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1 **Relict periglacial soils on Quaternary terraces in the Central Ebro Basin (NE**
2 **Spain)**

3

4 Short title: Periglacial soils in the Ebro Basin

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21 **Abstract**

22 Pedofeatures associated with ancient cold climatic conditions have been
23 recognized in soils on terraces in the Monegros area (central Ebro Basin), at a latitude of
24 41°49'N and an altitude of 300 m a.s.l. Eleven soil profiles were described on fluvial

25 deposits corresponding to the most extensive terrace (T5) of the Alcanadre River,
26 Middle Pleistocene in age (MIS8-MIS7). Each soil horizon was sampled for physical,
27 chemical, mineralogical and micromorphological analyses. Macromorphological
28 features related to pedocryogenic processes were described: involutions, jacked stones,
29 shattered stones, detached and vertically oriented carbonatic pendants, fragmented
30 carbonatic crusts, laminar microstructures, succitic fabric, silt cappings on rock
31 fragments and aggregates, and irregular, broken, discontinuous and deformed gravel and
32 sandy pockets. Accumulations of Fe-Mn oxides, dissolution features on the surface of
33 carbonatic stones, and calcitic accumulations were identified related to vadose-phreatic
34 conditions. The observed periglacial features developed under cold environmental
35 conditions in exceptional geomorphic and hydrological conditions. This soil
36 information may have potential implications in studies of the paleoclimate in the Ebro
37 Valley as well as in other Mediterranean areas.

38

39 **KEYWORDS**

40 Cryogenic pedofeatures, middle latitude, low altitude, calcareous soils, carbonatic
41 accumulations, Monegros

42

43 **1 INTRODUCTION**

44 Periglacial environments occur in non-glacial high-altitude, high-latitude and
45 continental domains characterized by cold climatic conditions promoting frost-action
46 processes that favour the occurrence of freezing and thawing cycles and/or permafrost¹⁻
47 ³. In the Iberian Peninsula, periglacial dynamics are currently restricted to the highest
48 mountain areas and very few cases of periglacial features from the Pleistocene have
49 been described in low-altitude inland areas⁴⁻⁶. In the Central Ebro Basin (NE Spain), the

50 17 ka-old stratified scree slopes from Valmadrid are the only periglacial deposits
51 reported in the literature⁷. The deformational features affecting Pleistocene terraces
52 around Zaragoza were interpreted as the result of periglacial cryoturbation and ice
53 wedges by some authors⁸⁻¹⁰, but others^{4,11-13} proposed gypsum dissolution and diapiric
54 activity as the main drivers of such deformations. Periglacial environments have been
55 associated with 20±3 ka-old loess deposits in the Ebro Basin¹⁴. Recent works indicate
56 the distribution and remarkable extension of 18-34 ka-old loess deposits related to cold
57 conditions at altitudes of 300-500 m a.s.l. in the lower Ebro Valley¹⁵⁻¹⁶.

58 The objectives of this work deal with i) the macro and micromorphological
59 characterization of soils and the interpretation of pedocryogenic features identified, and
60 ii) the geomorphic, stratigraphic, and past hydrological, and climatic conditions
61 controlling local periglacial processes in the area.

62

63 **2 STUDY AREA**

64 The study area is located in the North of Monegros area or Sariñena
65 depression¹⁷, which is drained by the Alcanadre-Flumen River system, and is located
66 within the central sector of the Ebro River Basin (Figure 1). Currently, the Central Ebro
67 valley supports a Mediterranean continental steppe type of habitat. Mean annual
68 temperature in Sariñena village during the 1945-2009 period is 13.7 °C, with January as
69 the coldest month with a mean temperature of 5.3 °C. Mean annual rainfall in the area is
70 405 mm.

71 Geological bedrock consists of horizontal layers of sandstones and mudstones of
72 the Sariñena Formation¹⁷ covered by a terrace sequence related to the Alcanadre-
73 Flumen fluvial system composed of nine cut-in-bedrock (strath) and fill Pleistocene
74 terraces¹⁸⁻¹⁹.

75

76 **3 METHODS**

77 Geomorphological mapping of the Pleistocene terrace sequence of the
78 Alcanadre-Flumen system in the Sariñena high plain was derived from stereoscopic
79 photointerpretation of aerial photographs from 1957 US Air Force flight B, printed at
80 1:33,000 scale. The resulting geomorphological map was digitized using ArcGIS® 10.3.
81 A digital elevation model generated in 2010 from airborne LiDAR data was used to
82 refine the photointerpretation. A subsequent field survey was carried out across the
83 Sariñena high plain and in the surrounding areas in order to identify different landforms
84 and processes. Fluvial terrace deposits were described using the sedimentary lithofacies
85 codes²⁰. We described and sampled 11 pedons (Figure 1) for physico-chemical analyses.
86 Different horizons and carbonatic accumulations were sampled for micromorphology
87 and clay mineralogy analyses in 8 selected pedons.

88 Soil profiles (Figure S1) were described following²¹⁻²² and classified according
89 to Soil Taxonomy²³. A total of 122 soil samples were collected for laboratory analyses.
90 Soil samples were air-dried, sieved to 2 mm and analysed for pH (1:2.5 in water),
91 electrical conductivity (1:5 in water), organic carbon (Walkley-Black method²⁴),
92 calcium carbonate equivalent (volumetric calcimeter method) and texture (pipette
93 method). The cation exchange capacity was determined as ammonium after saturation
94 with 1 N NH₄OAc at pH 7 and extraction with 1 N NaOAc at pH 8.2, and the
95 exchangeable cations (potassium, sodium, magnesium and calcium) by atomic
96 absorption spectrophotometry. Clay mineralogy was studied through X-ray powder
97 diffraction (XRD) using a Bruker D8 Advance diffractometer with graphite-
98 monochromated CuK(α) radiation and a linear Vantec detector. XRD patterns were
99 obtained from random powder mounts and oriented mounts. A total of 64 soil thin

100 sections (135×58 , and 58×42 mm large) of undisturbed soil horizons and selected soil
101 components were manufactured after impregnation with a cold setting polyester resin
102 and described²⁵⁻²⁷.

103 Three samples were collected for infrared stimulated luminescence dating
104 (IRSL), two of them from the same sand lens in a gravel quarry wall 2 km south of the
105 village of Sariñena ($41^{\circ}46'21''\text{N}$; $0^{\circ}10'24''\text{W}$), and a third sample from another quarry
106 1 km east of Sariñena ($41^{\circ}47'21''\text{N}$; $0^{\circ}8'38''\text{W}$). Dating was performed using k-
107 feldspar single grain post-IR IRSL procedure²⁸.

108

109 **4 RESULTS**

110 **4.1 The T5 terrace of the Alcanadre River**

111 The T5 terrace is well preserved along the Alcanadre River valley and, along
112 with the nearby lowest Alcanadre terrace T1¹⁸⁻¹⁹, constitutes a relevant regional
113 landscape marker that facilitates the correlation of other terraces forming the sequence.
114 T5 terrace has a triangular shape with a north-south axis of about 13 km and an east-
115 west axis of 4 km. Landforms related to the Alcanadre River, to the east, and to the
116 Flumen River, to the west, appear on this terrace (Figure 1). The altitude of the tread
117 surface corresponding to the T5 terrace is 30 m above the active channel. The mean
118 slope gradient in this sector is around 4.4 ‰, and the mean thickness of the alluvial
119 cover related to T5 varies between 2.5 and 7 m. Following the Miall terminology,
120 terrace deposits include massive (Gm) and cross-stratified (Gp and Gt) gravels
121 sometimes with basal channel surfaces. Gravels are sub-rounded and well sorted and
122 mostly consist of limestone and sandstone from the Pyrenean External Ranges.
123 Maximum grain size (Dmax) of gravels ranges from 8 to 16 cm and the mean grain size

124 (D50) from 2 to 5 cm. Interspersed stratified sand (St) lenses and overbank (Fm) silty
125 sediments appear occasionally capping the fluvial fining-upwards sequences.

126 The remnants of T6 terrace correspond to the residual reliefs of Santa Cruz and
127 Puyalón (Figure 1). Previous work has proposed that this terrace obstructed in the past
128 the external surface drainage and occluded a low-lying zone, thereby creating high
129 water tables that influenced the development of piping processes in the surrounding
130 sodium-rich Miocene clays and the formation of the Sariñena Lake²⁹.

131 Palaeomagnetic data for the T5 terrace indicate a normal polarity and
132 consequently an age younger than the Matuyama-Brunhes reversal at 781 ka BP¹⁸. The
133 samples analysed by IRSL dating provided ages of 235 ± 17 ka BP, 196 ± 13 ka BP, and
134 274 ± 18 ka BP. We therefore propose an age ranging from 274 to 222 ka BP for the T5
135 terrace of the Alcanadre River corresponding to the Marine Isotope Stage MIS8 and the
136 transition to MIS7³⁰.

137

138 **4.2 Main soil macromorphology and physico-chemical characteristics**

139 All soils studied showed processes of secondary accumulation of carbonates,
140 frequently producing petrocalcic horizons. On the other hand, only one soil profile
141 showed horizons with clay illuviation (Table S1).

142 Most soils were well drained, A and B horizons having a prominent reddish
143 colour with a hue from 7.5YR to 5YR, but C horizons frequently showed oxidation-
144 reduction features. Rock fragment content in A horizons was usually smaller than 15%,
145 but it was quite variable in Bwk and Btk horizons, reaching up to 70%, while in Bkm
146 and C horizons it was usually bigger than 70%. The A and Bwk horizons had fine or
147 moderately fine textures while C horizons had moderately coarse or coarse textures. No
148 accumulations or textural features were observed in the A horizons. The Bwk and Btk

149 horizons had frequent nodules, pendants, and coatings of CaCO₃, and the latter showed
150 few clay coatings with silt. The Bkm horizons were strongly cemented by carbonates
151 but no textural coatings were observed. C horizons included frequent pendants,
152 coatings, and powdery lime, as well as some coatings of Mn and Fe oxides. Textural
153 coatings of clay with silt also appeared in some coarse C horizons while coatings of silt
154 appeared in some fine C horizons. The synthesis of the soil macromorphological
155 information is reflected in Tables S1 to S4 of the Supporting Information.

156 The soil A and B horizons have moderately alkaline pH and C horizons are
157 strongly alkaline. All horizons are non-saline and calcareous and have low organic
158 matter concentrations. Values of cation exchange capacity are low to moderate,
159 exchangeable sodium percentage is always smaller than 4%, and calcium is the main
160 exchange cation, and therefore conditions are favourable for clay flocculation. Clay
161 mineralogy of the A and B horizons is similar with a great predominance of illites and
162 presence of chlorites. Pyrophyllite and kaolinite appear in a lesser proportion. The
163 synthesis of the physical-chemical and mineralogical information is reflected in the
164 Tables S5 to S8 of the Supporting Information.

165

166 **4.3 Soil cryogenic features**

167 Different cryogenic features have been identified at both the macro- and
168 micromorphological scales: involutions; jacked elements; shattered elements;
169 deformation and fragmentation of soil horizons; lenticular and laminar aggregates;
170 vesicular, vughy and planar porosities; soil cryogenic fabrics and silt cappings.

171 Four types of involution morphologies were identified in the field according to
172 the classification of Vandenberghe³¹⁻³². We described regularly spaced type 3
173 involutions, in which the lower soil horizons with a high proportion of gravels form

174 wedges or narrow festoons penetrating the fine or moderately fine textured upper soil
175 horizons, without dividing them. Involutions had a scalloped and symmetrical
176 morphology, and appeared regularly spaced (Figure S2a). In some areas type 2
177 involutions were observed with spacings and heights of more than 60 cm but without
178 lateral continuity (Figure 2a). Individual type 4 involutions (Figure S2b) and irregular
179 and contorted type 6 involutions (Figure 2b) were also described.

180 Most non-skeletal soils showed evidence of jacking of clasts up to 18 cm in size
181 (Figures 2b, S2a, S2b), which appeared pointing towards the finer-textured soil horizons
182 above them. Frequently, these verticalized clasts had subsequently developed CaCO₃
183 pendants in the lower side (Figure S5e). Clasts with their pendants rotated close to 90°
184 were commonly found, and in some cases several systems of pendants had developed in
185 the lower part (Figure 2c).

186 Frost shattering of different types of coherent materials such as alluvial clasts
187 (Figure S2c, S4a, S4b), pendants of CaCO₃ (Figures 2d, S3a, S3b, S4c), CaCO₃ nodules
188 (Figures 2e, S5a) and carbonatic crusts (Figures S2d, S3c) were identified.

189 CaCO₃ nodules had frequently undergone fracturing and rotation processes
190 followed by the precipitation of an alternating banded filling of spar and
191 micrite/microspar similar to the laminar pendants (Figures 2e, S5e). Such rotation also
192 indicates processes of internal deformation of the horizon by cryoturbation (Figure
193 S5e). Bladed cracks also appeared in laminar pendants (Figure S3b). At the microscopic
194 scale, fractures of textural coatings and redox accumulations of Fe-Mn oxides were also
195 observed (Figure S5b).

196 Break planes, planar gaps or new porosity often developed along the contact
197 between clasts and their pendants (Figure S5c), or within the calcitic pendants (Figure
198 S5d) or crusts (Figure S3c). These cryogenic features were usually identifiable under

199 the microscope due to the presence of textural coatings and infillings (Figure S3a).
200 Palisade morphologies of spar crystals in some bands of calcite accumulation within the
201 pendants indicated their growth in voids without volume restrictions (Figures S3a, S3b).

202 Features that mainly occurred in non-skeletal horizons included fragmentation
203 and deformation of the limits of C horizons (Figures S2e, S2f), rotation of pendants
204 developed in clasts (Figures 2c, S5e), rotation of nodules with pendants (Figures 2e),
205 and silt cappings made up of two generations (Figure S4d).

206 Frequent lenticular 0.2 -0.4 m thick beddings in fine sandy silt C horizons
207 appeared 2 to 3 m below the terrace surface (Figure 2f). Smooth planar fissures with
208 non-conforming boundaries demarcated the platy aggregates (Figure 2f, S4g). Vesicular
209 porosity was rare (Figure S3d) and vughy was more frequent (Figure S3d). Vughs,
210 cracks, and triangular or square star-like interpedal connected pores with planar voids
211 (Figure S3e) often occurred in non- skeletal fine-textured C horizons.

212 Rotation and succitic fabrics of sand grains or gravels were described at a
213 microscopic scale in Bwk and Btk horizons (Figure S3f). Areas with an organization
214 with preferential diagonal orientation (Figure S3g), as well as an orbicular rotational
215 fabric with an arched arrangement of the sand grains forming curved bands (Figure S3h)
216 were also identified.

217

218 **4.4 Textural features and Fe-Mn oxide accumulations**

219 Features showing particle translocation, such as coatings, cappings,
220 intercalations, and, in a lesser proportion, infillings and fragments of cutans, were
221 identified in B horizons of some soils. These features were usually complex, i.e. they
222 included several stages or phases of formation that differ in texture and color mainly
223 due to their different grain size. In some cases the coatings had been incorporated into

224 different carbonatic accumulations by the growth of the calcite crystals. These features
225 were distributed within the pedogenic porosity and in cracks of shattered stones (Figure
226 S4c, S4a).

227 Three types of textural pedofeatures were identified based on microscopy
228 birefringence and grain size. One type was composed of impure clay (Figure S4c) and
229 rarely dirty clay, and no clean or micro-laminated clay coatings were detected. A second
230 type was made up of clay mixed with silt in variable proportions (Figures S4a, S4b), silt
231 with some clay, clay with a small proportion of silt, or basal mass. The latter appear in
232 all types of B horizons and in skeletal C horizons (Figure S4e).

233 The third type of textural pedofeature was the occurrence of silt accumulations.
234 They were widespread in non-skeletal C horizons (Figure 2f). In skeletal C horizons
235 these accumulations appeared forming infillings between clasts, link cappings, and
236 cappings (Figure S4f). Pedofeatures with banded fabric (Figure S4g) were also observed
237 in the shape of a complex feature with sandy basal mass with laminar or lenticular
238 microstructure, silt caps, and layers of sorting sands.

239 In some cases, two families of silt cappings were recognized in the same soil
240 horizon representing two mobilization stages of the silty material, a younger capping,
241 linked to soil aggregates and planar porosity, and an older one which appears as near-
242 parallel silty intercalations within the soil groundmass. Figure S3d shows an example of
243 the latter arranged at an angle of about 60°-70° with respect to the direction of the
244 younger caps. Downturned silt cappings caused by soil deformation were also present
245 (Figure S4h).

246 Coatings of Fe and Mn oxides on gravels and coatings made up of fragments of
247 those coatings were described in skeletal C horizons (Figure S2g, S5b), while

248 impregnative diffuse nodules, hypo-coatings, and intercalations appeared in non-skeletal
249 Bwk, Btk, and C horizons.

250

251 **4.5 Carbonatic accumulations**

252 The most abundant CaCO_3 accumulations were pendants, nodules, and crusts,
253 though pseudomorphs of roots (queras), and infillings with different calcite habits
254 (acicular, microspar, and spar crystals) were also identified. Intense dissolution
255 morphologies were also identified on the surface of carbonatic rock fragments in C
256 horizons with over 70% of coarse fragments (Figure S5h).

257 Several types of pendants were identified. Laminar pendants, 0.1 to 45 mm
258 thick, appeared at the base of rock fragments (Figures S5c, S5d), carbonatic nodules
259 (Figure 2e), or crusts (Figure 3) in Bwk, Bkm, and Btk horizons. These pendants were
260 organized in coloured alternating bands of grey spar and brown micrite/microspar which
261 suggests alternating clay and fine silt enrichment (Figure S5d). The base of the bands
262 was smooth, wavy, or arched and lacked mammillary or botryoidal structures (Figure
263 S5c, S5d). There were also spar fillings in palisade or double palisade in planar voids
264 (cracks) of cryofractures (Figure S3a, S3b).

265 Columnar pendants with a length of 4-55 mm and a width of each individual
266 pendant of 0.15-20 mm appeared at the base of laminar pendants of stones and
267 carbonatic crusts (Figures 3, S2h), sometimes coalescing into a stalactitic mammillary
268 to botryoidal appearance (Figures 2g, 2h, S5f), in Bwk horizons and at the base of
269 fractured calcareous crusts. The presence of voids appeared necessary for unrestricted
270 calcite accumulation in these pendants (Figure 3). They were internally organized into
271 alternating arched bands of grey spar and brown micrite/microspar (Figure 2g). The
272 individual spar crystals showed a conspicuous morphology of elongated scalenohedrons

273 with a prominent radial extinction (Figure S5g). The most frequent form of the lower
274 limit of the bands was scalloped, mammillary, and digitated.

275 Frequent impregnative CaCO₃ nodules were identified in medium to fine
276 textured B horizons. Nodules ranged between 2 and 15 mm in size, were rounded or had
277 vertically elongated sections, and showed varying degrees of purity, the more reddish
278 ones containing a greater proportion of basal mass of the horizon. There were
279 differentiated up to three generations of carbonate accumulations associated with the
280 nodules (Figure S5a), mostly micrite but also microspar, often appearing as pendants.
281 The joint presence of nodule and pendant outside its original position allowed the
282 identification of nodule rotation due to soil deformation processes (Figure 2e). Break
283 planes produced by cryoclastic processes favoured the development of compound
284 accumulations similar to pendants (Figure 2e).

285 The calcareous crusts were mostly conglomeratic (Figure 2h), but some were
286 nodular-oolithic or with laminar facies at the top. Near-horizontal or cross-plane
287 fractures of the crusts (Figure S2d) with CaCO₃ precipitations and coalescent columnar
288 pendants were identified (Figure S2d, S3c).

289

290 **5 DISCUSSION**

291 **5.1 Genesis of pedofeatures**

292 Alternative explanations to the set of features described other than periglacial
293 processes, as proposed by some authors⁴, may be rejected. Mass wasting often results in
294 features similar to involutions³³⁻³⁴, but these processes have not been observed in the
295 soils of the T5 terrace, which has a general slope of about 1%.

296 Collapses related to karstic processes in gypsum or limestones¹¹ and volume
297 changes associated with anhydrite expansion into gypsum cannot explain the

298 deformities and fragmentation of soil horizons since the materials underlying the
299 alluvial deposits are detrital rocks, mainly lutite and sandstone, and there are no gypsum
300 rock or limestones in the area. Similarly, expansion-retraction of clay –rich materials
301 may be rejected as no expandable clays have been found in this region^{29,35}.

302 Windthrow of trees has been shown to cause deformation and involutions in
303 soils³⁶. However, the involutions identified in the soils studied are sufficiently
304 generalized spatially, and show a continuity, symmetry and depth that discard this
305 possibility.

306 The hypothesis of collapses due to piping, which is a frequent process in the
307 area²⁹ can be rejected for similar reasons. Tectonic deformations may also be
308 disregarded as an alternative explanation, even though liquefaction features along the
309 fault line may be mistaken for cryoturbation features³⁷, because the area presents low
310 seismicity³⁸⁻³⁹. Furthermore, sedimentary structures of load (load cast) or other
311 sedimentary irregularities in the stratification¹¹ do not seem to correspond to the features
312 described here.

313 Cryoturbation involves processes of sorting, heaving, stirring, wedging, and
314 cracking^{2,40}. The occurrence in our soils of all types of involution described by
315 Vandenberghe³¹⁻³², except type 2, requires intense cold conditions, although not
316 necessarily permafrost, and are facilitated by frost-defrost cycles. The traction exerted
317 by the growing of ice lenses within rigid elements (e.g., stones, nodules) included in a
318 matrix susceptible to frost progressively leads to the rotation and vertical alignment of
319 clasts⁴¹⁻⁴².

320 The mechanisms involved in frost shattering include frost wedging, ice
321 segregation, and hydraulic fracturing⁴¹. Frost shattering may also affect pedofeatures,
322 disrupting soft iron nodules, clay coatings, or carbonate precipitates⁴¹. Deformed and

323 broken horizons indicate mechanical stresses associated with cryoturbation that results
324 in displacement of the mass, ice segregation, and thermal cracking⁴⁰.

325 Platy structures may be formed by ice segregation and soil desiccation as ice
326 lenses grow in the course of soil freezing⁴³. Ice lenses develop perpendicularly to the
327 direction of the freezing front, and thus their orientation is generally parallel to the
328 ground surface. Soil aggregates become somewhat oriented because of repeated freeze-
329 thaw cycles. In frozen state lenticular fabrics are separated by not only horizontal ice
330 lenses but also by diagonal ice veins⁴⁴. The succitic fabric²⁷ has been identified in
331 different B horizons as a result, at microscale, of the traction exerted by growing ice
332 lenses on rigid elements included in a matrix susceptible to frost. This process
333 progressively leads to the rotation and vertical alignment of the clasts⁴².

334 Vesicular porosity results from the expulsion of the air confined by the structural
335 collapse that occurs during thawing, and the subsequent deformation of vesicular pores
336 produces the vughy porosity^{43,45}.

337 The clay coatings described cannot be primarily associated with periglacial
338 conditions as they require a temperate climate with moist periods both for the initial
339 formation of clay-sized material and its subsequent mobilization leading to the
340 formation of the coatings⁴⁶⁻⁴⁷. Furthermore, the reddish colour of these soils, with a hue
341 of 5YR or 7.5YR that is related to the presence of hematite, suggests a much warmer
342 climate than even the present one⁴⁷.

343 The abundance of textural features, with mixed clay and silt, in the studied soils
344 demonstrates a strong downward migration of fine particles during ground melting⁴⁸,
345 and although they are not pure clay cutans in the sense of those described by²⁵⁻²⁶, they
346 indicate a certain degree of sorting. These textural features are common in cryogenic
347 soils due to slaking under melting conditions and subsequent vertical frost sorting the

348 sand and coarse silt fractions⁴⁰. These clay and silt textural pedofeatures, as well as the
349 clayey pedofeatures previously discussed, have frequently been incorporated into
350 carbonatic accumulations by the growth of calcite crystals originating Btk and Btkm
351 horizons.

352 Silt cappings are also frequent in C horizons and have been linked to cryogenic
353 processes^{46,49}. Silt and sand banded cryogenic fabrics result from a combination of
354 compaction and cryodesiccation between growing ice lenses during soil freezing, and
355 illuviation on the upper surfaces of aggregates during soil thawing^{43,50}. Resulting fabrics
356 include dense platy peds separated by planar voids, banded fabrics, and lenticular zones
357 of denser matrix. Many periglacial soils exhibit downward migration of fine particles,
358 notably coarse silt, that bridge sand grains, fill macropores, and occur as caps on coarse
359 fragments⁴⁰. These coatings form due to the melting of the ice lenses and ice coatings
360 around the mineral grains.

361 Coatings of Fe and Mn oxides indicate conditions of soil water saturation and
362 reduction producing Fe²⁺ and Mn²⁺ soluble compounds that are able to migrate in the
363 soil solution and to later reoxidize and precipitate. In some cases cryoturbation
364 processes break up the coatings on clasts and fragments, and the pieces may migrate
365 gravitationally and accumulate in the form of Fe-Mn oxide cappings.

366 The diversity of traits described, their characteristics, and relationships reflect
367 processes of mixing, fracture, displacement and orientation of soil materials which
368 strongly suggest relict periglacial genesis^{2,32,40,41,49,51} and underline the complexity of
369 soil-landscape relationships⁵².

370

371 **5.2 Carbonatic pedofeatures**

372 Several studies have described cryopedogenic features in soils formed in
373 calcareous parent materials and / or with carbonatic accumulations⁵³⁻⁶⁰.

374 Among all the carbonatic features described in our soils (i.e., pendants, nodules,
375 nodules with pendants, powdery calcite, coatings, acicular crystals, root pseudomorphs,
376 and crusts) only columnar pendants may be associated with pedocryogenic processes,
377 but we do not discard that these processes may have been involved at some stage in the
378 development of some of those carbonatic features.

379 Columnar pendants require space for repeated precipitation of calcite phases.
380 This space may be produced by ice lensing and frost-induced moisture retractions
381 allowing the vertical growth of columnar pendants without space restrictions in a
382 similar pattern to stone jacking⁴⁹. Figure 3 shows particularly well-developed columnar
383 pendants with internal morphology similar to but thicker than those described by⁵⁵.

384 Although the formation of calcareous nodules, laminar pendants, and crusts may
385 not be related to cryoturbation phenomena, their fracturing and the subsequent infilling
386 of cracks with CaCO₃, as well as the rotation processes, can be associated with
387 periglacialism⁶⁰. Many studies demonstrate the role of ice on the mechanical weathering
388 of rocks or other indurated materials⁶¹. Petrocalcic horizons formed in-between non-
389 indurated soil horizons would be especially prone to cracking and disruption by
390 cryoturbation⁶⁰. The various observations that indicate fragmentation of soil
391 components, translocation of silty and/or clayey materials, and infilling of voids and
392 cracks by precipitation of calcite highlight the complexity and difficulty of elucidating
393 the true temporal sequence of these carbonate pedofeatures for dating purposes as
394 previously noted by⁶². We actually performed U/Th series dating of two petrocalcic
395 horizons sampled from the same quarry as the samples used for IRSL dating but the
396 results were inconsistent between them (113.6±2.5 ka BP and 13.1±2.5 ka BP for the

397 upper and lower samples, respectively). We suggest that the occurrence of various
398 polycyclic phases within these carbonatic accumulations requires very precise sampling
399 of well-defined and specific features in order to obtain meaningful dating results.

400

401 **5.3 Palaeoenvironmental significance of periglacial features**

402 The periglacial soil morphologies described are almost limited to the western
403 part of terrace T5 as in the central and eastern zones only some jacking of clasts,
404 prismatic carbonate pendants, and cryoturbation of crusts appeared.

405 The accumulations of Fe and Mn oxides together with the dissolution features on
406 carbonate clasts in horizons with a high proportion of rock fragments, indicate that the
407 high transmissivity of these horizons may have favoured their contact with a persistent
408 water table with variable temporal saturation in calcite, in support of the hypothesis of a
409 paleohydrological regime with a shallow water table in this area. This hypothesis is
410 coherent with previous work regarding the formation of Sariñena endorheic basin which
411 suggested that the T6 residual reliefs of Santa Cruz and Puyalón (Figure 1) occluded a
412 low-lying zone in the western Sariñena high plain where shallow water was available²⁹.

413 Up to now periglacial features at low altitude in the Iberian Peninsula have only
414 been described on the coast of Galicia (northwestern Spain)⁶³. Relict periglacial
415 cryoturbations and occasional ice wedge morphologies⁴ have been reported in the Duero
416 Basin at a similar latitude to Sariñena but at a higher altitude (about 800 m a.s.l.)⁵⁻⁶.

417 The soil morphologies described in Sariñena high plain also suggest conditions
418 of deep seasonal frost. The type 2 involutions are discontinuous and the other
419 periglacial features would require frequent alternating conditions of freezing and
420 thawing and/or long-term and deep seasonal freezing³². The thickness of the cryogenic-
421 affected layer, as inferred from the distribution of involutions and frost jacking in the

422 soil profiles, is 1.8 m in average. In Europe, the latitudinal limit of deep seasonal frost
423 for flat areas in France has been suggested at 43° latitude⁶⁴⁻⁶⁵, though small scale or
424 isolated cryoturbations occur in areas without permafrost that are subject to seasonal
425 frost⁴⁰. We therefore propose deep seasonal frost conditions, and not a continuous
426 periglacial environment, as the main driver of the cryopedogenic features described.

427 To our knowledge, fluvial deposits of terrace T5 and related soils surrounding
428 Sariñena high plane are the only morphopedosedimentary unit affected by periglacial
429 processes in the Quaternary sequence of staircase terraces developed along the
430 Alcanadre River valley. Considering the dates provided by IRSL dating technique the
431 T5 terrace formation occurred from 274 to 222 ka BP, under cold environment with
432 enough water availability to promote the production and transport of sediments to the
433 river channels. The periglacial features studied and associated processes would have
434 taken place at one or more of the various cold periods between 274-222 and 12 ka BP.

435 The aggradation process of terrace T5 was not fed by glacial outwash pulses
436 because the mountain headwaters (External Pyrenean Range) were not glaciated during
437 the Quaternary. Alternatively, it would be related to periglacial environmental
438 conditions⁶⁶ with enough water availability to enhance the sediment supply. Moreover,
439 the sparse steppe vegetation and the seasonal distribution of rainfall might have
440 favoured runoff from slopes and intensified mechanical bedrock weathering⁶⁷.

441 Therefore, we suggest the prevalence of periglacial conditions in the source areas
442 feeding the sedimentary fluvial aggradation in the Alcanadre River valley around 274-
443 222 ka BP. During the subsequent soil formation phase water availability would have
444 decreased ceasing the alluvial activity while cold conditions would remain favouring
445 active periglacial processes in soils and sediments.

446

447

448 **6. CONCLUSIONS**

449 Relict periglacial features have been identified in calcareous soils of a fluvial
450 terrace at a middle latitude (41°49'N) and a low altitude of 300 m a.s.l. in Europe. The
451 soil horizons showed a variety of cryopedogenic features at different scales, from the
452 field to the microscope, which are related to the deformation and disruption of soil
453 components and translocation of material due to deep seasonal frost conditions. These
454 macro and microfeatures, which are unique in the region, are the result of specific
455 edaphic conditions related to the occurrence of a shallow water table under a cold dry
456 seasonal-frost climate and soil materials with different frost susceptibility. The
457 periglacial features studied would have developed between 274-222 and 12 ka BP.

458 The presence of cryopedogenic features in soils of the Middle Ebro Valley may
459 have significant implications regarding the use of these and other mid-latitude
460 calcareous soils for geochronology and palaeoenvironmental reconstruction.

461 The calcareous composition of soils has conditioned the formation of
462 conspicuous microfeatures. A possible cryogenic genesis for columnar carbonate
463 pendants is proposed. Further work on the specific cryogenic processes associated with
464 features in calcic horizons is required, as well as a more precise dating of these features.

465

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471 the three anonymous reviewers for their helpful comments on a previous version.

472 We dedicate this paper to the memory of our colleague Carlos Sancho, who
473 passed away while this paper was under review.

474

475 **SUPPORTING INFORMATION**

476 **Figure S1** Cryogenic macromorphological features

477 **Figure S2** Cryogenic micromorphological features

478 **Figure S3** Cryogenic micromorphological textural features

479 **Figure S4** Micromorphological carbonatic and redox features

480 **Table S1** Macromorphological characteristics of the studied soils

481 **Table S2** Macromorphological features of pedon SAR-10

482 **Table S3** Macromorphological features of pedon SAR-11

483 **Table S4** Macromorphological features of pedon SAR-12

484 **Table S5** Physical and chemical data of pedon SAR-10

485 **Table S6** Physical and chemical data of pedon SAR-11

486 **Table S7** Physical and chemical data of pedon SAR-12

487 **Table S8** Clay mineralogy of selected soil horizons

488

489 **REFERENCES**

- 490 1. Tricart J, Cailleux A. Le Modelé des Régions Périglaciaires. Traité de
491 Géomorphologie, tome II, Paris: SEDES. 1967.
- 492 2. Washburn AL. 1980. Geocryology. New York: Wiley. 1980.
- 493 3. French HM. The Periglacial Environment, Third Edition. Wiley: Chichester.
494 2007.

- 495 4. Gonzalez-Martín JA, Pellicer F. Rasgos generales del periglacialismo de la
496 península Ibérica: Dominio continental de las tierras del interior. Cuad Inv
497 Geogr. 1988; 14: 23-80.
- 498 5. Serrano E, Pelleteiro R, Otero M. Huellas pleistocenas de frío intenso en la
499 Cuenca del Duero: Cuñas de arena relícticas en las terrazas del Pisuerga. In:
500 Úbeda X, Vericat D, Batalla RJ, eds. Avances de la Geomorfología en España,
501 2008-2010. Barcelona: SEG-Universitat de Barcelona; 2010: 417-420.
- 502 6. Oliva ME, Serrano A, Gomez-Ortiz MJ et al. Spatial and temporal variability of
503 periglaciation of the Iberian Peninsula. Quat. Sci. Rev. 2016; 137: 176-199
- 504 7. Valero-Garcés B, González-Sampériz P, Navas A, et al. Paleohydrological
505 fluctuations and steppe vegetation during the last glacial maximum in the central
506 Ebro valley (NE Spain). Quat Int. 2004; 122, 43-55
- 507 8. Brosche KU. Neue beobachtugen zu vorzeitlichen periglazialerscheinungen im
508 Ebrobecken. Z Geomorph N.F. 1971; 15:107-114.
- 509 9. Brosche KU. Vorzeitliche periglazialerscheinungen im Ebrobecken in der
510 umgebung von Zaragoza sowie ein beitrag zur ausdehnung von schuttund
511 bloakdecken in zentral-und-w-teil der Iberische habinsel. Gotting Geogr Abh.,
512 1972; 60: 293-316.
- 513 10. Johnson G. Cryoturbation at Zaragoza, Northern Spain. Z Geomorph N.F.1960;
514 4:74-80.
- 515 11. Van Zuidam R. 1976. Periglacial-like features in the Zaragoza region (Spain). Z
516 Geomorph N.F. 1976; 20:227-234.
- 517 12. Bomer B. Les phenomenes periglaciares dans le Bassin de l'Ébre et ses marges
518 (Espagne).In: Colloq. Perigl. d'*altitude du domaine Méditerranéen et abords.*
519 Strasbourg 12-14 mai 1977. Assoc Geogr. D'Alsace, pp 169-176.

- 520 13. Simón JL, Soriano A. Diapiric deformations in the Quaternary deposits of the
521 central Ebro Basin, Spain. *Geol. Mag.* 1986; 123: 45-57.
- 522 14. Lewis C, McDonald E, Sancho C, Peña-Monne JL, Rhodes E. Climatic
523 implications of correlated Upper Pleistocene glacial and fluvial deposits on the
524 Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy.
525 *Global Planet Change.* 2009; 67: 141-152.
- 526 15. Boixadera J, Poch RM, Lowick SE, Balasch JC. Loess and soils in the eastern
527 Ebro Basin. *Quat Int.* 2015; 376: 114-133.
- 528 16. Rodríguez-Ochoa R., Balasch JC, Olarieta JR et al. Loess deposits in the lower
529 Ebro Basin (NE Iberian Peninsula). In: Simó I, Poch RM, Pla I, eds.
530 *Proceedings of the 1st World Conference on Soil and Water Conservation under*
531 *Global Change-CONSOWA.* Lleida: Universitat de Lleida; 2015: 103-106.
- 532 17. Quirantes J. *Estudio Sedimentológico y Estratigráfico del Terciario Continental*
533 *de los Monegros.* Zaragoza: Instituto Fernando el Católico (CSIC); 1978.
- 534 18. Calle M, Sancho C, Peña JL, Cunha P, Oliva-Urcia B, Pueyo E. La secuencia de
535 terrazas cuaternarias del río Alcanadre (provincia de Huesca): Caracterización y
536 consideraciones paleoambientales. *Cuad Inv Geogr.* 2013; 39: 159-178.
- 537 19. Sancho C, Calle M, Peña-Monné JL et al. Dating the Earliest Pleistocene
538 alluvial terrace of the Alcanadre River (Ebro Basin, NE Spain): Insights into the
539 landscape evolution and involved processes. *Quat. Int.* 2016; 407: 86-95.
- 540 20. Miall AD. Lithofacies types and vertical profile models in braided river
541 deposits: a summary. In: Miall AD, ed. *Fluvial Sedimentology.* Can. Soc. Pet.
542 *Geol. Mem.* 1977; 5: 597-604.
- 543 21. Schoeneberger PJ, Wysocki DA, Benham EC. *Field Book for Describing and*
544 *Sampling Soils.* V. 3.0. Lincoln, USA: National Soil Survey Center; 2012.

- 545 22. CBDSA (Comisión del Banco de Datos de Suelos y Aguas). SINEDARES.
546 Manual para la Descripción Codificada de Suelos en el Campo. Madrid:
547 Ministerio de Agricultura, Pesca y Alimentación; 1983.
- 548 23. Soil Survey Staff. Keys to Soil Taxonomy, 12th ed. Washington: US Department
549 of Agriculture; 2014.
- 550 24. Walkley, A, Black IA. An examination of the Degtjareff method for determining
551 soil organic matter, and a proposed modification of the chromic acid titration
552 method. Soil Sci. 1934; 37: 29-38.
- 553 25. Bullock P, Fedoroff N, Jongerius A, Stoops G, Tursina T. Handbook for Soil
554 Thin Section Description. Wolverhampton: Waine Research Publ. 1985.
- 555 26. Stoops G. Guidelines for Analysis and Description of Soil and Regolith Thin
556 Sections. Madison, Wisconsin: Soil. Sci. Soc. Amer. Inc.; 2003.
- 557 27. Fox CA, Protz R. Definition of fabric distributions to characterize the
558 arrangement of soil particles in the Turbic Cryosols. Can J Soil Sci. 1981; 61:
559 29-34.
- 560 28. Rhodes EJ. Dating sediments using potassium feldspar single-grain IRSL: Initial
561 methodological considerations. Quat Int. 2015; 362: 14-22.
- 562 29. Castañeda C, Gracia FJ, Rodríguez-Ochoa R et al. Origin and evolution of
563 Sariñena Lake (central Ebro Basin): A piping-based model. Geomorphology
564 2017; 290: 164-183.
- 565 30. Lisiecki, LE, Raymo, ME. A Pliocene-Pleistocene stack of 57 globally
566 distributed benthic $\delta^{18}\text{O}$ records. Paleoceanogr. 2005; 20: PA 1003.
- 567 31. Vandenberghe J. Cryoturbations. In: Clark MJ, ed. Advances in Periglacial
568 Geomorphology. New York: Wiley; 1988: 179–198.

- 569 32. Vandenberghe J. Cryoturbation structures. In: Elias SA, ed. The Encyclopedia of
570 Quaternary Science, vol. 3. Amsterdam: Elsevier; 2013: 430-435.
- 571 33. Harris C. Mechanisms of mass movement in periglacial environments. In:
572 Anderson M, Richard K, eds. Slope Stability. London: Wiley; 1986: 531-559.
- 573 34. Van Vliet-Lanoë B. The significance of cryoturbation phenomena in
574 environmental reconstruction. *J Quat. Sci.* 1988; 3(1): 85-96.
- 575 35. Rodríguez-Ochoa R, Usón A, Olarieta JR, Herrero J, Porta J. Irrigation from the
576 sixties: Flumen-Monegros. In: Boixadera J, Poch RM, Herrero C, eds, Tour
577 Guide 8B: Soil Information for Sustainable Development. Lleida: International
578 Union of Soil Sciences; 1998: 1-51.
- 579 36. Armson KA, Fessenden RJ. Forest windthrows and their influence on soil
580 morphology. *Soil Sci Soc Amer Proc.* 1973; 37 (5): 781-783
- 581 37. Borchardt G, Taylor G, Rice S. Fault Features in Soils of the Mehrton
582 Formation, Auburn Damsite, California. Sacramento: California Division of
583 Mines and Geology; 1980.
- 584 38. Arlegui LE, Simón JL. Fracturación y campos de esfuerzos en el Cuaternario del
585 sector central de la Cuenca del Ebro. *Rev Cuat Geomorf.* 2000; 14(1-2): 11-20.
- 586 39. Peláez Montilla JA, López Casado C. Seismic hazard estimate at the Iberian
587 Peninsula. *Pure Appl Geophys.* 2002; 159: 2699–2713.
- 588 40. Bockheim JG, Tarnocai C. Recognition of cryoturbation for classifying
589 permafrost-affected soils. *Geoderma*, 1998; 81 (3–4): 281-293.
- 590 41. Van Vliet-Lanoë B, Fox C, Gubin. Micromorphology of Cryosols. In: Kimble
591 JM, ed. *Cryosols: Permafrost Affected Soils.* Berlin: Springer; 2004: 365-390.

- 592 42. Van Vliet-Lanoë B. Patterned ground and climate change. In: Podrovsky O, ed,
593 Permafrost: Distribution, Composition and Impacts on Infrastructure and
594 Ecosystems. New York: Nova Science Publishers; 2014: 67-106
- 595 43. Van Vliet-Lanoë B. Frost effect in soils. In: Boardman J, ed. Soils and
596 Quaternary Landscape Evolution. London: Wiley; 1985: 117-158.
- 597 44. Ping CL, Michaelson GJ, Kimble JM et al. Cryogenesis and soil formation along
598 a bioclimate gradient in Arctic North America. *J Geophys Res.* 2008; 113:
599 G03S12.
- 600 45. Van Vliet-Lanoë B, Coutard JP, Pissart A. Structures caused by repeated
601 freezing and thawing in various loamy sediments. A comparison of active, fossil
602 and experimental data. *Earth Surf Proc Land.* 1984; 9:553-565.
- 603 46. Tarnocai C, Smith CAS. Micromorphology and development of some central
604 Yukon paleosols, Canada. *Geoderma*, 1989. 45: 145-162.
- 605 47. Dampier L, Sanborn P, Smith S, Bond J, Clague JJ. Genesis of upland soils,
606 Lewes Plateau, central Yukon. Part 2: Soils formed in weathered granitic
607 bedrock. *Can J Soil Sci.* 2011; 91: 579-594.
- 608 48. Dimase AC. Fossil cryogenic features in paleosols of southern Italy:
609 Characteristics and paleoclimatic significance. *Quat Int.* 2006; 156/157:32-48
- 610 49. Van Vliet-Lanoë B. Frost action. In Stoops G, Marcelino V, Mees F., eds,
611 Interpretation of Micromorphological Features of Soils and Regoliths.
612 Amsterdam: Elsevier; 2010: 81-108.
- 613 50. Van Vliet-Lanoë B. The significance of cryoturbation phenomena in
614 environmental reconstruction. *J Quat Sci.* 1988; 3 (1): 85-96.
- 615 51. Vandenberghe J, Renssen H, Roche DM et al. Eurasian permafrost instability
616 constrained by reduced sea-ice cover. *Quat Sci Rev.* 2012; 34:16-23.

- 617 52. Dillon JS. Soils and Soil-Forming Processes in a Cool-Dry Environment: the
618 Upper Green River Basin, W.Wyoming U.S.A. [PhD dissertation]. Lawrence,
619 Kansas: University of Kansas; 2002.
- 620 53. Mermut AR, St. Arnaud RJ. A micromorphological study of calcareous horizons
621 in Saskatchewan soils. *Can J Soil Sci.* 1981; 61:243-260.
- 622 54. Dijkmans JWA, Koster EA, Galloway JP and Mook WG Characteristics and
623 origin of calcretes in a subarctic environment, Great Kobuk Sand Dunes,
624 northwestern Alaska, USA. *Arctic Alpine Res.* 1986; 18: 1443-1452.
- 625 55. Blank RR, Fosberg MA. Micromorphology and classification of secondary
626 calcium carbonate accumulations that surround or occur on the undersides of
627 coarse fragments in Idaho (USA). In: Douglas LA, ed, *Soil Micromorphology: A*
628 *Basic and Applied Science.* Amsterdam: Elsevier; 1990: 341-347.
- 629 56. Karlstrom ET. Relict periglacial features east of Waterton-Glacier parks, Alberta
630 and Montana, and their paleoclimatic significance. *Permafrost Periglacial Process.*
631 1990; 1: 221-234.
- 632 57. Van Vliet-Lanoë B, Dumont JL, Verrecchia E. Précipitations cryogéniques de
633 carbonates de calcium: mythe ou réalité. In: Lecolle F, ed, *Les Tufs et Travertins*
634 *Quaternaires des Bassins de la Seine et de la Somme, et des Régions*
635 *Limitrophes.* Caen: Centre Géomorphol. Bull. 1990; 38: 55-66.
- 636 58. Courty MA, Marlin C, Dever L, Tremblay P, Vachier P. The properties, genesis
637 and environmental significance of calcitic pendants from the High Arctic
638 (Spitsbergen). *Geoderma*, 1994; 61: 71-102.
- 639 59. Vogt T, Corte AE. Secondary precipitates in Pleistocene and present cryogenic
640 environments (Mendoza Precordillera, Argentina, Transbaikalia, Siberia, and
641 Seymour Island, Antarctica). *Sediment.* 1996; 43: 53-64.

- 642 60. Dillon JS, Sorenson CJ. Relict cryopedogenic features in soils with secondary
643 carbonate horizons, W.Wyoming, USA. *Permafr Periglac Process.* 2007;18(3):
644 285-299.
- 645 61. Murton JB, Coutard JP, Lautridou JP, Ozouf JC, Robinson DA, Williams RBG.
646 Physical modeling of bedrock brecciation by ice segregation in permafrost.
647 *Permafr Periglac Process.* 2001; 12: 1127-1129.
- 648 62. Brock AL, Buck BJ. A new formation process for calcic pendants from
649 Pahranaagat Valley, Nevada, USA, and implication for dating Quaternary
650 landforms. *Quat Res.* 2005; 63: 359– 367.
- 651 63. Blanco Chao R, Costa Casais M, Martínez Cortizas A, Pérez Alberti A,
652 Trenhaile AS. Evolution and inheritance of a rock coast: western Galicia,
653 northwestern Spain. *Earth Surf Proc Land.* 2003; 28(7): 757-775.
- 654 64. Andrieux E, Bertran P, Saito K. Spatial analysis of the French Pleistocene
655 permafrost by a GIS database. *Permafr Periglac Process.* 2015; 27(1): 17-30.
- 656 65. Bertran P, Andrieux E, Antoine P, et al. Distribution and chronology of
657 Pleistocene permafrost features in France: database and first results. *Boreas,*
658 2014; 43: 699–711.
- 659 66. Chorley RJ, Schumm SA, Sugden DE. 1984. *Geomorphology.* London:
660 Methuen; 1984.
- 661 67. Fuller I, Macklin M, Lewin J, Passmore D, Wintle A. River response to high
662 frequency climate oscillations in southern Europe over the past 200 ky. *Geology,*
663 1998; 26: 275-278

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668 Figure captions

669

670 FIGURE 1. Geomorphological map and soil location on Quaternary terraces in
671 the Central Ebro Basin (NE Spain).

672

673 FIGURE 2. Macro- and micromorphological cryogenic features. (a): Type 2
674 involutions. Soil SAR-18. (b) Type 6 contorted Involutions. Soil SAR-15. (c):
675 Calcitic laminar pendent rotated three times (successive vertical axes are
676 indicated by the white arrows). Soil SAR13/1, Bwk. Image PPL. (d): Carbonatic
677 laminar pendent fragmented and jacking, soil SAR-13/2 Ck1. Image PPX. (e):
678 Fragmented and rotated (arrow indicates the pendent vertical axis) calcareous
679 nodule (n) with pendants (p). Soil SAR-12, Bwk2. Image PPL. (f): Silt capping
680 (arrows) and laminar microstructure. SAR13/2 Ck. Image PPL. (g): Columnar
681 pendent with banded organization. Soil SAR-7, Bkm. Image PPX. (h):
682 Carbonatic crust with columnar pendent. Soil SAR-7, Bkm.

683

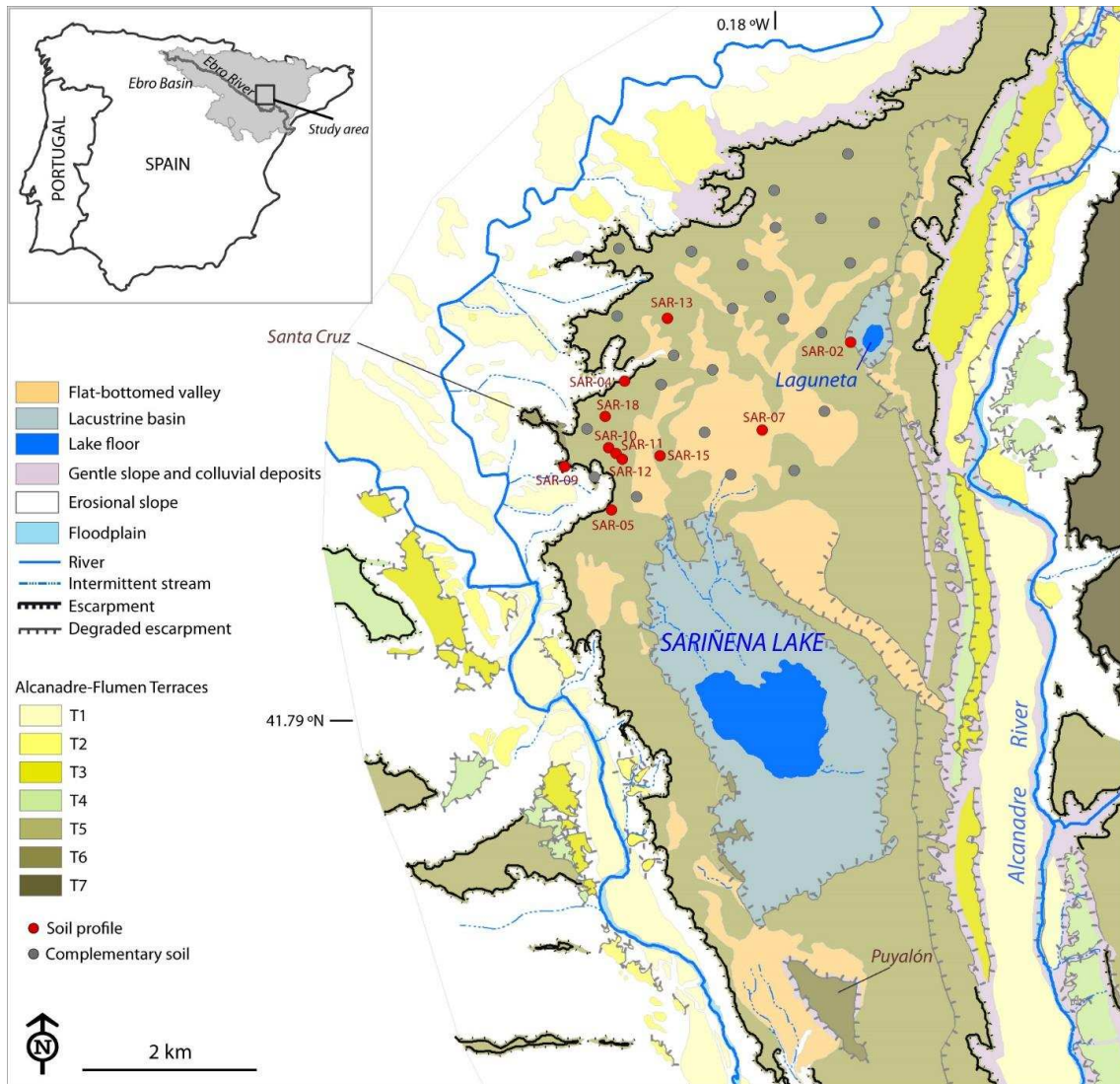
684 FIGURE 3. Columnar pendent formed under a carbonatic crust. Soil SAR-7
685 Bkm horizon. (a): Scanned soil thin section. (b): Illustrated thin section
686 highlighting different growing steps. A: Carbonate crust with reddish (r) and
687 grey (g) zones; B: Laminar pendent including Bkm fragments (f); C: Columnar
688 pendent with Bkm fragments (f) at the apices of the columns structure; D:
689 Groundmass infillings.

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Figure 1



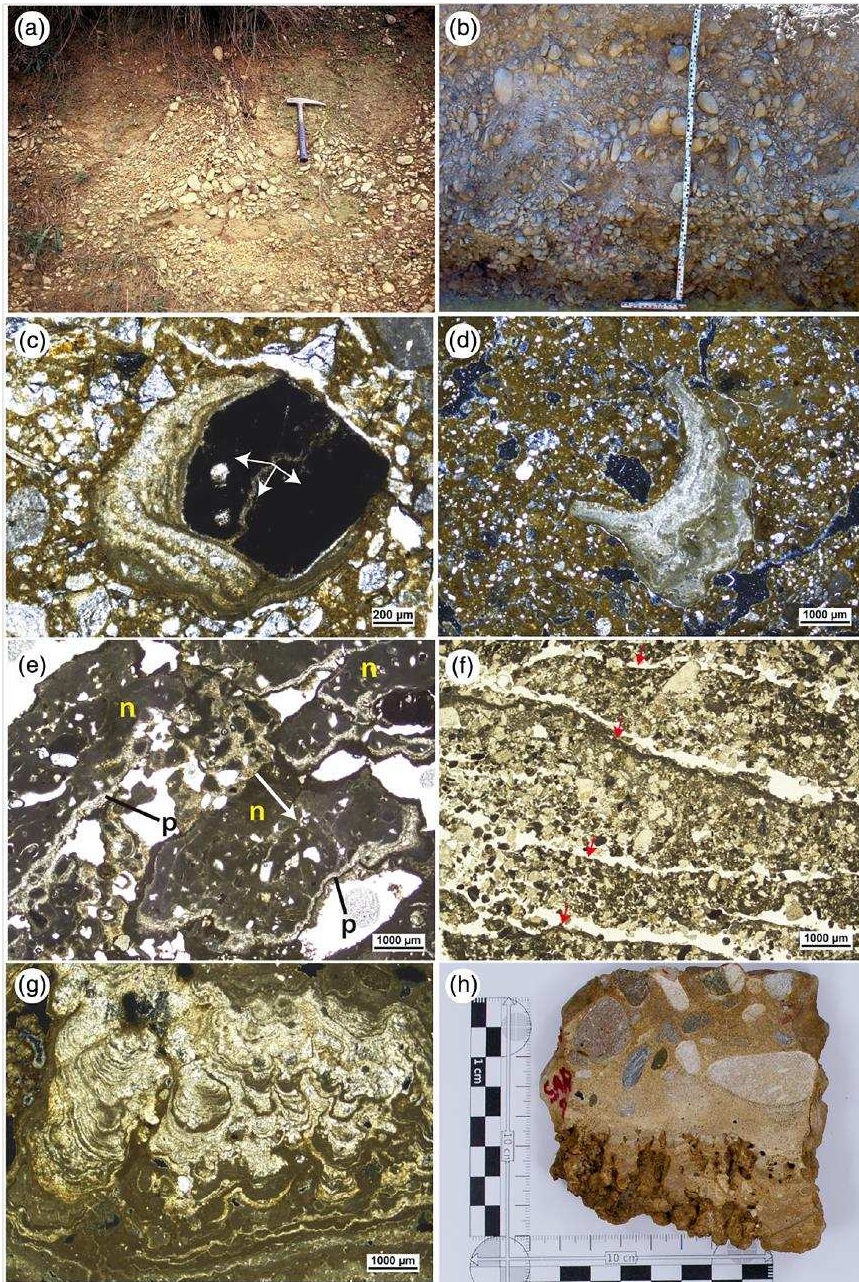
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Figure 2



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Figure 3

