetic anomalies defined by dipole alignments was used to locate and orientate several orthogonal transects that were then explored with Ground Penetration Radar (GPR). A RAMAC GPR device with different central frequency antennas of 50 MHz (unshielded), 100 and 250 MHz (shielded) was used, aiming to obtain different resolutions and potential penetration depths. GPR profiles were digitally processed in order to enhance the signal and filter frequencies out of range. When interpreting GPR profiles, attention was focused on lateral interruptions of the reflector continuity (probable faults) and slope reflector changes (probable fault tilting).

To allow differentiation and correlation of sedimentary units, several magnetic susceptibility logs were made by using a TERRAPLUS manual susceptometer (model KT-20), the corresponding values being expressed in dimensionless SI units.

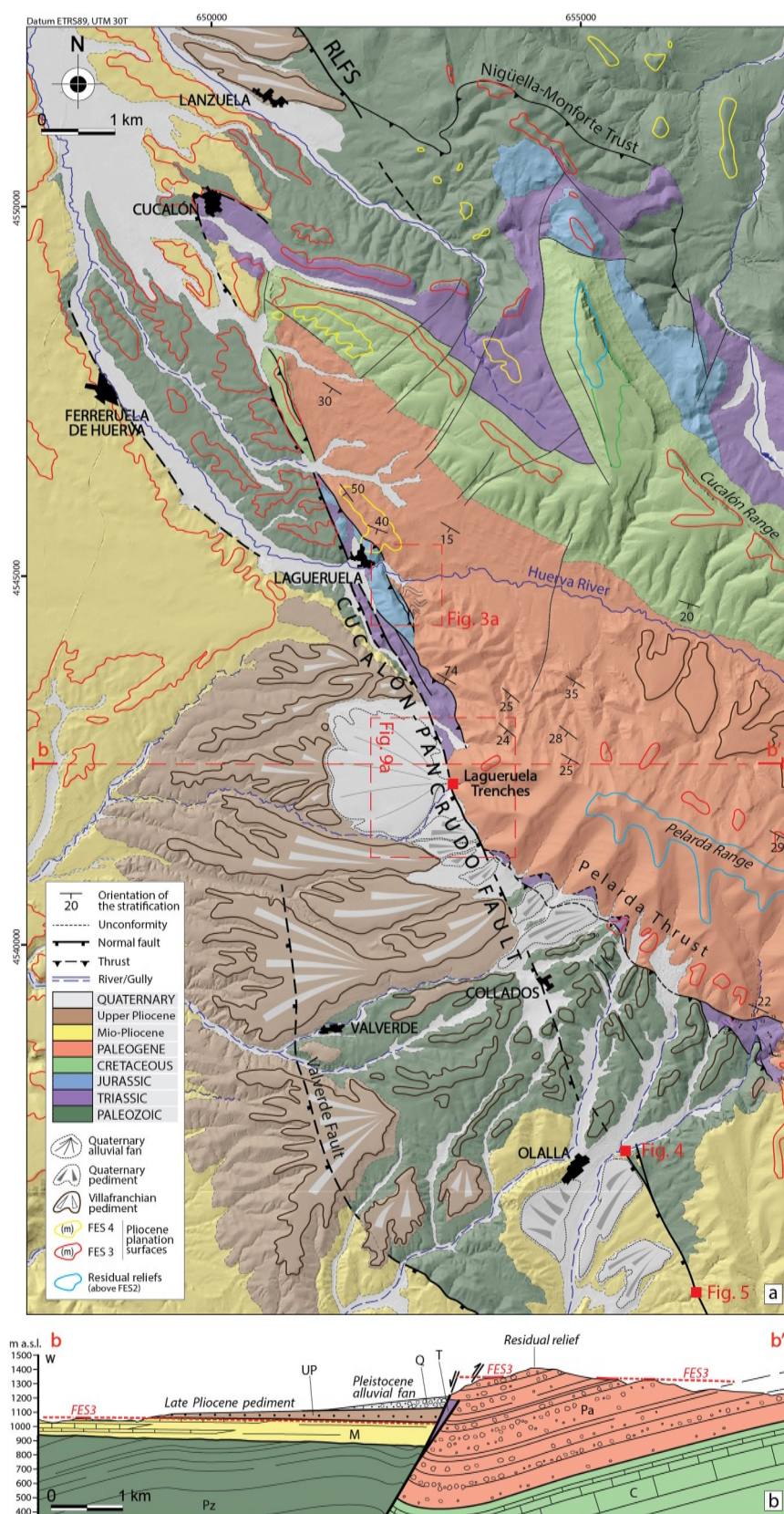


Fig. 2. (a) Geological–geomorphological map of the Lanzuela–Olalla area (on DEM image from Instituto Geográfico Nacional). Locations of Fig. 3a, 4 and 5, 9a, 10a, b, as well as the paleoseismological trenches south of Lagueruela, are indicated. Background: hillshade image generated from Digital Elevation Model (5 m grid) of Instituto Geográfico Nacional (IGN). (b) Cross section of the main fault (location in a).

3.3. Paleoseismological study

After geological mapping and geophysical exploration, two trenches crossing the inferred fault trace (LAG1 and LAG2) were dug on Quaternary alluvial materials. The excavator shovel initially provided a trench 1.3 m wide, although a segment of LAG1 trench was then widened to about 4 m for safety (the trench attained the local water-table at a very shallow depth, <2.5 m).

The trenches were studied according to the methodology proposed by McCalpin (1996). The most informative trench wall (southern, vertical wall of LAG1) was cleaned, equipped with a square grid (0.5 m), and logged with sketches and detailed photographs. Sedimentary units were defined based on colour, lithology, texture and sedimentary structures. Their boundaries were marked and used as deformation markers. The magnetic susceptibility logs contributed to correlate the units between both trench walls.

Analysis of the relationships between sedimentary units and faults has allowed to reconstruct the main deformation episodes, and hence to constrain the age of paleoseismic events. The throw (vertical separation of a marker) was measured for each fault, while the net slip vector was estimated only approximately, owing to the lack of information on the fault kinematics.

3.4. OSL dating

Given the lack of organic matter within the sedimentary units, Optically Stimulated Luminescence (OSL) was used to estimate their deposition age. A total of eight samples (seven of them from the LAG1 trench and one from LAG2) of fine clastic sediments were collected following the standard sampling procedures proposed by Nelson et al. (2015); in particular, opaque tubes were used to avoid exposure to daylight. Due to backhoe damage to the trench walls and water filtration, the lowest, oldest sample (LAG1-F) was extracted, under controlled light conditions in the laboratory, from the inside of a sediment block collected at the LAG1 trench bottom.

The samples were processed by the Luminescence Dating Laboratory of CENIEH (Burgos, Spain). Quartz grains of sizes 180–250 μm were extracted from each sample following standard procedures (Wintle, 1997). OSL response of the quartz grains was measured using an automated Risø OSL/TL reader (TL-DA 20). A SAR protocol (Murray and Wintle, 2000) was applied to define a dose response curve and estimate the accumulated dose of 48–60 multigrain aliquots of each sample. Dose recovery tests varying different parameters in the measurement sequence (preheat temperature, test dose and cleanout at the end of each cycle) were used to define the most suitable measuring conditions. Natural dose distributions derived from the measurement of 48–60 multigrain aliquots per sample were reduced by excluding the identified outliers; outliers have been defined as those values out of 1.5 times outside of the interquartile range. The resulting populations were normally distributed, with overdispersion values < 30%; the Central Age Model (CAM, Galbraith et al., 1999) has therefore considered appropriate to estimate the burial dose of each sample.

Environmental dose rates are calculated as a contribution from beta, gamma and cosmic radiation. The quartz grains extracted from each sample were etched with hydrofluoric acid for 50 min; this treatment removed the 10–17 μm outer layer of the grains (Duval et al., 2018) affected by alpha radiation; this is therefore, not accounted for in the dose rate received by the quartz grains measured by OSL. Beta and gamma contributions are derived from the radionuclide activity concentration determined by high-resolution gamma spectrometry. Radionuclide activity concentrations are presented in the table provided in Supplementary Material. The contribution of cosmic radiation was calculated from the sample depth according to Prescott and Hutton (1994), assuming a linear accumulation of sediments. Attenuation caused by moisture and grain size was taken into account. An uncertainty of 5% has been added to water contents to account for variability

during the burial period. The calculated dose rates, the burial doses estimated from the OSL measurements and the derived ages are summarized in Table 1 (section 4.3.5).

4. Results

4.1. Structure of the cucalón-pancrudo fault (CPF)

4.1.1. Overall structural description

The CPF is a nearly 40 km long extensional structure that extends from Cucalón to Pancrudo villages (see Fig. 1c). The main fault surface strikes N155°E in average and steeply dips towards W. Together with the Río Grío-Lanzuela fault, it makes the Río Grío-Pancrudo fault zone (RPFZ), both faults being separated by a 2-km-wide, right relay zone (Peiro and Simón, 2022). The northern sector of the fault zone obliquely crosses the Aragonese branch of the Iberian Chain (Paleozoic Calatayud-Montalbán massif); the central part partially constitutes the northeastern margin of the Calatayud Basin, while further south the fault crosses its Neogene infill, separating the Neogene Calatayud Basin from the Paleogene Montalbán Basin (Fig. 1c).

The CPF exhibits both contractional and extensional deformation features, evidencing a long history of movements during both the Alpine orogeny and the Neogene-Quaternary rifting. The eastern, Sierra Pelarda fault block underwent subsidence during contractional movements, while it was uplifted during the extensional ones. As a result, the fault zone shows anastomosing reverse and normal fault traces (especially in the Lagueruela sector), and inconsistently brings into contact formations of different ages in the hanging-wall (Cambrian, Neogene, Quaternary) and the footwall (Cambrian, Jurassic, Cretaceous, Paleogene) (Fig. 2a).

The north-central sector of the CPF, between Lagueruela and Olalla villages, shows the most noticeable features of extensional activation (Fig. 2a and b). The fault clearly offsets the Miocene series, while Villafranchian and Quaternary alluvial systems spreading from the fault mountain front are interrupted at the fault trace. Along this sector, other intrabasinal normal faults run parallel to the CPF, such as the Valverde fault, which generates metric offsets in the Villafranchian alluvial systems.

The trace of the central-southern sector, between Olalla and Alpeñés villages (Fig. 1c), is inferred from certain, almost straight lineaments cutting the Neogene Calatayud Basin. They represent a succession of ruptures, not fully connected but markedly aligned, which are evident in both aerial photographs and DEM. As explained later, those fault segments also offset the Fundamental Erosion Surface (FES; mostly level FES3), which allows inferring recent normal slip for this sector.

4.1.2. Contractional inheritance

Evidence of contractional inheritance of the CPF is provided by both the map pattern (Fig. 2a) and outcrop observations, mostly in the Lagueruela sector. Several meso-scale structures suggest a complex deformation history beyond the univocal behaviour as dextral strike-slip faults traditionally attributed to the NNW-SSE faults of the Iberian Chain (e.g., Guimerà, 1988; Guimerà; Álvaro, 1990; De Vicente et al., 2009).

At its northern sector, the fault zone runs parallel to a thrust system in the surroundings of Lagueruela village, sharing part of its trace with the NW-SE-striking Pelarda thrust (Fig. 2a). This thrust system, made of several, almost parallel or anastomosing branches, lifted its western block with Paleozoic rocks onto the Paleogene succession that, at present, constitute the Pelarda range, and enclosed lenses of Mesozoic rocks. In the surroundings of Lagueruela, anastomosing lenses also occur within the Jurassic units, while a number of tight, hectometre-scale, NNW-SSE trending folds affect the Paleogene succession (Fig. 2a and 3a).

At outcrop scale, Paleogene conglomerates are locally affected by: (i) Foliation planes (S) oriented 020,70°W on average, contiguous to a rupture plane (C) oriented 140,60°W (Fig. 3b and c), thus conforming a

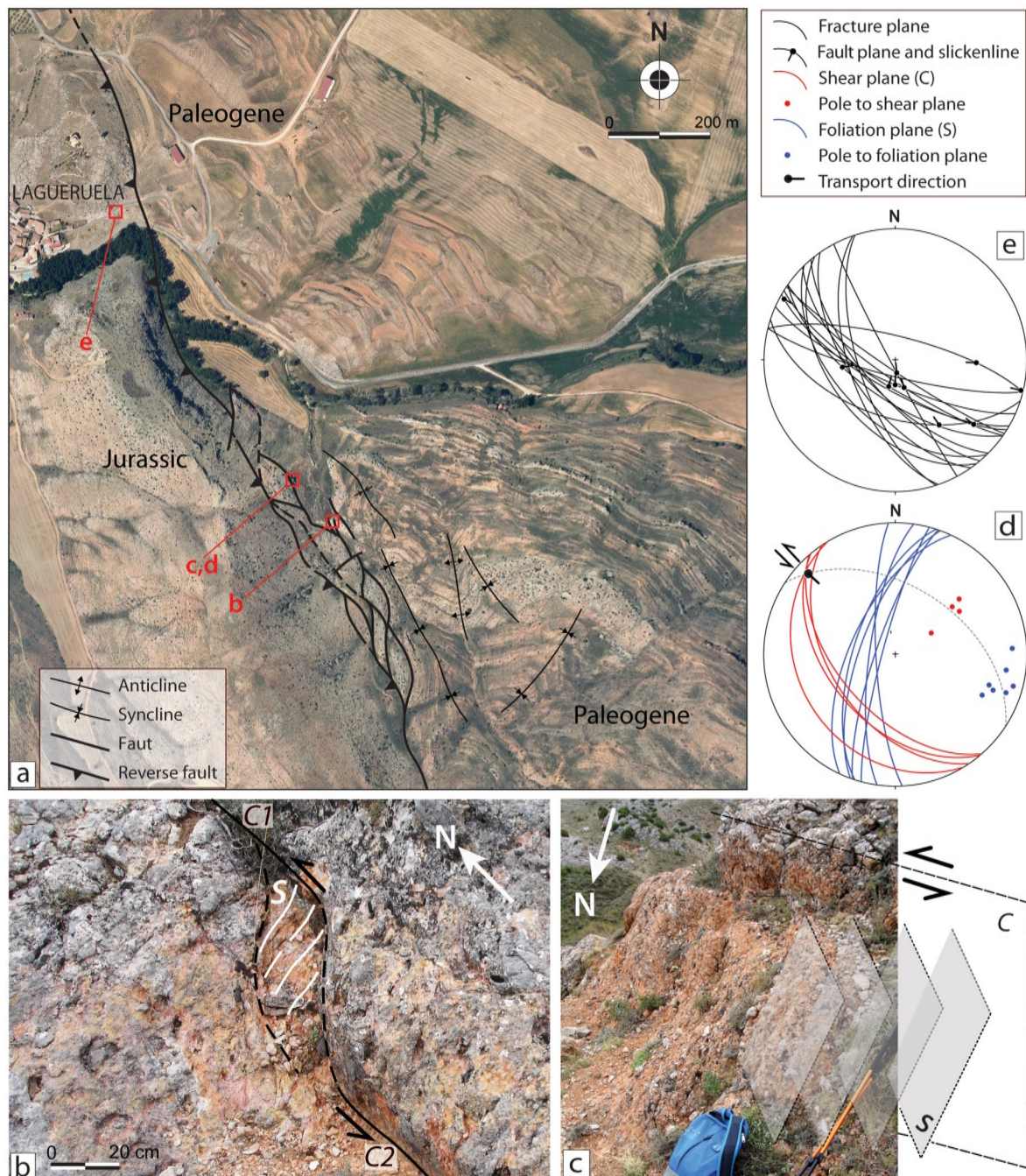


Fig. 3. (a) Orthoimage (Instituto Geográfico Nacional, IGN) of the area SE of Lagueruela, showing the anastomosing traces of the contractive fault zone. (b) Contractive relay zone between two N-S striking small faults (C1 and C2), in which a secondary foliation (S) has developed. (c) Shear surface with associated foliation planes (S-C structure s.l.). (d) Stereoplot of S and C planes at the former shear zone. (e) Stereoplot of minor faults with slickenlines cutting Jurassic limestones. See location of b, c-d and e labelled on the orthoimage.

sinistral shear zone. (ii) A fault relay between metre-scale, N-S trending faults, with internal foliation revealing its contractive character and, therefore, also its sinistral slip sense (Fig. 3d). Close to Lagueruela village, the fault zone in Jurassic limestones exhibit numerous NW-SE striking fault planes in which slickenlines reveal both dextral, sinistral and reverse movements (Fig. 3e).

4.1.3. Structural evidence of recent extensional activity

Unfortunately, there is a general lack of structural evidence about extensional activity of the CPF during Pliocene-Quaternary times, since no natural or man-made exposure shows any mechanical contact involving sediments of that age. A number of outcrops of extensional

fault segments belonging to the studied structure have been surveyed in its southern sector, but they only include Paleozoic, Mesozoic and Lower Miocene units. Next we briefly describe two of them (Olalla and La Pesquera sites; see location corresponding to Figs. 4 and 5 in Fig. 2a). The main pieces of evidence of extensional faulting will come from the morphotectonic analysis and observations made in a trench excavated south of Lagueruela village, which will be presented in sections 4.2 and 4.3, respectively. The cross section of Fig. 2b, which integrates map results and observations at outcrop scale, reveals the overall extensional structure of the northern CPF.

Olalla site. East of Olalla village, the CPF is clearly exposed owing to erosive incision of the La Riera gully. The CPF brings into contact



Fig. 4. Trace of the CPF, bringing into contact Paleozoic and Neogene materials. See location in Fig. 2a.

Paleozoic rocks of the footwall block with Lower Miocene units of the hanging-wall block, the latter dipping 45°W (Fig. 4; see location corresponding in Fig. 2a). Quaternary sediments are not directly involved, but they form an alluvial pediment that spreads from the fault scarp to the Calatayud Basin. In detail, the CPF appears as a 10-m-thick fault zone with an average orientation $147,75^\circ\text{W}$, consisting in Paleozoic rocks strongly deformed and locally brecciated. Neither geometric features nor kinematical indicators could be described or measured within the fault zone itself (due to inaccessibility), but two minor conjugate ruptures have been observed in the Neogene materials of the hanging-wall block, with orientations $175,60^\circ\text{E}$ and $167,85^\circ\text{W}$, respectively.

La Pesquera site. This exposure of the CPF is located halfway between Olalla and Nueros villages, in a tributary of the Tomelloso gully. The fault zone (Fig. 5a; see location corresponding in Fig. 2a) is oriented

$125,60^\circ\text{S}$, is approximately 1.3 m thick and affects two different Miocene units: orange lutite with scattered clasts (M1), within the footwall block, and brownish conglomerate made of angular centimetric clasts (of Paleozoic origin), with interbedded decimetric limestone layers (M2), within the hanging-wall block. Bedding of M2 is noticeably tilted (Fig. 5b), being oriented $112,40^\circ\text{S}$. This can be interpreted as part of a drag fold associated to recent normal slip of the main fault zone. A set of minor fault planes (oriented $118,55^\circ\text{S}$ in average) with low-pitch slickenlines offsets M2 layers (Fig. 5c and d), revealing a dextral strike-slip movement on the fault zone previous to the recent extensional one: after restoring the bedding and the minor faults to their original attitude, the fault planes turn out to become vertical (c. $110,90^\circ$; Fig. 5d), while the slickenlines remain nearly horizontal.

4.2. Morphotectonic analysis and long-term slip estimate

4.2.1. Planation surfaces used as deformation markers: overall reconstruction

As explained in section 3.1, Pliocene planation surfaces have been used as markers for characterizing recent deformation. The different sublevels of the Fundamental Erosion Surface (FES1, FES2, FES3; see section 2), as well as the Villafranchian pediments, have been identified and represented in the morphotectonic map of Fig. 6. In the surroundings of the CPF, FES3 is the most widespread marker, developed in the form of extensive pediment on Paleozoic, Mesozoic, Paleogene and Neogene rocks around residual reliefs. Its topographic reconstruction by means of the corresponding contours allows calculating fault throws since 3.5 Ma. Furthermore, we have defined and mapped a younger sublevel (FES4), which appears in the north of the study area.

Within the footwall block of the CPF, the FES3 flattens the Upper

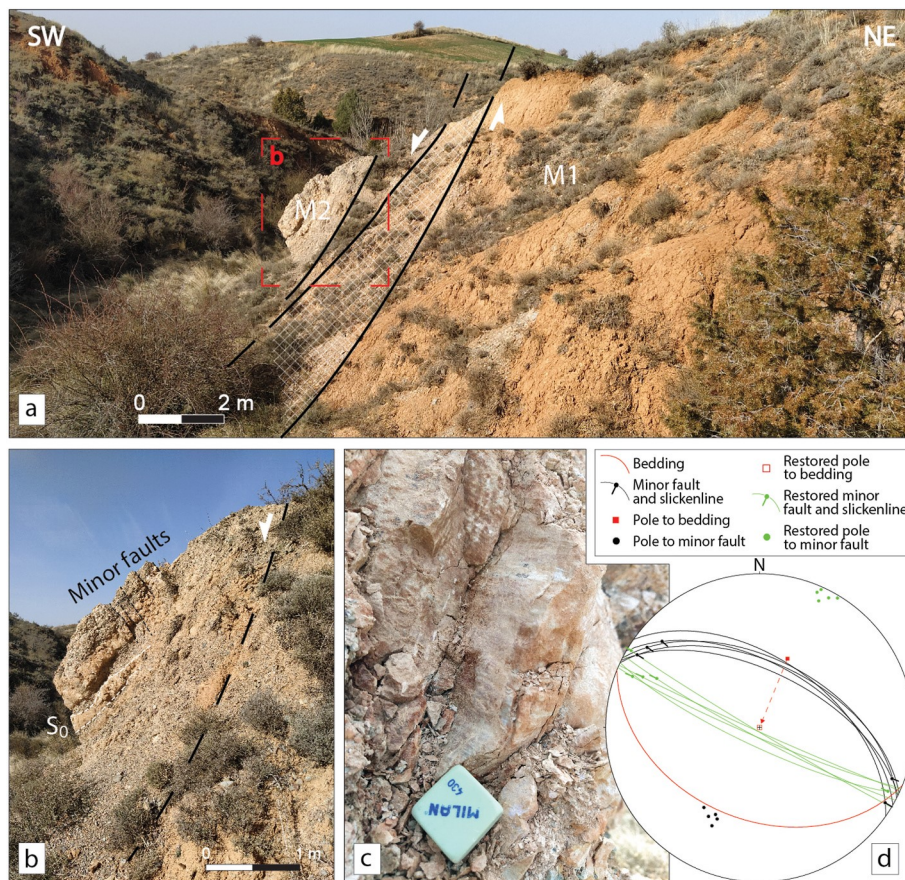


Fig. 5. (a) and (b) Exposure of the CPS rupture affecting two Miocene units (M1 and M2) in La Pesquera site. (c) Detail of minor faults with slickenlines. (d) Stereonet plot (equal area, lower hemisphere) of minor faults and slickenlines. See location in Fig. 2.

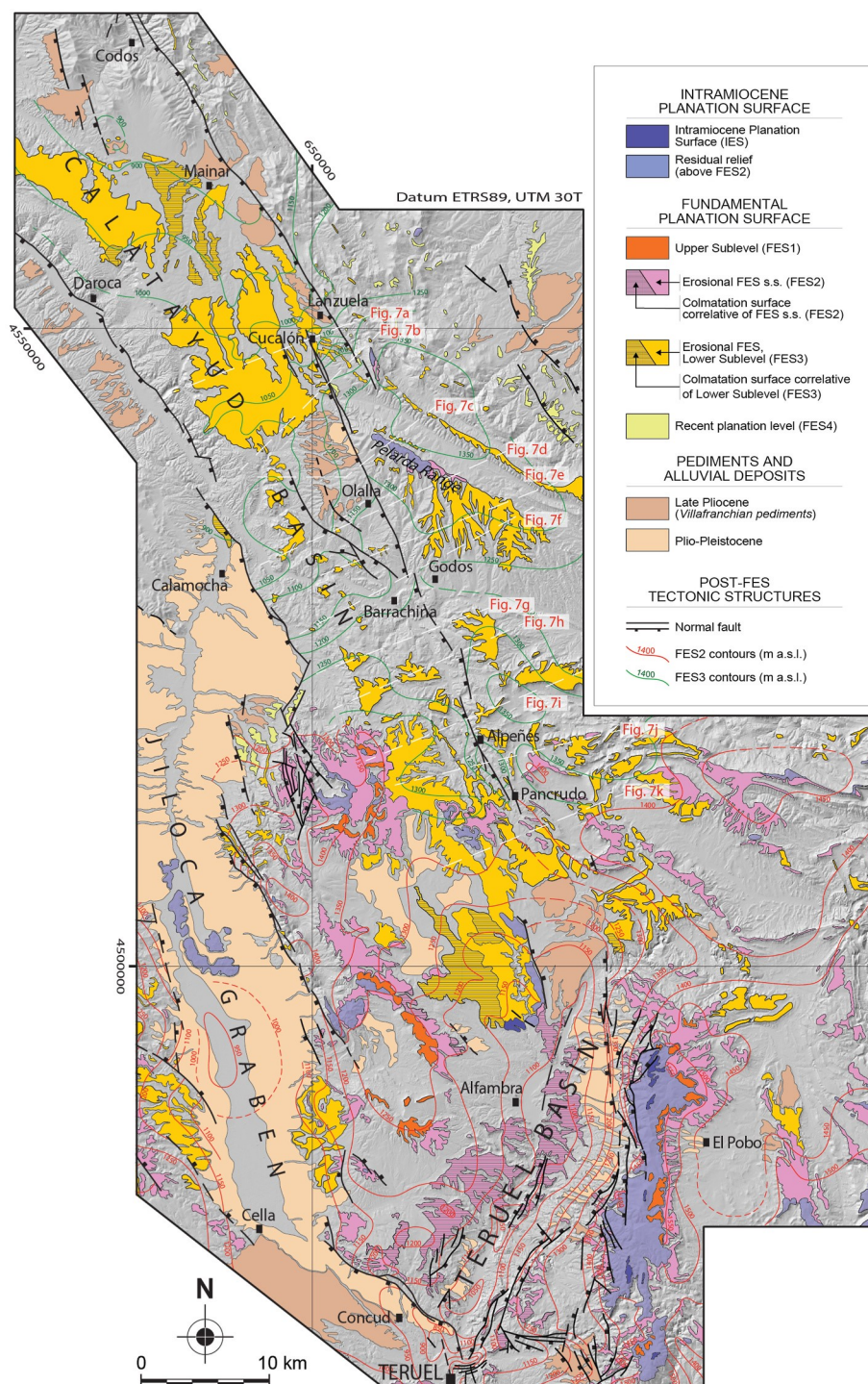


Fig. 6. Synthetic morphotectonic map of the Calatayud, Jiloca and Teruel basins and their surrounding reliefs. Late Neogene planation surfaces with their contours, as well as pediments and alluvial deposits, and the faults that offset them, are represented. with location of Fig. 2. 14d and 2.16a-k (modified from Peiro and Simón, 2022). Background: hillshade image generated from DEM (25 m grid) of Instituto Geográfico Nacional (IGN).

Cretaceous limestones affected by the large monocline of the Cucalón range (oriented $120,35^{\circ}\text{S}$), at an altitude of 1380 m a.s.l. (Fig. 2a). Towards the south, the altitude of FES3 attains 1300–1350 m around the Pelarda range, then decreases to less than 1250 m in the Barrachina sector, and then increases again up to 1300–1350 m near Alpeñes (see contours in Fig. 6). At the Pelarda range, FES3 lies below both a remain of FES2 and a residual relief in the range summit. The ensemble of the Pelarda range is made of a monoclinial series of Eocene conglomerates, sandstones and siltstones oriented $120,35^{\circ}\text{S}$ in average. Associated to

FES3, a thin (1–5 m) surficial, nearly horizontal sediment cover unconformably overlies the tilted Eocene units. This is an exceptional situation since, at the rest of the Iberian ranges, the FES3 level is systematically represented by a bare erosion surface, which physically correlates with the uppermost lacustrine carbonates (*Páramo 2* unit, Ruscinian) only at the Calatayud and Teruel basins. The cover consists of non-cohesive brown gravel made of subrounded quartzite pebbles and cobbles with muddy to sandy matrix. This sedimentary material clearly results from reworking of the Paleogene conglomerates, and extensively

covers the vast FES3 pediment that extends southwards up to the Godos village (Fig. 6). Moreover, such Pliocene sediments have been reworked again by surficial floods during the Quaternary, the pebbles being scattered over the slopes and gullies and amazingly covering a large part of the Pelarda range. Such distribution led in the past to the erroneous interpretation that the entire upper part of the range was covered by a Plio-Quaternary conglomeratic unit of more than 100 m thickness of unknown origin (Martín et al., 1977; Gabaldón et al., 1989, 1991).

Within the hanging-wall block, there is a southward increase of altitude (Fig. 6). Around Cucalón village and to the Calatayud Basin centre, the FES3 is an almost planar pediment developed at an average altitude of 1000 m on the *Páramo 1* and *Rojo 2* units (Hernández et al., 1983; Gabaldón et al., 1991). Towards the south, the marker raises till the Alpeñés-Pancrudo area, where Lower Miocene rocks (Lower Clastic Unit; Hernández et al., 1983) are modelled by the FES3 at an altitude slightly higher than 1300 m. This altitude diminishes up to c. 1200 m in a local depression, where it approaches the fault plane. Along the Cucalón-Olalla sector of the hanging-wall block, the FES3 surface includes a bending component and shows a stepped-shape, because several remains are truncated by intrabasin secondary faults like the Valverde fault. Locally, the hanging-wall block hosts red clastic deposits of Villafranchian age, several tens of metres thick, whose tops are modelled into pediments (Fig. 6).

At the northern tip of the Cucalón-Pancrudo fault, within the relay zone with the Río Grío-Lanzuela fault, the FES3 is preserved through dispersed irregular remains that level both Paleozoic and Miocene units (Fig. 6). FES3 diminishes its altitude from the southeastern sector of the relay zone, at almost 1300 m, till the centre of the Calatayud Basin, where it lies at c. 1000 m. It follows the common arrangement of a relay ramp between the main faults, due to bending and soft-linkage interaction between them.

4.2.2. Evaluating the fault throw: traverse profiles and throw-distance (T-D) curves

The fault throw has been measured on a number of transects across the CPF using the FES3 marker. As a first approach, the FES3 contours drawn on the morphotectonic map of Fig. 6, which provide the present-day 3D geometry of the envelope of FES3, were used for that purpose. The profiles depicted in Fig. 7 allow to refine such measuring along the successive transects. Where the preserved remains of FES3 are confronted close to the fault, the tip points can be reliably defined and throw calculation is more accurate, while the latter is less precise when the cut

points should be located by extrapolation from remains that are far from the main fault. In order to fully evaluate fault displacements in the study area, in particular to analyse slip transfer between the Río Grío-Lanzuela fault (RLF) and the CPF, profiles of Fig. 7a and b include the RLF.

Close to the Pelarda range, the FES3 in the hanging-wall block of the CPF is thrown down to 1020–1040 m, and is covered by the red clastic deposits of the Villafranchian pediment. In the footwall block, the remains of FES3 lie at around 1320 m, surrounding the residual relief of the Pelarda summit (Fig. 7c and d). The fault throw can be estimated up to c. 300 m (the maximum along the CPF; Fig. 7c), partitioned among throw on the main fault (190 m), throw on the Valverde fault (c. 20–30 m), and a gentle accommodation monocline.

Between Olalla and Barrachina villages, the remains of FES3 are quite far from the fault trace at both the hanging-wall and footwall blocks, but within the latter its height is well constrained along the Pelarda range (Fig. 7d and e). In this sector, a fault throw of 90–110 m can be inferred for the CPF, which becomes higher (160–190 m) if the bending component and the intrabasin Valverde fault are considered.

To the south, FES3 remains lack within the hanging-wall block of the CPF, but its altitude is still well constrained within the footwall block along the Pelarda range and the Mas de Teller plain (Fig. 7f,g,h). By extrapolating the contour lines from the surrounding sectors, a smaller vertical offset between 30 and 65 m is interpreted.

Displacement on the CPF again increases, up to 70–100 m, when approaching the southern fault tip, between Alpeñés and Pancrudo villages. Here the contour map suggests a local roll-over structure affecting the hanging-wall block, identified in the profiles of Fig. 7i and j.

Finally, no significant vertical deformation is inferred from mapping of the FES3 surface south of Pancrudo village, supporting the hypothesis that the CPF termination occurs in this zone (Fig. 7k).

The variation of fault throw recorded by the FES3 along the CPF is synthetically depicted in the throw vs. distance (T-D) graph of Fig. 8. Three distinct T-D curves have been elaborated for (i) southern sector of the Río Grío-Lanzuela (RLF), (ii) CPF s.s., (iii) composite of RLF + CPF + Valverde fault + bending component.

Concerning the RLF, only the curve of its southern sector is depicted, in order to show its relationship with the CPF curve at their relay zone. The RLF throw decreases from a maximum value of 240 m, estimated by Peiro and Simón (2022), up to virtually vanishing close to Lanzuela village (kilometre 58 in the D scale).

The T-D curve of CPF s.s. shows two maxima of c. 190 and 100 m around kilometres 58 and 85, respectively, which culminate two

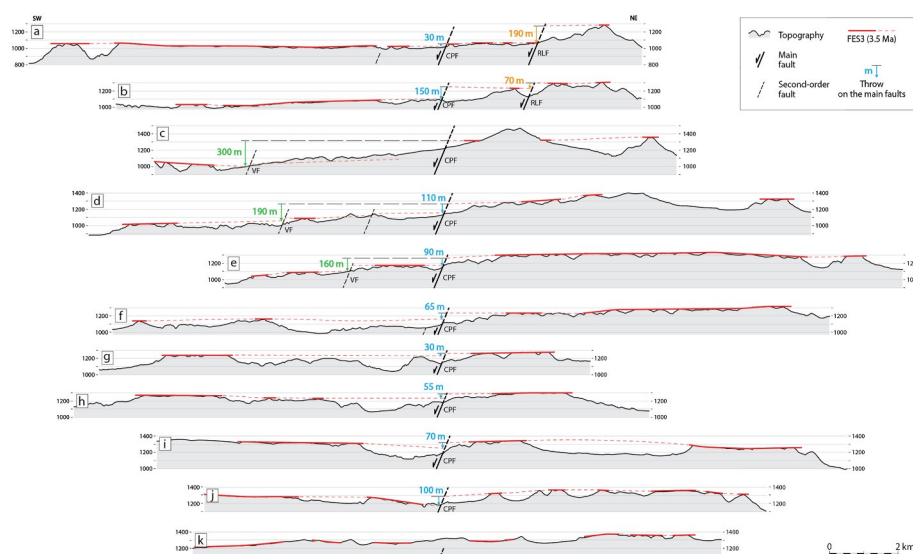


Fig. 7. (a–k) Topographic profiles across the Cucalón-Pancrudo fault (CPF), together with the Valverde fault (VF), and its relay zone with the Río Grío-Lanzuela fault (RLF), with estimate of the post-FES3 throw. See location in Fig. 6.

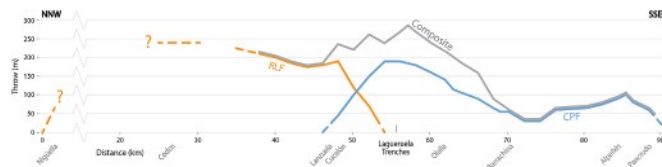


Fig. 8. Throw vs. distance (T–D) graph along the Río Grío-Pancrudo fault zone. RLF: Río Grío-Pancrudo fault (orange); CPF: Cucalón-Pancrudo fault (blue); composite: RLF + CPF + Valverde fault + bending component (grey). Curves represent the throw s.s. recorded by the FES3 marker. Data of RLF taken from Peiro and Simón (2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

symmetrical, more or less bell-shaped stretches. Between both maxima, there is a minimum (30 m) around kilometre 73. According to the evolutive models of fault coalescence through relay zones (e.g., Peacock and Sanderson, 1994; Gawthorpe and Leeder, 2000), this throw drop could correspond to the junction point between two fault segments previously disconnected, now linked through the old relay zone. Moreover, the strong displacement gradients shown by the RLF and CPF curves within their relay zone suggest a scenario of two interacting faults that transfer displacement to each other.

4.2.3. Net slip and long-term slip rate

Considering the age of the FES3 morphosedimentary marker (3.5 Ma; Ezquerro et al., 2020), and assuming a pure normal movement and an average dip of 65–70° for the fault, the maximum throw of the CPF, 190 m, involves a total net slip of c. 205 m, and a long-term slip rate of 0.06 mm/a. If the CPF is considered together with the bending component and the Valverde fault, a maximum throw of 280–300 m results, which implies a net slip of 305–325 m and a long-term slip rate of 0.09 mm/a.

4.3. Trench study in the lagueruela area

4.3.1. The trench site

The trench study was focused on the northern sector of the CPF, around 3 km south of Lagueruela village. In this site, the fault trace cuts the apex of a Pleistocene alluvial fan, which to the west overlays and reshapes the Villafranchian alluvial pediment (Figs. 2 and 9a). The alluvial fan deposits mostly consist of rounded cobbles and boulders of

Paleozoic and Triassic rocks, reworked from the Paleogene of the Pelarda range. These deposits are incised by the Valdefuente gully, which flows from the Pelarda range to the Calatayud Basin perpendicularly to the CPF. The gully exhibits its own Holocene fluvial sediments in a terrace whose surface lies 2 m above the talweg (Fig. 9a–c).

4.3.2. Geophysical exploration

Trench locations were selected based on a magnetometric and GPR survey carried out on the Valdefuente gully and the Pleistocene alluvial fan. The research followed the procedure explained in section 3.2, with the purpose of identifying magnetic anomalies that could be related to faults.

The Earth magnetic field map shows a variation range of nearly 30 nT (Fig. 10a and b), the individual dipoles showing amplitudes between 6 and 10 nT. The main change in the earth magnetic field defines an elongated domain oriented ENE–WSW with lower values of the magnetic field (blue colours in Fig. 10a). This change is not progressive and is defined by small dipoles in its margins. These dipoles are superimposed to a distribution of higher amplitude anomalies that can be interpreted as lateral sedimentary changes, which might be related with the sedimentary architecture of the alluvial fan itself. The main magnetic dipole lineation is identified at the southern sector in the margin of the southwestern positive anomaly (red colours in Fig. 10b). This anomaly is defined by a net, nearly linear change with an NW–SE orientation. This well-defined lineation is parallel to other minor dipole lineations along the surveyed area.

The GPR analysis aimed at characterising the subsoil structure (up to a maximum depth of c. 6 m) through profiles normal to the main magnetic dipole alignments, mainly focusing on the continuity and tilting of reflectors. GPR profiles show reflectors that are overall parallel to the topography but gain dip with depth to the SW (Fig. 10c). The sedimentary bodies bounded by reflectors also show thickening towards the SW, especially the most superficial ones. These sedimentary bodies show interruptions, either subvertical or steeply SW-dipping, which are frequently associated with changes in the reflector slope. Such interruptions were tentatively related to faults and, in combination with the magnetometric results, led us to select the most favourable locations for trenching (coloured strips in Fig. 10d).

4.3.3. The trenches

The paleoseismological trenches were dug at right angles of the

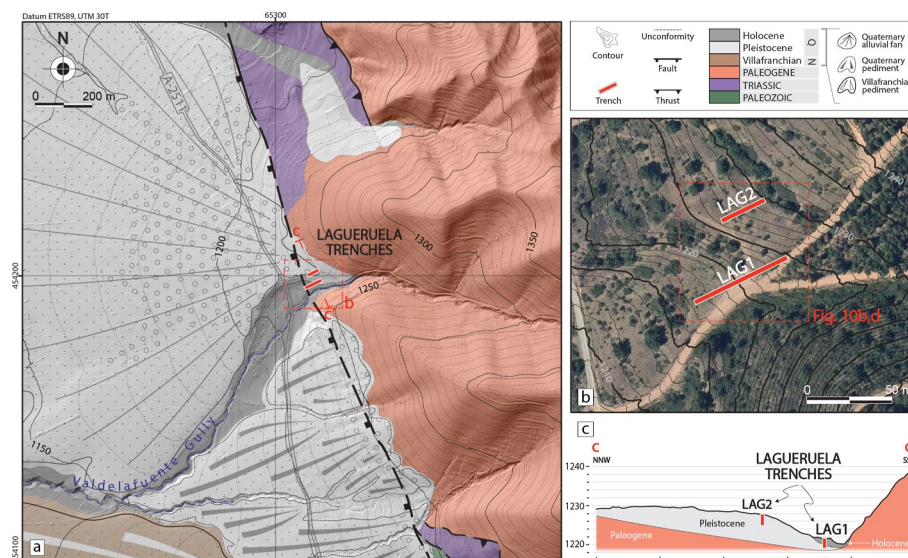


Fig. 9. (a) Detailed geological–geomorphological map of the area surrounding the Lagueruela trenches (see location in Fig. 2). Background: topography and hill-shade image from DEM (pixel under 1 m) generated with LIDAR 2^a Cobertura (2015–2021) LAZ data, IGN. (b) Detailed orthoimage (IGN), showing the location of trenches LAG1 and LAG2. (c) Geological cross section parallel to the CPF, showing the arrangement of Pleistocene and Holocene deposits.

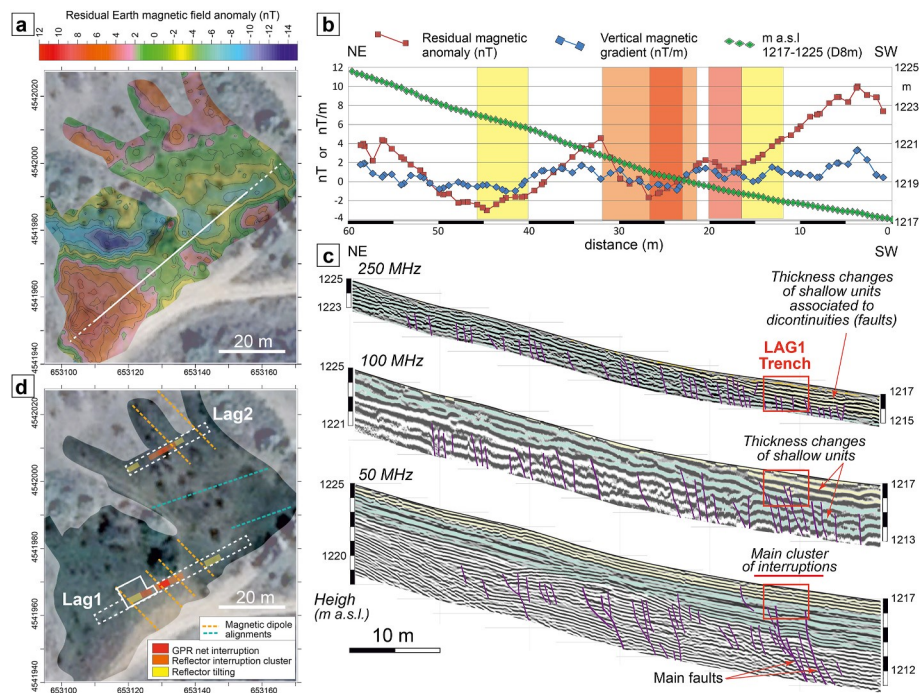


Fig. 10. Main geophysical results. (a) Residual magnetic field anomalies at the apex of the Valdelafuente alluvial fan (see location in Fig. 9b). (b) Magnetic profiles along the transect marked in a: residual magnetic anomaly, vertical magnetic gradient, and topography. For comparison, the segments with anomalies in GPR profiles are also marked (see colour code in d). (c) GPR profiles along the same transect marked in a, obtained with antennas of 50, 100 and 250 MHz. (d) Synthesis of results; LAG1 and LAG2: trenches. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

main CPF trace, hence with a trend close to N065°E. LAG1 trench (60 m long, 2 m deep, 1.3–4 m wide) was dug on the Holocene fluvial terrace of the Valdelafuente gully (Fig. 11a). Its western sector was widened from the initial 1.3 m width of the excavator shovel to about 4 m, in order to (i) improve the safety conditions for research work, and (ii) have a second, parallel section. The southern wall of that western sector of LAG1 (mainly from meter 11 to 16) was surveyed in detail, and constitutes the main source of paleoseismological data (Fig. 11b). LAG2 trench (25 m long, 2.5 m deep, 1.3 m wide) was dug on the top of the Pleistocene alluvial fan (Fig. 11c and d) and has provided much less information.

4.3.4. Sedimentary units

Quaternary alluvial and fluvial sediments cropping out in the LAG1 trench have been separated into nine units (Units 1 to 9; Fig. 12a and b). They mainly consist of mudstone and gravel intervals ranging in thickness between 0.3 and >1.2 m.

Units 2 to 9 have been identified at both the northern and southern walls of LAG1 trench (Fig. 12a and b), and correlated by considering (i) their lithological characteristics, and (ii) vertical profiles of magnetic susceptibility at both trench walls; the highest values of magnetic susceptibility correspond to units 7 and 8.

LAG2 was dug in a quite massive alluvial fan deposit in which no



Fig. 11. Field aspect of trenches. (a) Overall view of LAG1, showing the long, southern wall (right) and the short, northern one (left). (b) Sector of LAG1 (southern wall) surveyed in detail. (c) Overall view of LAG2. (d) Photomosaic of the northern wall of LAG2 showing a massive alluvial deposit, in which no stratigraphic marker was identified.



significant stratigraphic marker was identified (Fig. 11c and d). It consists in brown gravel with subrounded to subangular pebbles to boulders, with irregular intercalated levels of reddish mudstones with scattered clasts.

The OSL ages obtained from the eight analysed samples are derived from fast component dominated OSL signals, leading to well-defined dose response curves. This, together with the low scatter of the dose distributions, lead to estimated burial doses with associated uncertainties of less than 4% (1σ) and derived ages with less than 10% uncertainty (Table 1).

log of the units cropping out in the LAG1 trench (see Fig. 12a). The samples have been positioned within this log, their central age and the associated uncertainties being represented in a thickness-time diagram (Fig. 12c). Interpolation and extrapolation of ages along the stratigraphic series allows attributing the most probable age to the base of each sedimentary unit, by intersecting it with the age model curve, as well as their uncertainty. The results show how the age of the sediments exposed in the trench ranges from c. 41 ka to 2.6 ka (Latest Pleistocene to Holocene).

The age model could not be built as that of a continuous sedimentary succession, since the surveyed units include (i) ancient deposits belonging to the alluvial fan body, and (ii) recent alluvial terrace deposits associated to the incised Valdefuente gully. The boundary between both sedimentary ensembles can be identified from the features of the contacts between units, and especially from the available OSL

Table 1

Summary of the parameters and derived ages of samples dated with OSL from the Lagueruela trenches (Luminescence Dating Laboratory of CENIEH, Burgos, Spain). All ages are reported at 1-sigma ($k = 1$).

Sample	Unit	Laboratory reference	Depth (m)	Dose rate (Gy/ka)	Burial dose (Gy)	Age (ka)
LAG1-1	6	LM20132-01	1.1	3.1 ± 0.2	24.1 ± 0.9	7.7 ± 0.5
LAG1-2	6	LM20132-02	1.2	3.1 ± 0.2	32.4 ± 0.9	10.6 ± 0.6
LAG1-3	7	LM20132-03	0.9	3.0 ± 0.2	9.8 ± 0.3	3.2 ± 0.2
LAG1-5	5	LM20132-04	1.6	3.1 ± 0.3	33.6 ± 0.7	10.7 ± 0.9
LAG1-6	3	LM20132-05	2.1	3.6 ± 0.3	64.2 ± 2.1	17.8 ± 1.6
LAG1-7	2	LM20132-06	2.4	3.0 ± 0.2	90.7 ± 3.1	29.7 ± 2.2
LAG1-F	2	LM20132-10	2.6	3.1 ± 0.3	106.8 ± 2.3	34.6 ± 3.0
LAG2-1		LM20132-07	1	3.1 ± 0.3	99.5 ± 2.1	31.7 ± 2.8

dating. With this respect, the OSL age obtained close to the top of the alluvial fan (trench LAG2, sample LAG2-1; 31.7 ± 2.8 ka) represents a key constraint. This age is similar to that of sample LAG1-7 (29.7 ± 2.2 ka; middle part of Unit 2), their respective error bars overlapping completely. In contrast, the next OSL age (sample LAG1-6; 17.8 ± 1.6 ka; Unit 3) is clearly separated from the former. The chronological break is therefore between units 2 and 3.

Consequently, we infer that the primary incision process of the Valdelafuente gully: (1) took place between 30 and 18 ka ago, approximately, and (2) it is represented in the sedimentary record by the erosive contact between Unit 2 and Unit 3. The fact that Unit 3 does not appear at the northern wall of LAG1 is also an indication that it has little lateral continuity and is very probably entrenched in Unit 2. The contact between units 3 and 4, also strongly erosive, probably represents a further episode of incision occurred about 15 ka ago. Such episodes are represented by a discontinuity in the curve of the age model (Fig. 12c).

4.3.6. Structural description

Trench LAG1 exposes several domino-style normal faults located on the trace of the CPF, which cut both the Holocene sediments of the gully (units 3–8) at the top, and the Pleistocene deposits at the bottom (sedimentary units 1–2) (Fig. 12a). In most cases, the apparent dip of the fault planes shows a slightly listric geometry, with dips of $65\text{--}70^\circ$ at the top and up to 45° at the bottom. The geometry of the observed structure is full consistent with that previously inferred from the GPR profile (see Fig. 10c). Only one fault has been recognised at both trench walls (very probably, fault η).

No deformation has been observed within the LAG2 trench, very probably due to the massive character of the deposit and the lack of stratigraphic markers, which makes it impossible to differentiate units in it. Because of its lack of informative value, we chose not to depict the LAG2 trench log, although the general appearance of the exposure can be examined in Fig. 11d.

The orientation of rupture planes in trench LAG1 could not be measured due to the rapid degradation of the unconsolidated materials at the walls. Only the location of fault η at both the northern and southern walls allows interpolating the fault trace and inferring a general NNW-SSE strike for it. *In situ* measurements of kinematic indicators could not be collected neither. Nevertheless, evidence of shear along rupture planes (more precisely, on fault η) is evidenced by slickenlines observed in the removed block from which sample LAG1-F was extracted for OSL dating (Fig. 12d).

Every fault exposed within the LAG1 trench is synthetic with the CPF. Two groups of ruptures can be differentiated (Fig. 12a and b): (i) faults χ , α' and η' , which produced centimetric slip in the base of unit 5,

and vanish within this unit; and (ii) faults ε , δ , λ , β and α , which underwent decimetric vertical displacement after sedimentation of unit 6, and are covered by unit 7. Faults α' and η' are splay faults of α and η , respectively. Faults δ and $\alpha\text{--}\alpha'$ produce a greater vertical separation in the base of unit 3 than in the base of unit 4. We interpret that both faults underwent displacement before sedimentation of unit 4, and were then reactivated after deposition of unit 6.

The aggregate visible throw of the synthetic fault set is 1.05 m, as evidenced when comparing the height of the top of unit 2 at both edges of the southern log (Fig. 12a). There is a lack of information about slip vectors on the surveyed faults, since no slickenlines could be observed on them due to the coarse grain size of the affected sediments. However, a rough translation of this throw value into net slip can be achieved: by assuming a nearly pure normal movement and a fault dip of 65° (average apparent dip of the fault surfaces), the total net slip can be estimated at about 1.15 m.

4.3.7. Interpretation of paleoseismic events and retrodeformational analysis

Two main deformation events (X and Z), and an additional uncertain one (Y), have been interpreted at the LAG1 trench from the analysis of the relationships between sedimentary units and faults. The retrodeformational analysis of the southern-wall trench log has been performed as an auxiliary tool, for contrasting the succession of deformation events, and testing its kinematic consistence (Fig. 13). A number of faults were either formed, propagated or reactivated during each deformation event. Fault throws have been computed, and the horizontal extension values have been measured and visually expressed in the successive cross sections of Fig. 13.

The interpreted events at the LAG1 trench, all of them occurred after the incision of the Valdelafuente gully, are as follows:

Event X: Inferred from the presence of discontinuous remains of unit 3 in contact with faults δ and $\alpha\text{--}\alpha'$ (partially absent in their foot-wall blocks). Such arrangement can be explained by slip on those faults after deposition of unit 3 and prior to unit 4. Seeing at the available numerical ages, this event is younger than 17.8 ± 1.6 ka and older than 10.7 ± 0.9 ka. Seeing at the stratigraphy, it is predated by unit 3 and postdated by unit 4, i.e., it should be placed at the time gap between them (c. 14.9 ± 1.4 ka). The total, synthetic throw of this event is ~ 0.65 m, net coseismic slip estimated at ~ 0.75 m, and horizontal extension ~ 0.1 m.

Event Y (?): Tentatively interpreted from rupture and displacement of the base of unit 5 due to sin/post-sedimentary slip by faults χ , $\alpha\text{--}\alpha'$ and $\eta\text{--}\eta'$. It would be only slightly younger than the base of unit 5 (c. 11.2 ± 1.0), assuming a more probable event age of c. 11.0 ± 1.0 . The total coseismic net slip of this event would be ~ 0.2 m, and its horizontal extension less than 0.1 m. A second scenario where this deformation would have occurred simultaneously with Event Z cannot be ruled out.

Event Z: Identified from rupture and displacement of the base of unit 6 due to domino-style slip on faults ε , δ , λ , β , α and η , prior to deposition of unit 7. Seeing at the available numerical ages, this event is predated by sample LAG1-1 (7.7 ± 0.5 ka, close to the top of unit 6), and postdated by sample LAG1-3 (3.2 ± 0.2 ka, mid unit 7). The most probable age of this event is that of the limit between unit 6 and unit 7, i.e. 6.9 ± 0.4 ka. The total, synthetic throw of this event is ~ 0.25 m, and the net slip is estimated at ~ 0.3 m. The horizontal extension is close to 0.2 m.

The summation of coseismic slip values of the three events (1.25 m), based on the sum of the individual net slips on the faults, exceeds that calculated from the total throw (1.15 m) due to the slight bed tilting involved in the domino-style structure.

5. Discussion

5.1. Recent activity and seismogenic potential of the cucalón-pancrudo fault

The multidisciplinary (structural, morphotectonic, geophysical and

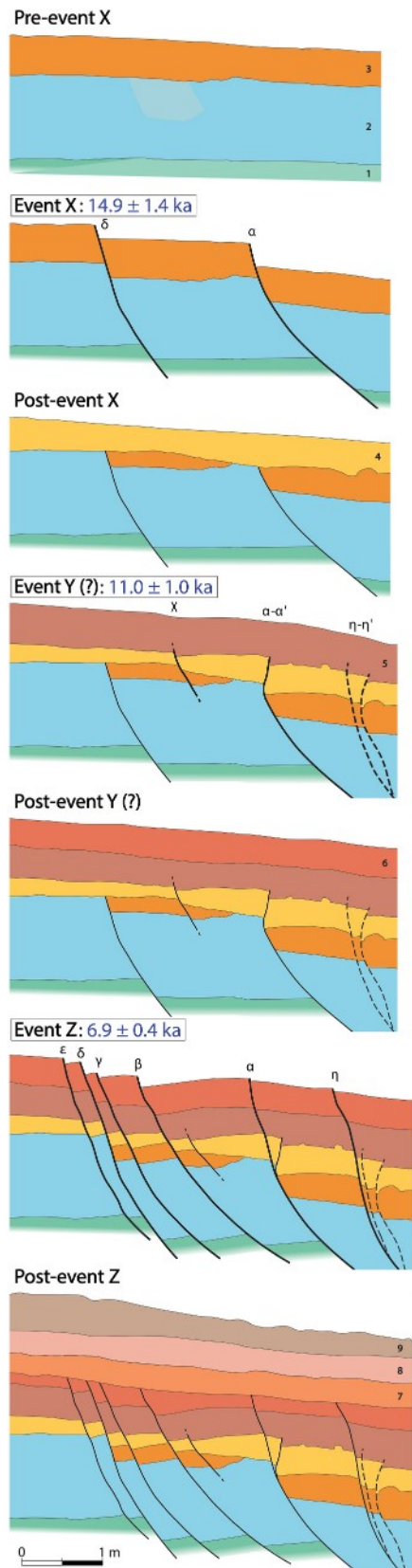


Fig. 13. Evolutionary model of sedimentation and deformation recorded at the southern-wall of LAG1 trench from retrodeformational analysis. Unexposed sectors below the trench have been locally reconstructed in the sketches in order to complete the model. Bold traces indicate faults are active during each event.

paleoseismological) approach here exposed has allowed characterizing the geometry and recent activity of the Cucalón-Pancrudo fault, an extensional structure not well known until just a few years ago. It shows an overall NNW-SSE direction and is about 40 km long. A morphosedimentary marker (FES3), widely represented in the region, has been very useful for calculating the distribution of the throw (up to 190 m), net slip (~205 m) and long-term slip rate (0.06 mm/a) of CPF since 3.5 Ma. If this fault is considered in combination with the Valverde fault, contiguous and parallel to CPF, the total maximum throw is 300 m, the net slip is ~325 m, and the slip rate is 0.09 mm/a for this period.

These long-term values are similar to those calculated by Peiro and Simón (2022), for the same period, for the neighbouring Río Grío-Lanzuela fault (240 m, 260 m, and 0.07 mm/a, respectively). The latter represents the northwards prolongation of the same fault zone (Río Grío-Pancrudo fault zone, RPFZ), which is probably the longest active structure in the Iberian Chain (~95 km in length; Peiro, 2023).

The information obtained from the Lagueruela trenches proves that CPF has undergone slip during Late Pleistocene and Holocene times. The deformation is concentrated on the mapped trace, in the form of a domino-style fault set that was evidenced in the GPR profile before being directly observed in the trench. The paleoseismological analysis of LAG1 trench has provided a succession of 2–3 deformational events occurred between 17.8 ± 1.6 ka and 3.2 ± 0.2 ka, with more probable ages in 14.9 ± 1.4 ka, 11.0 ± 1.0 (?), and 6.9 ± 0.4 ka, respectively (see a graphical synthesis of the paleoseismic results in Fig. 14). Considering the scenario of three events, the paleoseismological succession of LAG1 trench results in an average recurrence period of 4.0 ± 1.9 ka. If the scenario of two events is considered, the recurrence period is 8.0 ± 1.8 ka. Net coseismic displacement ranges from 0.2 to 0.75 m, with an average value of 0.5 m. The total net slip accumulated during the three events (since c. 14.9 ± 1.4 ka) is estimated at about 1.25 m, providing a short-term slip rate of 0.08–0.09 mm/a, very similar to the long-term slip rate.

In order to infer the seismogenic potential of the CPF, the regression model by Wesnousky (2008) can be applied, since it is the one recommended for approaching seismogenic parameters in slow intraplate normal faults according to the analysis carried out by Stirling et al. (2013) for the Global Earthquake Model (GEM). Assuming the length of the CPF trace (40 km) and the absence of structural segmentation, such regression provides a potential moment magnitude $M_w = 6.9 \pm 0.3$ for earthquakes generated by this structure. This M_w value fits the range obtained from other common regression proposals ($M_w = 6.8$ – 7.2 ; Wells and Coppersmith, 1994; Stirling et al., 2002; Leonard, 2010), but should be regarded as more precise. In addition, the Wesnousky (2008) model gives a potential average coseismic slip of c. 1.2 m, while the other mentioned regressions point to more dispersed values, in the range of 1–3 m.

The reliability and representativeness of the paleoseismic parameters obtained at the LAG1 trench for Holocene times should now be tested in the light of the former regression analysis. Assuming a stick-slip fault regime at a rate of 0.07–0.09 mm/a and a recurrence period of 4.0 ± 1.9 ka (3-events scenario), the coseismic slip would lie in the range of 0.15–0.53 m. In the 2-events scenario (recurrence period of 8.0 ± 1.8

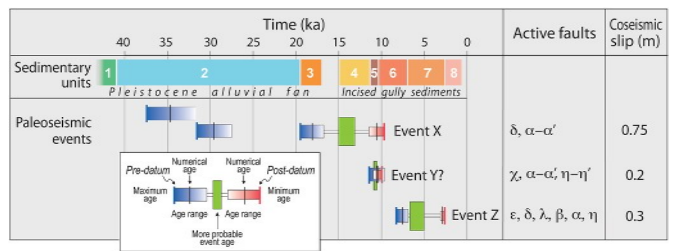


Fig. 14. Synthetic diagram of the paleoseismic results at trench LAG1. See detailed explanation and discussion in the text.

ka), the coseismic slip would be in the range of 0.43–0.88 m. Both scenarios are compatible with the coseismic slip values directly obtained from field data (0.2–0.75 m), but significantly lower than the ones obtained from regression models considering rupture of the entire, 40-km-long fault (1.0–3.0 m, more probably closer to 1.2 m).

Such disagreement opens the door to distinct scenarios for the coseismic ruptures recorded in the LAG1 trench. A realistic scenario is that the CPF only underwent partial rupture, probably along the northern segment identified in section 4.2.2, represented in the T-D curve by the bell-shaped stretch between kilometres 50 and 70, approximately (Fig. 8). From the 0.2–0.75 m range of coseismic displacement, a surface rupture length between 5.3 and 30.2 km would be expected (based on Wells and Coppersmith, 1994; Leonard, 2010) and, more accurately, in the range of 6.7–23.3 km (using Wesnousky, 2008). The northern segment of the CPF is about 20–25 km long, therefore it perfectly fits this scenario. Wesnousky's (2008) regression provides a potential moment magnitude $M_w = 6.8 \pm 0.3$ for earthquakes generated by this segment of the CPF (M_w in the range of 6.2–7.2, according to regressions by Wells and Coppersmith, 1994; Stirling et al., 2002; Leonard, 2010).

A second scenario is derived from the GPR profile (Fig. 10c), which shows abundant distributed fractures across the surveyed sedimentary units, beyond those identified in trench LAG1 (Fig. 12a and b). The listric geometry of faults in the LAG1 trench and their attitude suggest that they were rooted in a main fault plane at a very shallow depth. The grey and brown mudstone of Unit 1 was probably the local detachment level that distributed the deformation and from which splay faults were propagated. It is therefore likely that the deformation structures exposed in this trench do not represent a complete record of the identified events, and that more splay faults rooted in the main fault may have moved during these events. The total coseismic slip for each event could therefore be larger than that computed in Section 4.5.6 and Fig. 14, and could approach, indeed, the more probable value (c. 1.2 m) for a 40-km-long fault rupture. In summary, the scenario of complete rupture of CPF is also reliable, in particular for Event X (net slip recorded in LAG1 trench c. 0.75 m).

Finally, a scenario of rupture propagation along the whole Río Grío-Pancrudo fault zone, i.e. of both the RLF and the CPF, should not be completely ruled out. RLF and CPF are separated by a right relay-zone 2.5 km wide (Fig. 1c and 6) that, according to Biasi and Wesnousky (2016), might not represent a barrier to propagation. These authors determined that 54% of relay zones ≥ 1 km wide, in dip-slip faults longer than 10 km, are overcome during fault propagation, and that such relay zones are less effective at stopping normal than reverse ruptures. Such scenario of combined rupture on RLF + CPF (95 km long) is much less likely than rupture of the CPF alone or a segment within it (as the trench results suggest), but it should also be kept in mind. The maximum earthquake generated in such a case could reach a magnitude of 7.0 ± 0.3 (according to the regression model by Wesnousky, 2008).

We should not believe that the paleoseismic record in the LAG1 trench is completely representative of the slip history of the CPF over the past tens of thousands of years. It is known that other extensional faults in the region split into several branches that are separately mapped (e.g., Calamocha, Concud, Teruel or Valdecebro faults; Lafuente et al., 2014; Simón et al., 2016, 2017, 2019), a given branch accommodating only a fraction of the total slip. Hypothetic branches of the CPF could remain unestablished, and could undergo additional events during the explored time window (since c. 35 ka). This issue was carefully considered during field mapping, although no evidence of such distinct branches was found. In particular, accurate observations along and close to the trace of the Pelarda thrust (Fig. 2a) did not reveal any sign of extensional activity. In any case, as stated above, partitioning of the total displacement of the CPF among a number of clustered splay faults is strongly suggested by the GPR profile (Fig. 10c). Some of those smaller-scale faults, not exposed at the LAG1 trench, could represent either additional events or additional slip for the interpreted events X, Y and Z).

More trenches would be needed for building a robust and complete paleoseismic record of the CPF, but for the moment no other favourable locations have been identified along the fault trace for this purpose. In any case, the calculated parameters and the evidence of displacement during Holocene times (at least its northern sector) definitely allow classifying the CPF as an active fault, according to most scientific classifications and legal regulations (e.g., NRC, 1997; Machette, 2000; Strom, 2017).

5.2. One of the youngest events recorded in the Teruel rift system

Among the results of the paleoseismological analysis of the LAG1 trench, it is worth highlighting the evidence of a last event (Most Recent Event, MRE) Holocene in age (6.9 ± 0.4 according to our age model) at the Río Grío-Pancrudo fault zone. Until recently, no paleoseismic events of this age had been identified in the Iberian Chain. Recent works are beginning to report them, something that was probable and foreseeable considering that the average recurrence periods on active faults in the region are usually less than 10,000 years. Determining the age of the MRE, i.e. the Elapsed Time, is critical for considering adequately the role of active faults in Seismic Hazard Assessment.

In the Concud fault, the most intensively studied one in the region, the most recent recorded movement occurred between 13.5 and 2.7 ka (Simón et al., 2016). The available dating has not allowed a narrower age constraining. However, on the basis of overall assessment of the paleoseismological results, it is likely that not one but two events took place in this time range, and that at least the second event occurred in the Holocene (Simón et al., 2016). In the Daroca fault, the age of the MRE has been bracketed between 2.4 and 1.5 ka (Gutiérrez et al., 2020), i.e. clearly within the later Holocene. The present work provides new evidence of Holocene slip on another major extensional structure within the Iberian Chain.

Unfortunately, no striations or other kinematic indicators have been reported at the concerned fault surfaces (neither in the present work), so that the precise slip vectors for those Holocene rupture events are unknown. Nevertheless, seeing at the slip directions surveyed in most of the active faults of the region for Pleistocene times (Lafuente et al., 2014; Simón et al., 2017; Peiro and Simón, 2022; Peiro et al., 2022, 2023) a nearly pure normal slip should be considered as the most probable scenario.

Despite the incompleteness of the kinematic data of the Río Grío-Pancrudo fault zone (RPFZ), its mapping, dating and structural characterization represent valuable information for being incorporated to the Quaternary Active Faults Database of Iberia (QAFI).

5.3. Assessing recent activity of CPF within the context of the eastern Iberian Peninsula

The long-term slip rate inferred at the Cucalón-Pancrudo fault segment since 3.5 Ma (0.06 mm/a), or the one obtained for this main fault together with the bending component and the Valverde fault (0.09 mm/a), do not differ from the one reported for the adjacent Río Grío-Lanzuela fault (0.07 mm/a; Peiro and Simón, 2022) for the same time period, neither from those of the main extensional faults in the eastern Iberian Chain. The latter range between 0.05 and 0.16 mm/a for faults at both the neighbouring Jiloca graben and the Teruel Basin (Simón et al., 2012, 2016, 2017, 2019; Ezquerro et al., 2020; Peiro et al., 2022, 2023a).

The apparent short-term slip rate recorded at the LAG1 trench for the last 15 ka (0.08–0.09 mm/a) remains almost equal to the long-term slip rate, which disagrees with the regional tendencies. Within the Teruel and Jiloca basins, fault slip rates tend to increase from Late Pliocene (long-term rate, 3.5–3.8 Ma) to Late Pleistocene times (Simón et al., 2016). The same tendency had been already manifested during Neogene times at the eastern margin of the Teruel Basin: comparing the two extensional episodes defined in the region (Late Miocene to Early

Pliocene and Late Pliocene-Quaternary, respectively), a clear increase is evidenced from 0.05 to 0.07 mm/a, during the first episode, to 0.12–0.16 mm/a, during the second one (Ezquerro et al., 2020). On the contrary, a tendency to slip rate decrease has been reported within the easternmost Iberian Peninsula (Maestrat and Catalanian grabens; Masana, 1995; Masana et al., 2001; Perea et al., 2006).

Three controlling factors have been proposed by Ezquerro et al. (2020) for explaining the increase in slip rate at the Teruel and Jiloca basins: (a) onshore, westwards propagation of extensional deformation from the inner parts of the Valencia Trough; (b) crustal doming at the central-eastern Iberian Chain, responsible for the onset of multidirectional tension regime characterizing the second extensional episode; (c) progressive fault linkage during Neogene-Quaternary times. We should add a fourth factor, related to a further mechanism within the complex dynamic framework in which the active faults of the central-eastern Iberian Chain develop (Fig. 15). Liesa et al. (2019) and Simón et al. (2022b) suggest that the prevalent ENE-WSW σ_3 trajectories in the Teruel region really consolidates in the Pleistocene, while ESE-WNW trending σ_3 trajectories tend to be kept in the eastern sector (Maestrat grabens). The NNW-SSE compression transmitted to the interior of the Iberian Plate from the Betic margin during the Pliocene-Quaternary, which persists to the present day (Herraiz et al., 2000), determines the orientation of the maximum horizontal stress (S_{Hmax}) and, therefore, the orientation (ENE-WSW) of the orthogonal σ_3 trajectories. Under such a stress field, both (i) the propagation of a large NNW-SSE trending extensional structure as the Río Grío-Pancrudo fault zone, and (ii) active slip on every parallel fault, longitudinal with respect to the Iberian Chain, would have been strongly favoured.

The fact that the CPF activity recorded at the LAG1 trench does not reflect such regional tendency could be explained by the occurrence of a hypothetical spatial limit to the above-stated westwards propagation of the doming and rifting processes. Nevertheless, no evidence has been published in this regard. On the contrary, Peiro and Simón (2022) have reported a slip rate of 0.30–0.36 mm/a for the neighbouring Río Grío-Lanzuela fault (RLF) since c. 67 ka, i.e., significantly higher than

that calculated for the last 3.5 Ma (0.07 mm/a).

Another, more probable explanation is the incompleteness of the paleoseismological record studied at the LAG1 trench. We should again remember that the GPR profile suggests the occurrence of small faults not exposed in the trench (see Section 5.1, Fig. 10c), which would represent additional slip on the CPF during the explored time window. Without completely excluding the possibility that there are other large fault branches or bending monoclines not yet known, such small splay faults could have accumulated together a significant slip, which would involve (i) a higher average coseismic slip than that computed at the trench, as discussed in Section 5.1, and (ii) a higher slip rate as well, and perhaps approaching that recorded by the RLF. With this respect, we should also inspect the T-D curves of Fig. 8: at the site of the Lagueruela trench (c. 56 km in the abscissa axis), they show a total throw accommodated on the CPF close to its maximum, and similar to the maximum on the RLF. Therefore, similar maximum short-term slip rates should also be reasonably expected for both faults.

5.4. The context of intraplate Iberia and Western Mediterranean

Within the framework of intraplate Iberia, the Río Grío-Pancrudo fault zone (RPFZ = RLF + CPF) could represent one of the main active structures with nearly pure extensional kinematics. Moreover, it is one of the scarce faults that show evidence of Holocene activity, although have no historical large earthquake associated to them. It constitutes a paradigmatic example of intraplate fault zone able to undergo reactivation in recent times (Misra and Mukherjee, 2015): (i) zone of crustal weakness, inherited from pre-existing structures, and (ii) favourably orientated with respect to the recent to present-day stress field. The active tectonic setting in which such reactivation has occurred can be considered as hybrid or intermediate between two end members represented by the easternmost extensional systems (Catalanian ranges and eastern Iberian Chain) and the western strike-slip faults (e.g., Plasencia, Manteigas-Vilarica-Bragança), respectively. The first ones are controlled by pure extension linked to rifting at the Valencia Trough (Perea et al., in

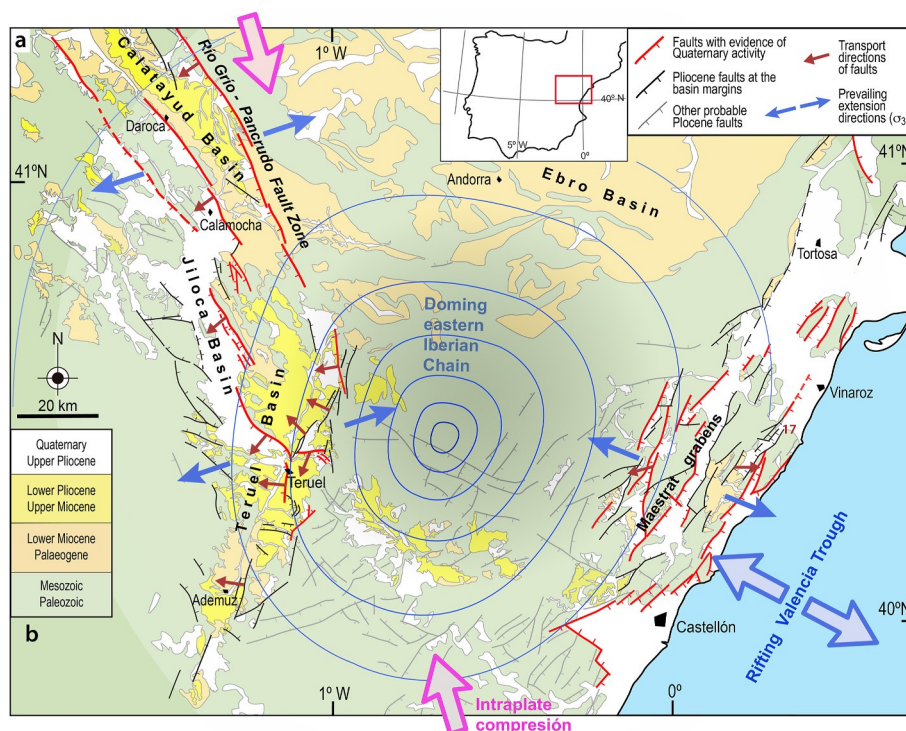


Fig. 15. Tectonic framework of the active faults in the central-eastern Iberian Chain, combining three geodynamic mechanisms: rifting at the Valencia Trough, crustal doming, and intraplate compression. Modified from Simón et al. (2022b).

Sanz de Galdeano et al., 2019), their NE-SW to NNE-SSW trend being nearly orthogonal to the regional extension direction. The NE-SW to NNE-SSW, left-lateral strike-slip fault system at the western Iberian Massif has been reactivated by NNW-SSE to NW-SE intraplate compression (Rockwell et al., 2009; Cabral, in Sanz de Galdeano et al., 2019). The NNW-SSE trending Río Grío-Pancrudo fault zone has been reactivated owing to its favourable orientation with respect to the same intraplate compression direction (S_{Hmax} trajectories), but its pure normal kinematics is determined by the extensional stress regime induced by rifting (Simón et al., 2022b).

Such spatially variable tectonic setting illustrates how the different factors controlling extensional systems work and interact. Lithospheric-scale processes determine where a rifting process occurs, but the orientation and geometry of individual extensional structures, their connections and spatial distribution depend on the structural inheritance and the prevailing stress field. Such interaction has been highlighted in diverse intraplate regions (e.g., East African Rift, SE Brazil, Rhine Graben, or west Norwegian margin; Misra and Mukherjee, 2015).

The Neogene-Quaternary extensional tectonics of the Iberian Cordillera is part of the geodynamic evolution of the western Mediterranean, controlled by two main processes: (i) collision of the African and Eurasian plates (together with small intermediate plates such as Iberia and Adria), and (ii) subsequent extension that, since the Oligocene-Early Miocene, opens the Valencia-Provence and Tyrrhenian troughs and moves the Corsican-Sardinian continental block eastward. It is significant how two distant extensional systems, such as the central Iberian Cordillera and the Campidano basin (Sardinia), have evolved in parallel within this geodynamic context. The Campidano graben is a large structure, 100 km long and 20 km wide, that cuts SW Sardinia. Its NNW-SSE trend (the same as the Jiloca graben and the RPFZ) is nearly parallel to the prevalent compression direction between Africa and Eurasia. Its development also occurs during the Pliocene-Late Quaternary, involving total throws >700 m on its master faults, and accumulation >600 m of Pliocene-Quaternary sediments (Casula et al., 2001; Cocco, 2014). Southern Sardinia also underwent development of several erosion surfaces during the Neogene-Quaternary, one of them in the middle Pliocene (3.5 Ma), which is preserved in the subsurface as the base of the sedimentary infill and has been used as a marker to reconstruct the geometry of recent deformations (Cocco et al., 2013; Cocco, 2014).

6. Conclusions

The Cucalón-Pancrudo fault (CPF) is a c. 40-km-long, NNW-SSE striking, extensional fault that is part of the Río Grío-Pancrudo fault zone (RPFZ). The latter is a Late Variscan strike-slip structure, then reactivated under Paleogene compression, and finally inverted during Neogene-Quaternary extension. It represents the largest active structure within the central-eastern Iberian Chain, and probably one of the main nearly pure extensional active structures within intraplate Iberia. As such, shall be incorporated to the Quaternary Active Faults Database of Iberia (QAFI).

The recent extensional activity of CPF has been mostly evidenced from morphotectonic analysis and trenching. The contour map of a widespread morphosedimentary marker (FES3, 3.5 Ma), together with a series detailed topographic profiles (Figs. 6 and 7), have allowed calculating the distribution of fault throw. The maximum value is estimated to about 280–300 m (Sierra Pelarda area), partitioned among throw on the main fault (190 m), on the Valverde fault (c. 20–30 m), and a gentle accommodation monocline. Based on the geometry and slip directions of the active faults in the region, we assume nearly pure dip slip on a fault plane dipping c. 65–70°. This involves net slip of c. 305–325 m, and long-term slip rate of 0.09 mm/a.

A paleoseismological trench (LAG1), dug in a Holocene fluvial terrace incised into the Valdelafuente Pleistocene alluvial fan, has provided evidence of Holocene faulting at the CPF trace. Several listric, domino-style normal faults, parallel and synthetic to the main fault, are

exposed at LAG1, with a total visible throw of 1.05 m. In addition, other small, parallel faults have been inferred from GPR profiles beyond the limits of the surveyed transect of the trench. All of them are interpreted as splay faults rooted in the main fault, on which (assuming nearly pure dip slip on a fault plane dipping 65°W) the total net slip is estimated at 1.15–1.25 m.

The age of the exposed materials, according to an age model based on OSL dating, ranges from c. 41 ka to 2.6 ka. Two main deformation events (X and Z), and an additional uncertain one (Y), have been identified affecting such sedimentary sequence: Event X, 14.9 ± 1.4 ka in age, with net coseismic slip estimated at ~ 0.75 m; Event Y (?), 11.0 ± 1.0 ka, coseismic slip ~ 0.2 m; Event Z: 6.9 ± 0.4 ka, coseismic slip ~ 0.3 m. This paleoseismological succession results in a recurrence period of 4.0 ± 1.9 ka or 8.0 ± 1.8 ka depending on whether a scenario of three or two events, respectively, is considered. In any case, the total net slip accumulated during these events (1.15–1.25 m, since c. 14.9 ± 1.4 ka) provides a short-term slip rate of 0.07–0.09 mm/a, very similar to the long-term slip rate.

This apparent steady rate could be seen as an anomaly within the regional framework. Most recent extensional faults within the central Iberian Chain show long-term slip rates similar to that of CPF, but such rates significantly increase during Pliocene-Pleistocene times (Simón et al., 2016; Ezquerro et al., 2020; Peiro and Simón, 2022). Nevertheless, such apparent anomaly may not be real. It is very likely that the faults exposed in trench LAG1 do not represent a complete record of the paleoseismic events, and that more splay faults rooted in the main fault are associated to them. This would involve that the true coseismic slips were higher than the computed ones (0.2–0.75 m), approaching the value (1.0–3.0 m, more probably 1.2 m) obtained from regression models based on the rupture length (40 km). Moreover, additional, yet unknown possible CPF branches could accommodate additional events. As a result, the real slip rate during the studied time period could be significantly higher, maybe approaching that reported for the neighbouring Río Grío-Lanzuela fault (0.30–0.36 mm/a; Peiro and Simón, 2022).

The Cucalón-Pancrudo fault could produce maximum earthquakes with $M_w = 6.9 \pm 0.3$, in the case of a complete rupture, or $M_w = 6.8 \pm 0.3$ if only a northern, 20–25-km-long segment was activated. Such earthquakes have recurrently happened during Late Pleistocene and Holocene times. In summary, although more trenches would be necessary for improving its paleoseismic record, CPF should be considered as a first-level active fault within the interior of the Iberian Plate, and therefore as a critical seismic source that should be considered in seismic hazard assessment of the region.

CRediT authorship contribution statement

Alba Peiro: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis E. Arlegui:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Carlos L. Liesa:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Aránzazu Luzón:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Alicia Medialdea:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Óscar Pueyo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **M^a Asunción Soriano:** Investigation, Formal analysis, Data curation. **José L. Simón:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsg.2024.105234>.

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