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Paleosol charcoal: 12,700 years of high-altitude mediterranean vegetation history in relation to forest fires in the southwestern baetic cordillera (Spain)

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ABSTRACT

Mountain forests are sensitive ecosystems. This is why in recent years the dynamics of these forest ecotones have been researched from several different approaches. One of these has been the paleoecological perspective, which is particularly interesting in the mountainous areas of the Mediterranean region, where interactions between climate, vegetation and anthropic activities have been documented for millennia. This is the case of the Sierra de las Nieves Natural Park (southwestern Baetic Cordillera), a mountainous area that constitutes an important refuge for flora in southern Iberian Peninsula. At present, endemic trees such as *Abies pinsapo* and *Quercus faginea* subs. *alpestris* are found. However, its strategic geographical location may also have served in the past as a refuge for other tree taxa. In order to reconstruct the vegetation history in this protected natural area, this research aims to use pedoanthracological analysis in an unexplored area of this mountainous system. The results obtained have allowed to identify a new paleopopulation of *Abies*, a finding that provides new keys on the paleobiogeography of this species. This is the oldest evidence of this genus and at the highest altitude of those found to date in the southwestern Baetic Cordillera, which would confirm that this fir tree was present in high elevations of the Sierra de las Nieves during the Pleistocene-Holocene transition. Likewise, the first anthracological evidence of *Pinus nigra/sylvestris* type in the southwestern end of the Baetic Cordillera has been obtained. Forest fires could have been one of the main factors which would be determined the shaping and evolution of the vegetation landscape, as suggested by the fire events identified from the soil analysis. This information can be useful for the conservation and adaptive management of the most threatened forests and their habitats in the face of global change.

1. Introduction

Throughout the Holocene, landscapes have undergone important transformations in a context of global change, where climatic variability, paleoecological processes and increasing human activity have played a defining role in the last 12,000 years (Cunill et al., 2015; Carrión, 2022; Jiménez-Moreno et al., 2023). In this changing scenario, highlighting certain processes experienced by coniferous orophile forests, as are the altitudinal fluctuations and the extinction of populations (Bai et al., 2011; Malla et al., 2023), whose comparative study could offer valuable paleoenvironmental information with transfer possibilities (Wingard et al., 2017), especially in those mountainous areas that may have played an important role as interglacial refuges (Wieser et al., 2014; Tourville et al., 2023).

This is the case of the Sierra de las Nieves National Park (hereafter SNNP), located at the southwestern end of the Baetic Cordillera. The strategic location of this territory near the Strait of Gibraltar, in an area of geographical crossroads, has meant that its forests have been subjected to all the paleoecological dynamics experienced by the western Mediterranean region, as well as to a long process of humanisation whose consequences are largely unknown (Gómez-Zotano and Olmedo-Cobo, 2021; Pardo-Martínez et al., 2023). The current vegetation landscape is the result of a declining trend in forest cover dating back to the Holocene, particularly significant in the case of some of the

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most threatened endemics species of the Mediterranean region, such as *Abies pinsapo*, *Quercus faginea* subsp. *alpestris* or *Taxus baccata* (Alba-Sánchez et al., 2019; Cabezudo et al., 2021; Gómez Zotano and Olmedo Cobo, 2021; Olmedo Cobo et al., 2021). Local extinction processes of species currently absent in the SNNP are also presumed, as in the case of *Pinus nigra/sylvestris* type, whose macroremains have recently been found in the neighbouring Sierra Blanca de Igualeja (Gómez-Zotano et al., 2023). Greater uncertainty lies in the presence of *Cedrus atlantica*, whose native status in the Iberian Peninsula during the Quaternary period remains a subject of debate (Magri et al., 2017; Jiménez-Moreno et al., 2020). The absence of macrorremains (burned wood) of *Cedrus* in the European continent (González-Hernández et al., 2022) is compounded by the little evidence shown by this genus in the different paleopalynological diagrams available for the Iberian Peninsula (see, for example, the bibliographic compilation edited by Carrión, 2022). Both circumstances would suggest that the pollen grains identified in Iberia were likely transported by wind action from North Africa (Magri and Parra, 2002; Magri, 2012; Jiménez-Moreno et al., 2020).

The wider geographical distribution of these forest species in the past, or the reduced and fragmented current distribution of those that have survived over time, leads to the following question: Where were these species found and what determined the causes of their local extinction in much of the SNNP? There are no definite answers because knowledge of the paleobiogeography of this protected area is partial and deficient despite its uniqueness and biogeographical originality, as well as the development of methodologies and techniques for reconstructing the paleovegetation landscape in recent years.

There is consensus that the causes of the reduction of tree cover are of both natural origin, due to the gradual warming of the climate, and anthropogenic, with large forest fires being the most important (Cabezudo et al., 1998; Blanca et al., 1999; Cabezudo and Talavera, 2005; Pérez-Latorre et al., 2021). The SNNP is immersed in the present scenario of global change, where the Mediterranean region is considered to be one of the territories that is already experiencing unknown dynamics of anthropogenic origin (Giorgi, 2006; IPCC et al., 2023). Within the latter, the mountainous reliefs in its western part will be particularly affected by a decrease in precipitation and a rise in temperature (Nogués-Bravo et al., 2008). In this sense, the proven trend towards warmer and drier climatic conditions expected for the Iberian Peninsula (Giralt et al., 2017), as well as future projections (Amblar et al., 2018), compromise the viability of fir and gall-oak forests in the Sierra de las Nieves, particularly considering that these forests are already showing signs of decline, decreases in growth and reductions in their potential distribution area (Linares et al., 2010; Gutiérrez-Hernández, 2018). Moreover, the areas in the summits will be where these formations are found which are expected to be most affected in terms of biodiversity loss due to the impossibility of migration at altitude for the species that thrive there (Quézel and Médail, 2003; Huber et al., 2006; Cheddadi et al., 2017).

In spite of all these circumstances, the protected area has the characteristics of a refuge for flora, which in part means facilitating the survival of this type of biota under climatic scenarios that have changed over centuries to millennia (Keppel et al., 2012). As an example, the SNNP is home to the only representation of oromediterranean vegetation in the western Baetic Cordillera and the most southwestern one in Europe (Pérez-Latorre et al., 2021). Given the danger that this role of refuge may disappear in the near future, its identification as such is essential to analyse its potential role in recovering and safeguarding biological diversity (Hannah et al., 2014). The SNNP would thus form part of a group of refuges for flora present throughout the Baetic Cordillera in particular, and in the Mediterranean basin in general (Petit et al., 2003; Médail and Diadema, 2009). These enclaves, called cryptic Southern refugia, are particularly important during periods of warm weather for species that do not tolerate high temperatures (Stewart et al., 2010), such as *A. pinsapo* or *Q. faginea* subsp. *alpestris*.

Temporal changes in the landscape of the SNNP, as in other similar geographical areas, can be reflected in the characteristics of the supporting soils (García-Ruiz et al., 2015). This occurs because changes in vegetation cover lead to modifications in geomorphological and edaphogenetic processes, which are evident in the different soil properties and the formation of soil horizons (Chesworth, 2007). Additionally, this is also manifested through the storage of pollen and charcoal in sedimentary deposits that are subsequently subjected to edaphogenetic processes (Olmedo-Cobo et al., 2021; Pardo Martínez et al., 2023). For both reasons, it is essential to characterize soil profiles and their horizons, accompanied by laboratory analyses that provide data on their properties to offer an overview of the paleolandscape.

Therefore, the geographic-historical framework of the SNNP constitutes an interesting experimental field for recognizing the spatiotemporal dynamics of forests, as well as the needs arising from its conservation and management policies in the face of global change.

This paper aims to discuss (1) changes in the composition and structure of the tree cover during the Holocene in the SNNP; (2) the role played by this protected natural area as a refuge for flora, especially mountain conifers; (3) and explore the role of paleofire events in the configuration of the vegetation cover in the SNNP. To achieve this, the high-resolution study of forest dynamics during the Holocene is proposed through pedoanthracology, complementing previous studies conducted by Olmedo-Cobo et al. (2021), with a new pedoanthracological sampling in the geographical area known as the Plateau of Quejigales in the upper area of SNNP.

2. Material and methods

2.1. Study area

The SNNP, declared in 2021 with an area of 22,979.76 ha, is located in the western sector of the Baetic Cordillera (southern Iberian Peninsula), constituting the highest area of the southwestern Baetic Cordillera (Fig. 1). The relief is structurally controlled rendering in a very complex orography from the topography, geology and geomorphology point of view, with altitudes ranging between 300 and 2000 m a.s.l. (maximum altitude: Torrecilla Peak, 1919 m a.s.l.). The landscape is characterised as follows: river valleys in the southern and eastern sectors, with dominant peridotitic and schist lithologies; mountain ridges in the northern and western sectors, mainly composed of calcareous rock; both articulated by a raised massif and plateau in the central sector, also fundamentally constituted by calcareous rocks, affected by strong jointing and exogenous and endogenous karstic processes, as well as periglacial processes (Menjíbar-Romero et al., 2023a,b).

The experimental area of this study is located in the sector considered as high Mediterranean mountain within the national park according to the criteria of Kapos et al. (2002): land between 1500 and 2499 m a.s.l. and mean slopes exceeding 2°. Specifically, the area is located in the spot known as the Plateau of Quejigales, situated at an altitude of 1685 m a.s.l. (Fig. 1). Olmedo-Cobo and Gómez-Zotano (2017) identify in this area a Mediterranean climate variety with a semi-continental character and a subhumid-humid ombroclimate, with high mountain conditions at the summits: a hyperhumid semi-continental regime, exceeding 1300 mm y^{-1}, especially on the slopes most exposed to moist air masses from the Atlantic Ocean, and less than 9 °C of annual average temperature. Absolute minimum temperatures below −15 °C are recorded in winter months, particularly in the valley bottoms and on high altitude plateaus. The combination of several geographical factors allows it to be categorized as high mountain: altitudes above 1600 m a.s.l. occupy a sufficient extension to give the orographic entity of an elevated plateau, open to the arrival of both maritime air masses from the Atlantic and continental air masses from the interior of the European continent. The maritime thermal influence barely affects it due to the existence of relief of sufficient altitude between it and the coast, distancing it from the thermal effect of the sea. Furthermore, in the vegetation landscape, there are evidences supporting to this high

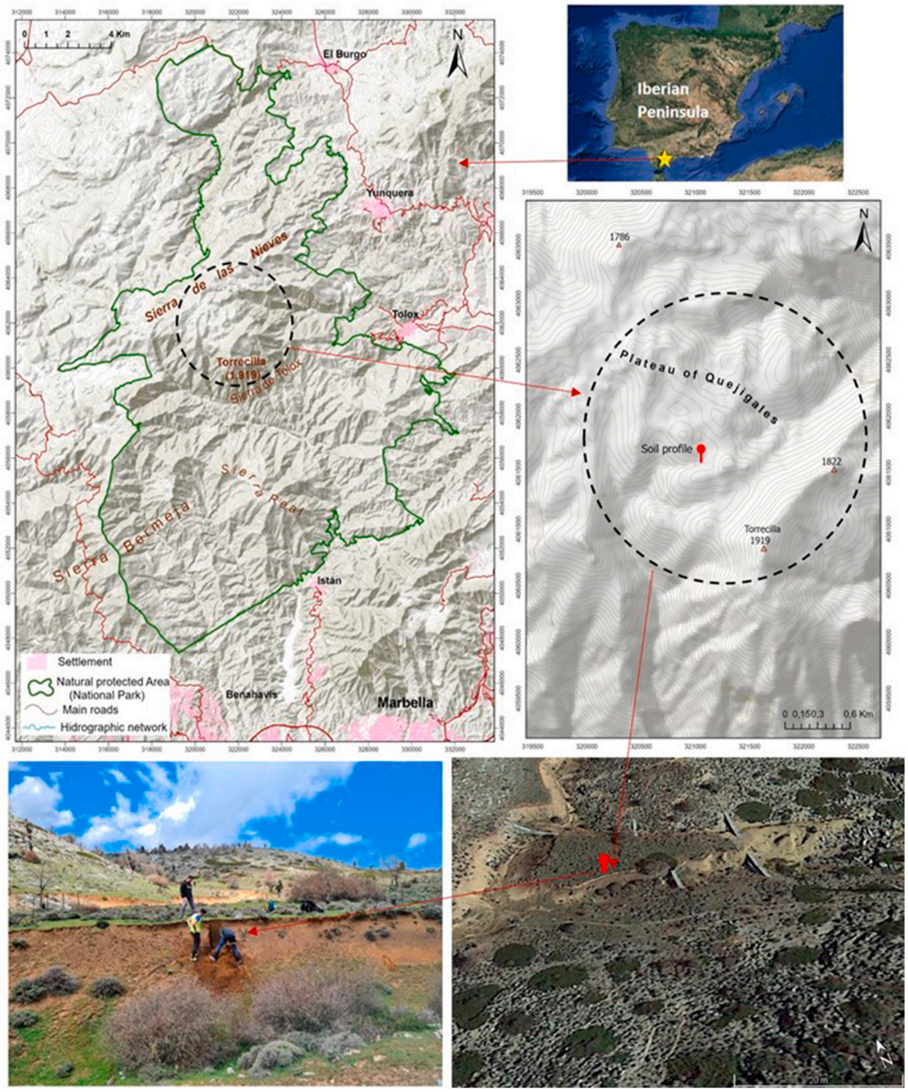

Fig. 1. Location and limits of SNNP, detailed location of the soil profile in the Plateau of Quejigales and landscape general view of the surroundings. Source: own elaboration from geo-data retrieved and modified from Centro Nacional de Descargas del IGN and Google Earth Images.

mountain character: plant species adapted to cold thermal conditions and intense winds (shrubs: *Bupleurum spinosum* L., *Juniperus sabina rastrera* L., *Erinacea anthyllis* L.; tree species: *Q. faginea* subsp. *alpestris*).

2.2. Methodology

2.2.1. Fieldwork

The charcoal samples were extracted from a soil profile opened by taking advantage of the escarpment formed by the incision and erosion process resulting from the activity of a valley bottom gully, in one of the depressions (hollows) of the Plateau of Quejigales in the SNNP (Fig. 2). This procedure followed the pedoanthracologycal protocol described by Thinon (1992) and Talon et al. (1998), later adapted by Cunill (2010). After the manual cleaning of the soil profile, this was characterized according to IUSS Working Group WRB (2022). On ce described, a total of 9 samples was collected (5–10 kg each at least), corresponding to each of the differentiated levels visually identified in the field. The vertical distribution of these samples was as follows: 0–3, 3–28, 31–50, 50–81, 81–99, 99–118, 118–132, 132–142, and >142 cm.

2.2.2. Laboratory work

2.2.2.1. Soil analysis. The samples were taken to the laboratory for air-dried and physical-chemical characterization, involving the determination of various parameters, such as colour (using Munsell charts for soil), electrical conductivity (EC) (dissolution method in distilled water 1:2 and measured using a conductivity meter), and pH (dissolution method in distilled water 1:2 and measured using a pH meter) (ISRIC, 2002). Carbonates (CO3 =) were determined using the Bertrand calcimeter method, while cations (Ca, K, Mg, and Na), cation exchange capacity (CEC), and base saturation (BS) were assessed according to Bower et al. (1952). Organic matter (OM) were determined through calcination in a muffle oven, and soil carbon (OC) was calculated applying a coefficient of 1.74 (Heiri et al., 2001). Granulometry was analysed as well by laser diffractometry for textural classification.

2.2.2.2. Charcoal analysis. The following tasks were carried out during this phase.

- Sieving. The soil samples collected in the field, once air-dried, have been sieved. Although dry sieving was possible, in this case wet

Fig. 2. General aspect of the soil profile derived from the sampling, where the IX (9) identified levels can be distinguished. Source: authors.

sieving using sieves with mesh sizes of 0.8, 2, and 5 mm has been used.

- Triage of the charcoal. During this stage of work, manual selection of the charcoal was carried out using a binocular microscope to isolate it from the mineral residue on each sieve.
- Calculation of anthracomass. This value was obtained by dividing the weight in milligrams of the charcoal from each sampling level by the mass in kilograms of the sampling, subtracting from it the weight of mineral material with a size larger than 5 mm.
- Taxonomic identification. Once selected, the charcoals has been appropriately prepared for identification. Using tweezers and a scalpel, various cuts have been made to visualize the three anatomical planes of the wood (transverse, tangential and radial), allowing the identification of key anatomical characteristics. For this purpose, an Olympus BX51 reflected light optical microscope has been used, with a magnification range between 50x and 500x. This identification has been based on different atlases of comparative wood and charcoal anatomy (Jacquiot et al., 1973; Schweingruber, 1990; Vernet et al., 2001), as well as in the reference collection of Mediterranean species. The number of fragments identified in each sampling level has been a maximum of 50, except in level IX, where only 37 charcoals have been found. The total number of taxonomically identified charcoals has been 437.
- Radiocarbon dating. 21 charcoal fragments have been dated. The laboratory selected for this task has been the Alfred-Wegener-Institut (Bremerhaven, Germany). The criteria chosen to determine which fragments should be subjected to radiocarbon dating have been primarily ecological reasons. Specifically, 15 fragments of *Abies* sp., 2 of *P. nigra/sylvestris* type, 2 of deciduous *Quercus*, 1 of *Pinus* sp., and 1 of *T. baccata.* Finally, the samples have been calibrated using Oxcal v.4.4 software and the IntCal20 database (Reimer et al., 2020), 2 sigma (95% probability).
- Analysis and interpretation of the anthracological information obtained.

3. Results

3.1. Soil properties and classification

Despite showing a tendency towards morphological uniformity and horizons with similar chromas and textures, the field review of the profile revealed complex features with the superposition of soil processes. The physical-chemical analysis indicates compartmentalization of the soil profile into two sedimentary blocks, each associated with distinct forming stages. Therefore, utilizing colour allows for a preliminary macroscopic assessment, highlighting the existence of two distinguishable units in the profile. Indeed, the wet colour (Cw) varies between HUE 2.2 YR and 5.8 YR, with dry chromas (Cd) being brownish-yellow (10 YR 5.3/5.4 YR) from the top to a depth of 99 cm. Below this depth, the tones are also brownish-yellow, but with a more variable wet HUE (3.3/5.8 YR) and less variation in the dry condition (6.4/7.6 YR) (Table 1, Fig. 3). The parent material upon which the paleosol forms exhibits yellowish wet chromas (10 YR 7.6) and brownish-yellow dry chromas (10 YR 5.8). The vertical distribution of colours may indicate the presence of a buried soil below 50 cm, under a darker wet-coloured material with higher organic matter content and a brownish-yellow hue in the dry state.

The pH values range between 6.5 and 7.5, showing a shift from slightly alkaline values up to 28 cm, slightly acidic from 31 to 132 cm, and neutral below 142 cm. Meanwhile, EC, an indicator of salinity, ranges from 0.02 (>142 cm) to 0.11 dS n^{-1} (at the surface) as the minimum and maximum values across the entire profile. This highlights a main trend of decreasing salinity with depth, indicating a non-saline soil (Table 1, Fig. 3). OM and OC, on the other hand, are more abundant in the upper section of the profile, above 80 cm, with values ranging from 7.3 to 4.2 (maximum at the surface) and 1.8 to 1.0 (>142 cm), respectively. However, the decrease from the surface is not continuous; both properties show a slight increase between 31 and 50 cm (5.8 and 3.3%), and a more pronounced increase between 50 and 81 cm, reaching 6.5 and 3.8% in organic matter and organic carbon content, respectively. This could further indicate the presence of a buried paleosol (Fig. 3). $CO^{3=}$ exhibit considerable homogeneity throughout the profile, consistently indicating almost complete absence of carbonates. Despite the low values, they distribute along the profile similarly to other properties, once again suggesting the possibility of a buried paleosol at 50 cm. Regarding cation availability at different sampled depths, two trends are observed (Table 1, Fig. 3): Ca and Na concentrations decrease from the surface to 31–50 cm, where they slightly increase, then decrease again until >142 cm, showing a slight rise. On the other hand, Mg and K cations gradually decrease from the surface to the base of the profile. The first trend is also reflected in CEC and BS, indicating a soil very low in bases due to its low values, common in silty soils over marly rocks. The rise at a depth of 31–50 cm might reinforce the hypothesis of a buried paleosol, coinciding with the increase in OM and OC at the same level, before decreasing again towards the base of the profile, revealing an ancient process of base leaching.

The particle distribution (Table 2) indicates a total sand percentage throughout the profile below 20%, with low clay contents as well. However, loam contents consistently dominate, always exceeding 75%. Gravel, on the other hand, significantly increases towards the base of the profile from the surface. Sands reach their lowest proportion at around 10–11% from 31 to 81 cm, a depth where the ancient surface of the paleosol could be located. Regarding clays, there are levels with

Table 1

Physical-chemical characterization of the Pilones profile. Abbreviations and units: sampling level (SL), depth (Prof., cm), dry colour (Cd), wet colour (Cw), pH, electrical conductivity (EC, dS n-1), organica matter content (OM, %), organic carbon content (OC, %), total content of carbonates (CO3 = , %), calcium content (Ca, meq 100g-1), potassium content (K, meq 100g-1), magnesium content (Mg, meq 100g-1), sodium content (Na, meq 100g-1), base saturation percentage (BS, %), cation exchangeable capacity (CEC, meq 100g-1), water content in field capacity (FC, %), and water content in wilting point (WP, %).

SL	Prof.	Cd	Cw	pH	CE	OM	OC	$CO^{3=}$	Ca	K	Mg	Na	BS	CEC
I	0–3	10YR5.4	10YR3.3	7.5	0.11	7.3	4.2	0.8	6.2	0.17	1.17	0.17	24.5	31.3
II	3–31	10YR5.4	10YR3.3	7.5	0.03	5.0	2.9	1.3	4.0	0.06	0.66	0.17	16.6	29.1
III	31–50	10YR5.4	10YR3.3	6.8	0.06	5.8	3.3	0.3	6.7	0.06	0.64	0.16	22.6	33.3
IV	50–81	10YR5.3	10YR2.2	6.7	0.07	6.5	3.8	1.1	10.1	0.06	0.44	0.20	28.9	37.4
V	81–99	10YR5.4	10YR3.3	6.8	0.04	4.0	2.3	0.6	5.2	0.04	0.21	0.17	18.2	30.6
VI	99–118	10YR6.4	10YR3.6	6.5	0.03	3.2	1.9	0.8	2.4	0.03	0.13	0.13	13.7	19.8
VII	118–132	10YR6.6	7.5YR4.4	6.7	0.04	2.9	1.7	0.7	2.2	0.05	0.15	0.16	14.3	18.0
VIII	132–142	10YR7.6	10YR5.6	6.6	0.03	1.5	0.9	0.6	2.3	0.03	0.18	0.15	19.4	13.5
IX	>142	10YR7.6	10YR5.8	7.0	0.02	1.8	1.0	0.6	2.6	0.04	0.20	0.16	20.0	14.8

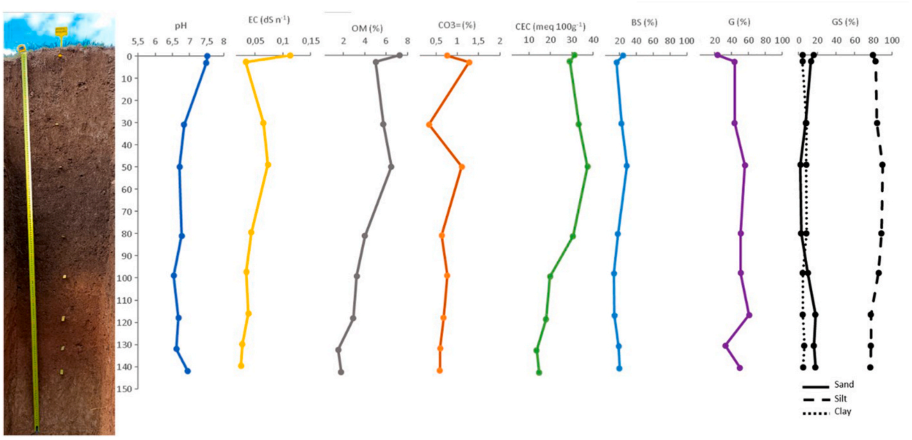

Fig. 3. Variability of the analysed soil properties along the soil profile from the study site. Abbreviations: EC, electrical conductivity; OM, organic matter; CO3 = , total carbonate content; CEC, cation exchangeable capacity; BS, total base saturation; G, gravel content; GS, grain size distribution.

Table 2

Granulometry characterization of the Pilones profile. Abbreviations and units: sampling level (SL), depth (Prof., cm), gravel content (G, %), very coarse sand (Svc, %), coarse sand (Sc, %), medium sand (Sm, %), fine sand (Sf, %), very fine sand (Svf, %), total sand (S), coarse silt (Sic, %), fine silt (Sif, %), total silt (Si, %), and clay (Cl, %).

SL	Prof.	G	S_{vc}	S_c	S_m	S_f	S_{vf}	S	Si_c	Si_f	Si	Cl	Texture
I	0–3	24	0.0	0.0	3.0	3.7	9.3	16.0	23.3	56.2	79.5	4.5	Silty loam
II	3–31	44	0.0	0.0	0.5	3.5	9.3	13.2	24.6	58.0	82.6	4.3	Silty loam
III	31–50	44	0.0	0.0	0.9	1.5	5.0	7.4	21.5	62.5	84.0	8.5	Silty
IV	50–81	56	0.0	0.0	0.3	0.3	1.4	1.9	10.6	79.5	90.1	8.0	Silty
V	81–99	51	0.0	0.0	0.0	0.1	2.8	2.8	11.1	77.6	88.7	8.5	Silty
VI	99–118	51	0.0	0.0	0.6	2.4	6.8	9.8	22.4	63.3	85.7	4.5	Silty
VII	118–132	61	0.0	0.1	4.7	4.0	9.1	17.9	22.3	55.3	77.6	4.5	Silty loam
VIII	132–142	33	0.0	0.0	2.2	4.4	9.7	16.4	27.2	50.4	77.6	6.0	Silty loam
IX	>142	50	0.0	0.1	2.5	3.9	11.6	18.2	29.8	47.2	77.0	4.8	Silty loam

proportions between 4 and 5% and around 8% at intermediate levels, coinciding with the presence of the possible paleosol. Clay mineralogical analysis reveals the presence of illite-muscovite and feldspar. Silt-sized particles dominate throughout the profile, especially around the surface of the potential paleosol mentioned on several occasions. The distribution ratio of different-sized sands shows that the coarser fractions are not present throughout the sampled profile, and the coarse fractions are almost negligible at the base. The other three sandy fractions tend to have a higher presence on the surface, up to 30 cm, decrease at this level to approximately 1 m, and then increase again towards the base, with the finer fractions being more evident. This could be related to the absence of rocks, both in the parent soil material and in the surroundings, from which weathering generates abundant coarser sand particles.

3.2. *Pedoanthracological analysis*

The total anthracomass of the sampling conducted in this research amounts to 2313.9 mg kg^{-1}. By soil levels, the deepest (IX: >142 cm) has shown the lowest anthracomass value, at 63.6 mg kg^{-1}. On the other hand, the highest anthracomass value has been calculated in level VII (118–132 cm), with a value of 545.4 mg kg^{-1} (Fig. 4).

A total of 437 charcoal fragments have been identified (Table 3). Out of these, 11 fragments (2.5%) were classified as undetermined samples. On the other hand, 46 charcoals (10.5%) were classified within the category of gymnosperms, while 26 of the analysed samples (5.9%) corresponded to angiosperms, without being able to determine a more specific taxonomic rank in any case.

By genera, *Juniperus* has been the most abundant taxon in the pedoanthracological record, being present in all analysed sampling

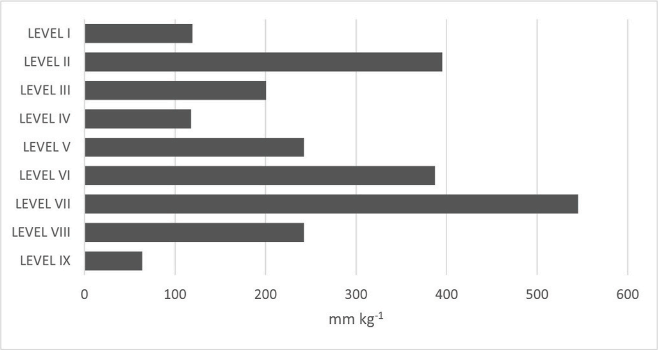

Fig. 4. Calculated anthracomass values (expressed in mg kg-1) at each of the identified sampling levels.

levels. Specifically, 162 fragments of this genus have been identified, which accounts for 37.1% of valid identifications. Other genera such as *Abies* and *Quercus* also stand out, although with more discrete percentages, with 49 (11.2%) and 36 (8.2%) fragments identified, respectively. The genus *Pinus* has been identified in 22 charcoal samples (5%). Finally, 6 of the analysed samples correspond to the genus *Acer*.

By families, Rosaceae was the most representative with 33 samples (7.6%). It is followed by Cistaceae and Caprifoliaceae with 16 (3.7%) and 10 samples (2.3%). On the other hand, families such as Ericaceae, Lamiaceae and Leguminosae have been identified in 4 of the fragments analysed (0.9%).

Finally, it is noteworthy that the species level or taxonomic group has been determined in two cases. These are *T. baccata*, of which 4 fragments have been identified, and *P. nigra/sylvestris* type, a category that has been identified in 2 of the samples analysed.

On the other hand, Fig. 5; Table 4 shows the chronologies obtained from the radiocarbon datings conducted during the course of the present research. The chronologies range from 12,738–12,671 cal yr. BP to 159-

Table 3
Taxonomic identifications (expressed in absolute numbers) by sampling levels.

Taxa	I	II	III	IV	V	VI	VII	VIII	IX	TOTAL
Abies sp.	12	6	7	8	–	–	2	7	7	49
Acer sp.	–	4	2	–	–	–	–	–	–	6
Caprifoliaceae	–	–	–	3	–	4	1	–	2	10
Cistaceae	–	–	–	3	8	3	–	2	–	16
Ericaceae	–	–	–	–	–	1	–	–	–	1
Juniperus sp.	19	25	19	19	14	11	15	23	17	162
Lamiaceae	–	–	–	1	–	–	–	1	–	2
Leguminosae	–	1	–	–	–	–	–	–	–	1
Cf. *Pinus*	–	–	–	–	3	1	–	–	–	4
Pinus sp.	–	–	–	1	5	6	8	–	2	22
Pinus nigra/sylvestris type	–	–	–	–	–	1	1	–	–	2
Quercus sp.	2	6	9	2	–	–	14	3	–	36
Deciduous *Quercus*	–	1	2	1	–	–	1	–	1	6
Rosaceae	–	–	1	6	8	12	1	2	3	33
Taxus baccata	–	–	2	–	–	–	1	1	–	4
Angiosperm	3	1	3	5	6	–	2	6	–	26
Gymnosperm	11	3	5	1	5	10	3	4	4	46
Unclear	3	3	–	–	1	1	1	1	1	11
TOTAL	50	50	50	50	50	50	50	50	37	437

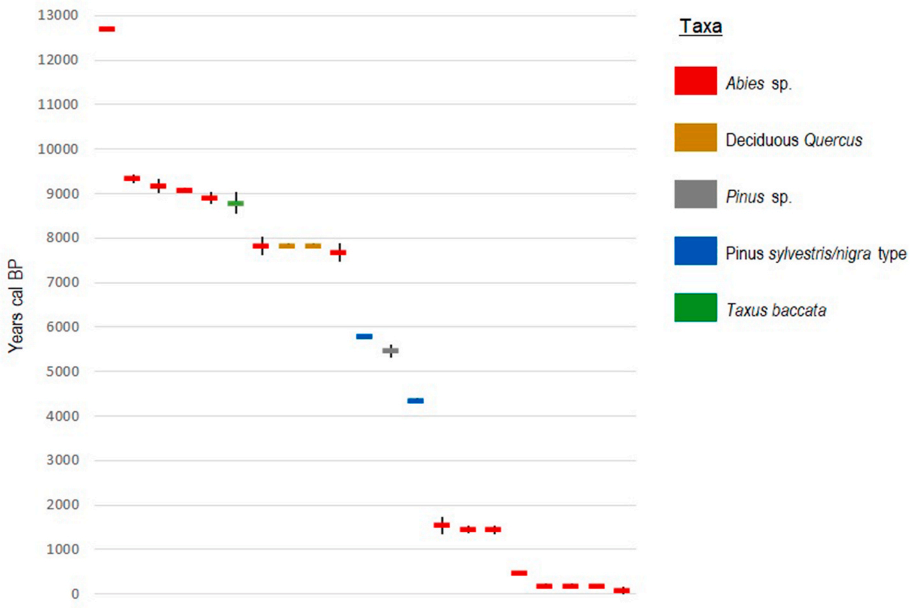

Fig. 5. Chronologies obtained for the 21 charcoal fragments dated by radiocarbon. Both the mean values (horizontal line) and the maximum and minimum values (vertical line) are shown.

Table 4
Radiocarbon dates obtained during the present investigation.

Site	Laboratory code	Sampling level	Taxa	14C age (BP)	Cal. age 2σ (cal BP)
Plateau of Quejigales	11414.1.1	IV	*Abies* sp.	10695 +- 32	12738–12671
	10684.1.1	IX	*Abies* sp.	8295 +- 27	9424–9245
	10681.1.1	VIII	*Abies* sp.	8206 +- 65	9319–9009
	10680.1.1	VIII	*Abies* sp.	8116 +- 27	9125–9042
	10685.1.1	IX	*Abies* sp.	8043 +- 38	9026–8768
	10682.1.1	VIII	*Taxus baccata*	7955 +- 95	9025–8546
	10920.1.2	VIII	*Abies* sp.	7031 +- 121	8038–7612
	10678.1.1	VII	Deciduous *Quercus*	7012 +- 26	7882–7781
	10683.1.1	IX	Deciduous *Quercus*	7021 +- 25	7880–7789
	10919.1.1	VIII	*Abies* sp.	6831 +- 128	7878–7474
	10679.1.1	VII	*Pinus nigra/sylvestris* type	5110 +- 24	5826–5752
	10686.1.1	IX	*Pinus* sp.	4773 +- 77	5603–5319
	10677.1.1	VI	*Pinus nigra/sylvestris* type	3898 +- 24	4414–4283
	10918.1.1	IV	*Abies* sp.	1656 +- 92	1722–1352
	10916.1.1	IV	*Abies* sp.	1578 ± 51	1544–1353
	10915.1.1	IV	*Abies* sp.	1560 ± 51	1536–1348
	10913.1.1	III	*Abies* sp.	380 ± 50	509–419
	11255.1.2	II	*Abies* sp.	182 ± 50	232–125
	11413.1.1	III	*Abies* sp.	177 ± 23	225–139
	11412.1.1	III	*Abies* sp.	191 ± 23	221–142
	11254.1.1	I	*Abies* sp.	153 ± 65	159–0

0 cal yr. BP.

4. Discussion

4.1. Considerations on the process of soil profile formation

In summary, the analysed profile reveals at least two soil horizons. The upper, current horizon extends from the surface to approximately 50 cm. This upper horizon shows a reduction in organic matter (OM) and organic carbon (OC) up to that depth, a loam-silty texture, alkaline pH, presence of cations without being fully saturated, albeit with evidence of leaching towards its lower part. The lower horizon, from approximately 50 cm to the base of the profile, could constitute an ancient soil fossilized by the upper horizon after a depositional dominating period. The increase in OM and OC, cations, and textural changes may be evidence of this phenomenon pending radiocarbon dating.

From an edaphological perspective, two phases are distinguished in the profile (Fig. 2). The upper part (0–50 cm depth), corresponding to the sedimentary block and the roof of the second block, is affected by edaphogenetic processes leading to the formation of a Haplic Umbrisol (FAO, 2015), with the accumulation of OM on the surface, low BS, and crumb structure. Below, buried by the preceding edaphological unit, the presence of a Cambic Umbrisol (FAO, 2015) is observed. It is characterized by an upper umbric horizon with higher OM than the overlying layer, crumb structure, very low BS, and transitionally extends in depth to the marly bedrock.

4.2. New data about composition and structure of the tree cover during the holocene in the sierra de las Nieves National Park

The data from the soil charcoal analysis have provided new insights on the patterns of change in the composition and structure of forests of the SNNP. Among the most significant findings is the discovery of the first anthracological evidence of *P. nigra/sylvestris* type in the Sierra de las Nieves, where this taxonomic group is currently not present. Additionally, pedoanthracological analysis has enabled the identification of a new paleopopulation of *A. pinsapo*, which is an important step toward to further reconstructing the distribution area of the Spanish fir in the southwestern Baetic Cordillera after the Last Glacial Maximum. The importance of this discovery lies not only in finding the oldest evidence but also at higher altitudes of *Abies* in the Sierra de las Nieves and, therefore, in the southwestern Baetic Cordillera as a whole. The chronology obtained, dated at 12,738–12,671 cal yr. BP, enabled us to delay by almost two millennia the first reference of *A. pinsapo* in the southwestern Baetic Cordillera, which until now had been established at 9931-9616 cal yr. BP in Sierra Palmitera (Sierra Bermeja) (see Gómez-Zotano et al., 2023; Pardo-Martínez et al., 2023). Finally, this study provides the first radiocarbon dating of a *T. baccata* charcoal found through pedoanthracological analysis in the southern Iberian Peninsula, dating back to 9025-8546 cal yr. BP.

This evidence is framed in a geographical context, such as southern Spain, where knowledge about the composition and dynamics of mountain forests in the past is still insufficient (Gómez-Zotano and Olmedo-Cobo, 2021; Olmedo-Cobo et al., 2021; Pardo-Martínez, 2023), especially when compared with other mountain systems in the north of the Iberian Peninsula (see, for example, the bibliographic compilation edited by Carrión, 2022).

4.3. Holocene dynamics of orophyllous pine forests in the southwestern end of the baetic cordillera

The discovery of *P. nigra/sylvestris* type charcoal in the SNNP represents a significant advance in paleoecological terms (Fig. 6). This

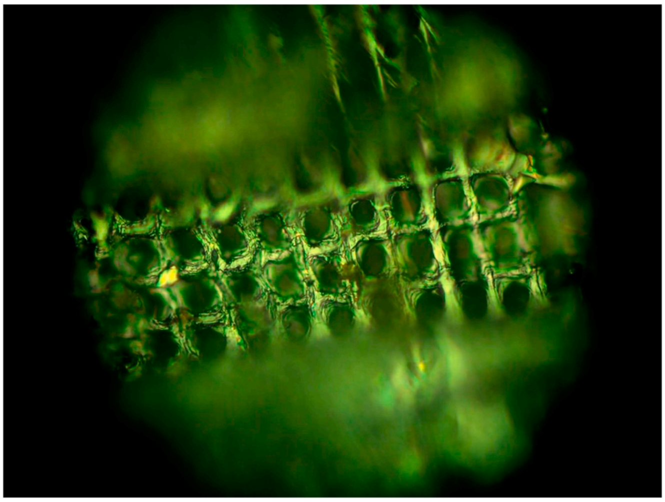

Fig. 6. Microscopic photo of the radial longitudinal plane of P. nigra/sylvestris type. Among other features, it is possible to distinguish fenestriform pits, a key characteristic of this taxonomic group.

finding, contextualised with the results obtained by Gómez-Zotano et al. (2023) in nearby mountains, provides an overview of the dynamics experienced by *P. nigra/sylvestris* type during the Holocene in the southwestern end of the Baetic Cordillera. These authors confirmed the presence of this taxonomic group in two mountainous localities near the study area: Arroyo de los Lobos 1, an enclave located at 1122 m a.s.l., with a chronology dated at 10,645 cal yr BP; and Cascajares 4, a site located at 1260 m a.s.l., where *P. nigra/sylvestris* type was present during the period between 8352–8267 and 8013 cal yr. BP. Both evidences are consistent with the conclusions of Pérez-Obiol et al. (2011), who suggested the dominance of the pine forest in large areas of the Baetic Cordillera during the Early-Holocene.

The sampling carried out in this study is located at an altitude of 1685 m a.s.l. This circumstance, together with the age of the two *P. nigra/sylvestris* type charcoal fragments identified, whose chronologies have been dated between 5826–5752 and 4414-4283 cal yr. BP, would indicate the progressive altitudinal migration that the orophilous pine forests would have experienced during the course of the Holocene, a period in which, in general, a progressive increase in temperatures was observed (Jalut et al., 2000). Our results are consistent with the general approach that mountain forests move to higher elevation during climate warmings (Gottfried et al., 2012). Our data are also consistent with other similar dynamics identified at regional level, such as in the Sierra Nevada, where Jiménez-Moreno et al. (2023) report, from the paleopalynological record analysed in Laguna Seca, several altitudinal shifts in the treeline where *P. sylvestris/nigra* type is present in response to climatic oscillations. In coastal areas relatively close to the study area, such as the Nerja and Gorham caves, anthracological analysis revealed the existence of cryophilic pine forests until the beginning of the Holocene period (Aura et al., 2002; Carrión et al., 2008; Finlayson et al., 2008). From that moment on, the anthracological evidence of these mountain conifers begins to decrease considerably, which could indicate their migration to higher altitudes in search of more optimal conditions, a hypothesis that is fully in line with our results.

The remarkable altitudinal gradient of the SNNP, whose maximum altitude reaches 1919 m a.s.l. at Torrecilla Peak, would have made it possible for *P. nigra/sylvestris* type to take refuge in this mountainous system during most of the Holocene. Both the causes of its disappearance and the specific moment of its definitive extinction in the southwestern end of the Baetic Cordillera are more uncertain. On the one hand, Pérez-Obiol et al. (2011) point out that it is very likely that the decrease in precipitation and the increase in the aridification process during the Late Holocene could have caused the reduction of forest species, including *Pinus*, in the mountainous areas of the Iberian Peninsula. In the specific case of the Sierra de las Nieves, the palynological analysis carried out by Alba-Sánchez et al. (2019) in the Cañada de las Ánimas (1403 m a.s.l.) identified *P. nigra/sylvestris* type pollen with chronologies between ~1180 and 1400 cal yr. AD. However, this is a very small percentage (3.9–0.8%), which does not guarantee that this taxonomic group could be locally present in the sampling area. In addition, the last anthracological evidence of *P. nigra/sylvestris* type at high altitudes in the Sierra de las Nieves appears between 4414 and 4283 cal yr. BP (4483-4228 cal yr. BP in the case of *Pinus* sp., according to the study carried out by Olmedo-Cobo et al. (2021)).

4.4. *New paleobiogeographical evidence of A. pinsapo, Q. faginea subsp. Alpestris and T. baccata*

The present research has allowed the discovery of a new paleopopulation of *A. pinsapo* in the southwestern Baetic Cordillera, the second to be identified in the SNNP, after the one previously discovered by Olmedo-Cobo et al. (2021) on the site known as Fuenfría Alta. Although it is true that the sampled locality is relatively close (~1 km) to the natural distribution range of this fir (Fig. 7), the new chronologies obtained represent an important step forward to further unveil the Holocene dynamics of the species and the role played by the Sierra de las Nieves as a refuge for mountain conifers.

This finding adds to the advances made by Gómez-Zotano et al. (2017, 2021), Olmedo-Cobo et al. (2017), Pardo-Martínez et al. (2021), Gómez-Zotano et al. (2023) and Pardo-Martínez (2023), who previously identified up to 4 localities where *Abies* is currently absent: Sierra Palmitera (1), Sierra del Oreganal (1) and Sierra Blanca de Igualeja (2). In addition to these, a paleopopulation was found during the course of this research, identified in the site known as Plateau of Quejigales (1685 m a.s.l.), in the SNNP. The paleoecological revelance of this finding is also due to the fact that it represents the oldest evidence of *A. pinsapo* (12, 738–12,671 cal yr. BP) and at the highest altitude (almost 1700 m a.s.l.) of those found to date. Our results would confirm that Spanish fir was

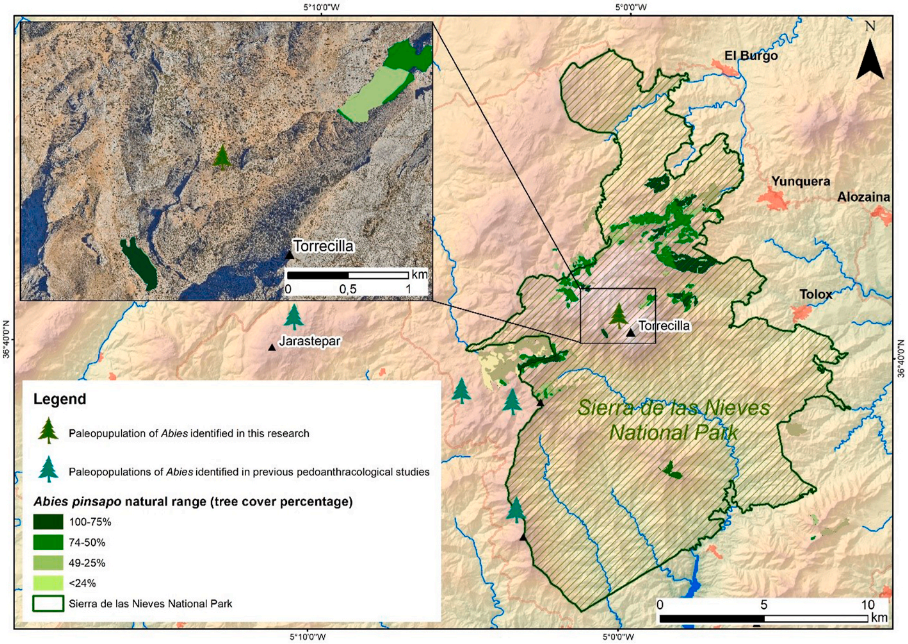

Fig. 7. Paleopopulation of Abies found in the study area. Source: own elaboration based on REDIAM information layers.

present at high altitudes in the Sierra de las Nieves during the Younger Dryas (12,900–11,700 cal yr. BP), coinciding with the return to colder conditions (Rasmussen et al., 2014). According to various paleopalynological approaches (see Carrión, 2022), this period meant an increase in the percentages of *Abies* pollen in different enclaves of the southern Iberian Peninsula, reporting a possible expansion of this genus in areas of low and mid-altitude (current upper thermomediterranean and lower mesomediterranean bioclimatic floors) (Alba-Sánchez et al., 2018; Alba-Sánchez and López-Sáez, 2013). However, anthracological evidence from our study has shown that this taxon was also present in higher areas of the southwestern Baetic Cordillera during the late Upper Pleistocene, a time in which the high mountain areas of the Sierra de las Nieves could have been under the influence of conditions typical of the upper oromediterranean and even cryo-mediterranean bioclimatic floor (Badal et al., 2013). Unlike other locations at lower altitudes (<1500 m a.s.l.), where the Spanish fir is no longer present today, such as Sierra Palmitera and Sierra del Oreganal, the chronologies obtained would confirm that this fir has managed to survive in the highest areas of the southwestern Baetic Cordillera for the last ~13,000 years.

Likewise, the present research provides new dates for two fragments of deciduous *Quercus*, whose chronologies are between 7882 and 7781 cal yr. BP. These samples probably correspond to *Q. faginea* subsp. *alpestris* since, in addition to the unfavourable conditions for holm oaks or kermes oaks (Pérez-Latorre et al., 2021), several old specimens of mountain gall oak are currently preserved in the area around Plateau of Quejigales, which would allow us to affirm that this singular tree formation has been present here for at least the last ~8000 years. This information, contextualised with the chronology obtained for a fragment of *Abies* (7878-7474 cal yr. BP), would suggest the coexistence in the past of mountain gall oak and Spanish fir at high altitudes in the SNNP.

The paleoecological contribution of this research also includes *T. baccata*, a taxon that shows important knowledge gaps from a paleobiogeographycal point of view (Uzquiano et al., 2015; Beato-Bergua et al., 2019). Although this work is not the first pedoanthracological evidence of this species in the Sierra de las Nieves (see Olmedo-Cobo et al., 2021), it does provide the first radiocarbon dating of yew charcoal in the SNNP, with the age of this sample being 9025-8546 cal yr. BP. This is not the case in other mountainous areas of the Iberian Peninsula, especially in the north of this territory, such as the Cantabrian Mountains and the Pyrenees, where several chronologies of *T. baccata* are available (Beato-Bergua et al., 2019; Uzquiano et al., 2015; Saulnier et al., 2020).

Although new radiocarbon dates are needed to further investigate the Holocene evolution of yew, our data represent a first step towards revealing the paleobiogeography of this species in the southwestern Baetic Cordillera, a mountainous region that constitutes the southern limit of yew distribution in the Iberian Peninsula and one of the European Mediterranean areas where this conifer is most threatened (Serra and Garcia-Marti, 2008).

4.5. *Fire as a key factor in vegetation landscape dynamics*

The new dates obtained, a total of 21, are added to those previously obtained by Gómez-Zotano et al. (2017, 2023), Olmedo-Cobo et al. (2017, 2019a,b), and Pardo-Martínez et al. (2021, 2023), providing up to 131 chronologies for the southwestern Baetic Cordillera as a whole (Fig. 8). 50 of these chronologies correspond to the SNNP. This information significantly improves the knowledge gap about fire history in the southwestern Baetic Cordillera, unlike in other mountainous areas in the north of the Iberian Peninsula, where this topic has been extensively studied by authors such as Bal et al. (2011), Pérez-Obiol et al. (2016), Carracedo et al. (2018), Leunda et al. (2020) and Sánchez-Morales et al. (2022), to name a few.

The data obtained provide a detailed understanding of the occurrence of local fires in this SNNP over the last ~13,000 years. Ultimately, this important paleofire network, covering from 12,738–12,671 cal yr. BP to the present, supports the idea that fire has historically played a key role in the vegetation landscape configuration of the Sierra de las Nieves, in line with Pardo-Martínez et al. (2023) for other mountainous locations in the southwestern Baetic Cordillera. The same claim can be extrapolated to the southwestern Mediterranean region as a whole, as pointed out by authors such as Bond and Keeley (2005), Turner et al. (2008) and Vannière et al. (2008).

The nature of these fires (or fire events) presents greater uncertainty, as determining the natural or anthropogenic origin from a charcoal with a specific date is a very complicated task (Saulnier et al., 2020).

In general terms, fire activity in the Early Holocene (11,700–8200 cal yr. BP) could be due to natural factors. Firstly, because human presence in high altitude areas of the SNNP during this period would have been very limited (Gómez-Zotano, 2004, 2006; Ramos-Muñoz et al., 2017; Castaño-Aguilar, 2021). Meanwhile, several paleoecological records report a possible correspondence between the increased fuel load in the landscape and the increase in fire activity in different areas of the Baetic Cordillera, whose peaks ocurred between 11,000–10,200 and 9400-8400 cal yr. BP (Carrión, 2022; Jiménez-Moreno et al., 2023). This

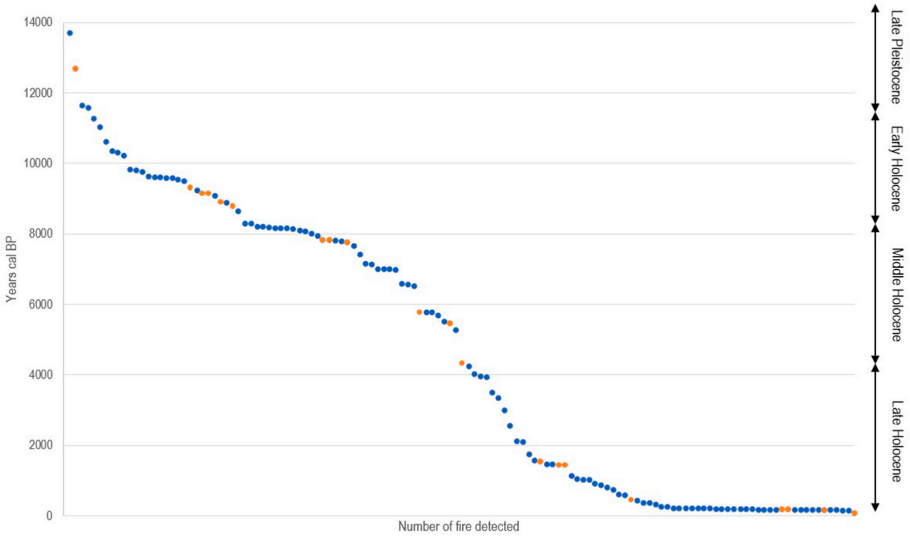

Fig. 8. Evidences of fire detected in the southwestern Baetic Cordillera as a whole. The signs detected during this research are shown in red.

is a dynamic that coincides with the observed increase in temperatures that occurred during the beginning of the Holocene period (Jalut et al., 2000), which would cause, among other consequences, an increase in tree cover in large areas of medium and high mountains (Blanco and Casado, 1997; Carrion et al., 2007; Jiménez-Moreno and Anderson, 2012). This trend could also have been reflected in the Sierra de las Nieves, as suggested by the high number of fire events dated between 9810 and 8672 cal yr. BP (mean values) that have been identified from the pedoanthracological record.

During the Middle Holocene (8200-4200 cal yr. BP), the fires detected in the study area could have had both natural and anthropogenic origins. The progressive trend toward arid conditions which started in the previous period (Cacho et al., 2001), coincides with the process of Neolithization of the southern Iberian Peninsula, with chronologies ranging between 7700 and 7300 cal yr. BP (Mejías-García et al., 2023). Our data reveal breaks in fire activity at various times during Early Neolithic (7500-6750 cal yr. BP), as well as in the Middle Neolithic (6750-5500 cal yr. BP) and during the period between 5300 and 4300 cal yr. BP, coinciding with the first manifestations of the Chalcolithic in the south of the Iberian Peninsula (Mejías-García et al., 2023). This hypothetical reduction in fire activity could be due to the lower forest cover that would exist at this time as a consequence of the aridification and cooling that the climate experienced around 7000 years, a trend that intensified after ~6000-5000 years, as pointed out by Pérez-Obiol et al. (2011) and Jiménez-Moreno et al. (2023).

During the Late Holocene (4200 cal yr. BP-present) contrasting trends can be identified. The chronologies obtained suggest a lower incidence of fire during the period between 3500 and 1800 years, which could probably be related to a negative NAO phase, resulting in a wet period detected between ~3100 and 1600 years (Martín-Puertas et al., 2008; Ramos-Román et al., 2016). During the last ~1500 years there has been an intensification of fire activity in the southwestern Baetic Cordillera as a whole, coinciding with a period characterised by intense climatic oscillations on a centennial scale in the south of the Iberian Peninsula (Ramos-Román et al., 2016). In general terms, this time is framed within a climatic context characterised by an initial trend towards increasing aridity (Jalut et al., 2000). This dynamic would be briefly interrupted during the Medieval Climatic Optimum (950–1250 AD), a time span that in the southern peninsular resulted in a warmer and wetter climate (Font-Tullot, 1988), although it would intensify again during the Little Ice Age (1300–1850 AD), which, in addition to being arid, marked a return to colder conditions (Oliva et al., 2018). This is the framework within which our data report the occurrence of a high number of fire events, a scenario that could have been unfavourable for the vegetation of the southwestern Baetic Cordillera. These results are consistent with the conclusions obtained by Alba-Sánchez et al. (2019) from the only pollen analysis available in this protected natural area. These authors report a significant decline in the forests of the Sierra de las Nieves over the last few centuries, which can also be observed in the southwestern Baetic Cordillera as a whole (Gómez-Zotano and Olmedo-Cobo, 2021; Pardo-Martínez et al., 2023), highlighting the 19th century disentailments and the consequent emergence of the farmhouses related to transhumant livestock farming. This dynamic is framed within a context of strong anthropisation of the natural environment in the mountains (Goméz-Zotano and Olmedo-Cobo, 2021). It is therefore very likely that the anthropogenic activities had a greater impact than the natural factors in reducing the surface extent of unique tree formations such as Spanish firs and mountain oaks. In fact, in the case of the Spanish firs, it could have been the point of no return for some of the populations that were once present in the SNNP (Alba-Sánchez et al., 2019; Pardo-Martínez, 2023).

5. Conclusions

This study has provided new keys about the Holocene dynamics of the forests of the SNNP. The main results obtained from the pedoanthracological analysis include the discovery of the first evidence of *P. nigra/sylvestris* type in this protected natural area. It has also been possible to identify a new paleopopulation of *Abies*, which is also the oldest evidence of this genus found to date in the southwestern Baetic Cordillera. Finally, the first chronology obtained from the radiocarbon dating of a fragment of *T. baccata* is provided.

From a paleoecological point of view, the information obtained represents an important step forward to further improve the knowledge gap about the flora refugia in southern Europe. Our data would confirm the important role that the southwestern Baetic Cordillera, and especially the Sierra de las Nieves, played as a refuge for mountain conifers after the Last Glacial Maximum. Likewise, the paleofire network generated over the last few years provides information on the extent to which forest fires would have had on the configuration of the vegetation landscape of the southwestern Baetic Cordillera during the last ~13,000 years.

The results demonstrate, once again, the usefulness of pedoanthracological analysis to understand the paleoecological dynamics of orophilous tree species such as *A. pinsapo*, *Q. faginea* subsp. *alpestris*, *P. nigra/sylvestris* type and *T. baccata*. These are ecosystems that are particularly sensitive to any type of disturbance, being considered an important indicator of ecological monitoring in an uncertain context such as that of global change. In addition to the pedoanthrological data, it will be necessary to add, in future research, dating of the sediment in which the identified charcoals were found. This will make it possible to complete the paleogeographic reconstruction of the study area and the eco-geomorphological processes that occurred within the framework of the dynamics of climatic fluctuations and anthropogenic pressures.

It is therefore necessary to continue analysing the vegetation landscape of the SNNP from a paleoecological perspective. This includes continuing to expand the network of pedoanthracological sampling to unexplored zones of this protected natural area. This would provide new evidence on how anthropogenic impact and historical climate variability have affected the dynamics of the mountain forests of the SNNP, an information that could be implemented in the management of the most threatened habitats.

Data availability

All data used in the analysis for this study are included in the manuscript and supplementary files.

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CRediT authorship contribution statement

Rubén Pardo-Martínez: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Mario Menjíbar-Romero:** Writing – review & editing, Supervision, Methodology, Investigation. **José Gómez-Zotano:** Writing – review & editing, Supervision, Funding acquisition. **Juan F. Martínez-Murillo:** Writing – review & editing, Supervision, Funding acquisition.

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 article.

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