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Plant taphonomy and palaeoecology of Stephanian limnic wetlands in the eastern Pyrenees (Catalonia, Spain)

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Abstract

Late Pennsylvanian (Stephanian C) limnic wetlands from the Surroca-Ogassa coalfield, (eastern Pyrenees, Catalonia, Spain) are characterised for the first time based on combined sedimentological, taphonomic, and palaeoecological analysis. Peat mires occurred in floodplain settings, and they were probably formed by monospecific stands of *Sigillaria*. These mires were swept away by pyroclastic flows, which produced the accumulation and orientation of sigillarian logs on the top of the volcanoclastic deposits. Floodplains were generally devoid of vegetation, with the exception of small sphenopsid stands. *Calamites* also grew within active fluvial channels. They were accompanied by marattialean tree ferns in low-regime fluvial channels. Medullosan pteridosperms bearing *Alethopteris* foliage and *Pachytesta* seeds were extremely abundant in particular horizons and grew probably in floodplain margins covering ancient peat mires. Parautochthonous cordaitalean remains were abundant in distal alluvial deposits. ***To cite this article: C. Martín-Closas, D. Martínez-Roig, C. R. Palevol 6 (2007).***

Résumé

Taphonomie des plantes et Paléoécologie des marécages limniques stéphaniens des Pyrénées orientales (Catalogne, Espagne). Les marécages limniques du pennsylvanien supérieur (Stéphanien C) du bassin houiller de Surroca-Ogassa (Pyrénées orientales, Catalogne, Espagne) sont caractérisés, pour la première fois, à partir d'une analyse sédimentologique, taphonomique et paléoécologique combinée. Des tourbières monospécifiques à *Sigillaria* se développaient dans des environnements de plaine d'inondation fluviatile. Ces tourbières étaient balayées par des flux pyroclastique qui produisaient l'accumulation et l'orientation de grands troncs au sommet des dépôts volcanoclastiques. Les plaines d'inondation fluviatiles étaient normalement dépourvues de végétation, à l'exception de petits groupes de sphénophytes. Des *Calamites* poussaient aussi dans les chenaux fluviatiles actifs. Ils étaient accompagnés par des fougères marattiales arborescentes dans les faciès de bas régime du canal. Les ptéridospermales médulosacées à feuillage aléthoptérideen et porteuses de graines de type *Pachytesta* sont extrêmement abondantes dans

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certains niveaux et poussaient probablement dans les marges des plaines d'inondation, au-dessus d'anciennes tourbières. Les restes parautochtones de Cordaitales sont fréquents dans les dépôts d'éventail alluvial distal. ***Pour citer cet article : C. Martín-Closas, D. Martínez-Roig, C. R. Palevol 6 (2007).***

Keywords: Late Pennsylvanian; Pyrenees; Coal Swamps; Palaeobotany; Spain

Mots clés : Pennsylvanien supérieur ; Pyrénées ; Marécages à charbon ; Paléobotanique ; Espagne

1. Introduction

Late Pennsylvanian wetlands are an essential reference in the study of plant palaeoecology. The long-lasting multidisciplinary study of these environments enabled ancient plant communities to be reconstructed in a detail that is difficult to reach for other periods and contexts. Palaeoecological models of Stephanian wetlands were mainly proposed based on data from the Illinois Basin (United States). These reconstructions were significant to the understanding of plant community evolution in a period of dramatic change, palaeoclimatically driven, in the Northern Hemisphere. However, these Late Pennsylvanian (Stephanian) models of plant community reconstruction referred to coastal lowlands, i.e. paralic, mainly brackish, swamps. A second set of palaeoenvironments include the coeval freshwater or limnic wetlands, which occurred in small intramontane basins of the Hercynian Range. This type of environments was abundant in the South European sector of the chain, but only a few of them have been characterized palaeoecologically [19,25]. New data from a different sector of the Hercynian Range allow us to report relatively different plant communities in comparison to previous records, providing deeper insight into the diversity of these Stephanian upland swamps.

2. Material and methods

Two outcrops, corresponding to the abandoned opencast mines of Can Camps and Faig, were available for study in the ancient coalfield and municipality of Surroca-Ogassa (Catalonia, Spain). Detailed stratigraphic logs were constructed in these mines, which are separated and isolated from each other by faults (Fig. 1). Layer-by-layer sampling of fossil plant remains was carried out in parallel with sedimentological and taphonomic analyses. Quantitative evaluation of the composition of plant remains was undertaken in the field, following the point-quadrat technique developed by Scott [21,22]. The percentage cover data provided by this technique are considered an indicator of the standing biomass in autochthonous and parautochthonous assemblages [21]. Most plant remains found in this basin are adpressions. Permineralization was not found, as is the rule in most limnic basins. Fossil plant remains were determined based on the taxonomic studies available, especially those by Alvarez-Ramis et al. [1] and Wagner [26]. The material is housed in the Palaeontological Collection, Facultat de Geologia, Universitat de Barcelona.

3. Geological and Palaeobotanical Settings

The ancient Surroca-Ogassa Coalfield belongs to the Castellar de N'Hug–Camprodon Basin, which is the easternmost of the Late Hercynian basins described by Gisbert et al. [16] and Gisbert [15] in the eastern Pyrenees. These basins were narrow intramontane grabens formed within the Hercynian Range after the main compressive stages and synorogenic erosion. The studied basin contains a succession of Late Stephanian and Permian rocks, organised in three lithostratigraphic units. The base of the sedimentary record is represented by alluvial conglomerate and fluvio-lacustrine sandstone, shale and coal with subordinated volcanic rocks in what is known as the Boundary Unit (for 'Unitat de Trànsit'), Stephanian and Autunian in age. This unit reaches a thickness of up to 250 m in the coalfield [15]. The Boundary Unit is covered unconformably by a thick succession of red beds, Permian in age, which belong to the so-called Lower and Upper Red Units.

A depositional model for the basin during the sedimentation of the Boundary Unit was developed by Gisbert and Broutin [5] and Gisbert [15]. According to this model, the basin was elongated in shape and almost endorrheic. From east to west, the facies went from proximal alluvial fans to braided river systems draining into a distal, inundated area including lacustrine-like conditions (playa-lake). Coal was mainly formed at the edges of this distal area. The clastic inputs to the basin were mainly from the east but minor influxes were received from elsewhere. The present study refers only to the distal part of the basin.

The Stephanian and Permian succession was strongly involved in Alpine structures of the most internal

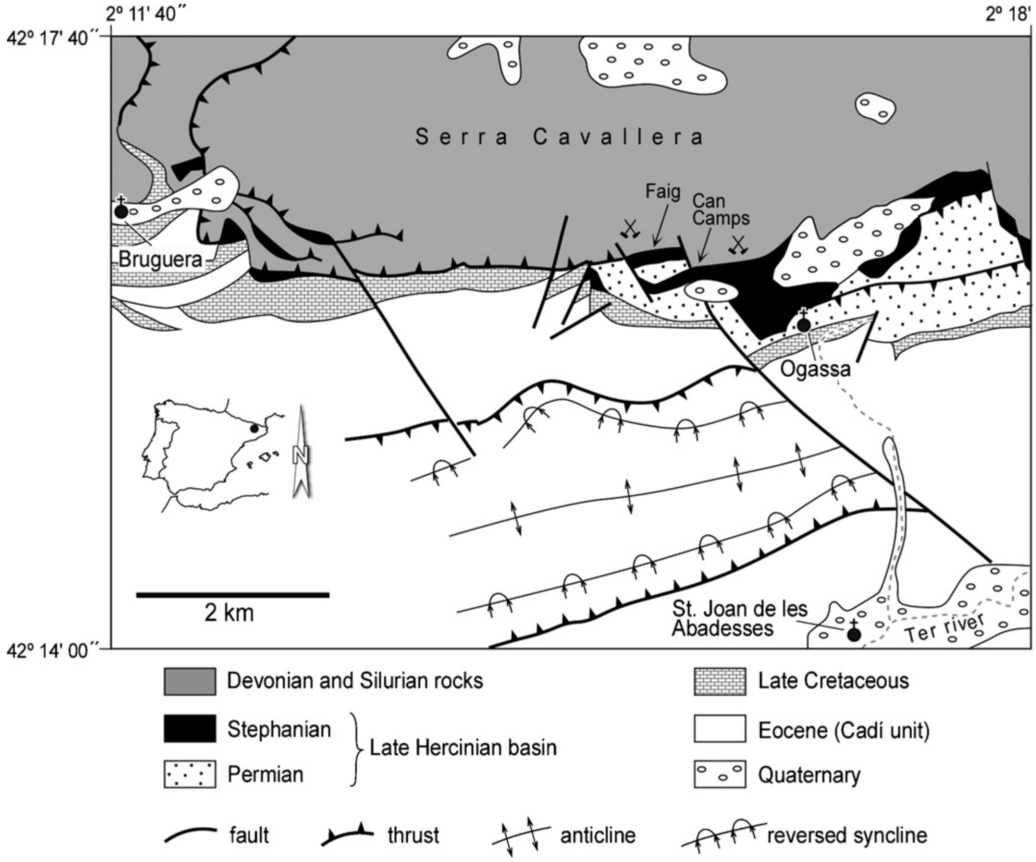


Fig. 1. Simplified geological map of the area studied. Modified from [20].
Fig. 1. Carte géologique simplifiée de la zone étudiée. Modifiée d'après [20].

part of the Pyrenean Range, mainly during Eocene times [20] (Fig. 1). Because of this important Alpine deformation and thrusting, the Stephanian–Permian units are intensely fractured, making it difficult to reconstruct into detail the original spatial relationships between today's outcrops.

The Stephanian flora of the Surroca-Ogassa coalfield was already documented in the late 19th century, when the mining district was active [23]. A first summary of fossil plant remains was provided by Faura i Sans [12], who reported about 20 taxa, determined in part by R. Zeiller (Paris). Later, Dalloni [8] provided a new list compiled by P. Bertrand (Lille). These early studies were summarized by Jongmans [18]. They were carried out in a biostratigraphic scope and a Middle–Late Stephanian age was assigned to the coal-bearing deposits. Detailed taxonomic studies were not available until the second part of the 20th century. Wagner [24,25] described *Alethopteris pennsylvanica* var. *pyrenaica* Willière, which is one of the most abundant taxa in the Faig opencast mine. Comprehensive taxonomic studies including for the first time a list of spore genera (mainly *Punctatoporites*, *Florinites*, *Densosporites*, *Acanthotriletes*, *Thymospora*, *Laevigatosporites*, *Calamospora*, *Speciososporites*, *Granasporites*, *Reticulatisporites*, and *Verrucosisporites*) were reported by Alvarez-Ramis et al. [1,2]. The macroflora reported by these authors comprised 25 morphotaxa, which were assigned to the Stephanian-C (Uppermost Pennsylvanian, according to Heckel and Clayton [17]). Diéguez [9] studied the polymorphism of *Annularia stellata* and recognized two forms in the Surroca-Ogassa coalfield. The polymorphism of *Alethopteris pennsylvanica* var. *pyrenaica* and the pteridosperm and cordaitalean ovules from Surroca-Ogassa were documented by Arnau and Vicente [5] and Arnau i Baig [3] respectively. Later, Arnau-i-Baig [4] listed more than 100 morphospecies from the basin. However, a recent revision of the flora from Ogassa, housed in the 'Museu de Ciències Naturals' from Barcelona, by Wagner [26] reduced this number to 45 morphospecies. He also provided a detailed description of a rare species, *Gondomaria grandeuryi*

(Zeiller) Wagner et Castro [27], from the coalfield. In sum, the total diversity in the basin may be evaluated at about 40 whole-plant species, most of which belong to pteridosperms and sphenopsids, with a less important contribution of ferns, lycopsids, and cordaitales.

The Autunian (Early Permian) flora of the coalfield was studied by Doubinger et al. [11], and Broutin and Gisbert [6]. This flora occurs in outcrops cartographically disconnected from those studied here, but belonging to the same lithostratigraphic unit.

4. Sedimentology

The two outcrops studied, Can Camps and Faig, show the base of the Stephanian succession in contact by fault with Devonian Limestone. The opencast mine of Can Camps (Fig. 2) shows an up-to-60-m-thick succession, which begins with alluvial conglomerates. The main thickness is represented by up to 35 m of a fluvial sequence dominated by clastic floodplain deposits and coal, which is interrupted twice by volcanic layers. The top of the series is rippled sandstone facies of the same fluvial system. A fault separates this succession from the overlying conglomerates of the Lower Red Unit. In the opencast mine of Faig, the succession begins with an alluvial layer, which is covered by 15 m of cinerite (Fig. 3). The main part of the series is formed by 30 m of floodplain siltstone, shale, and coal passing upwards to fluvial sandstone. The top is formed by a 15-m-thick conglomerate resulting from debris flows. Both Can Camps and Faig are similar in their succession of floodplain and fluvial-channel deposits upon more marginal alluvial facies. However, they differ in the abundance of volcanoclastic deposits, which are much more significant in the Faig mine. In conclusion, the two successions may represent two approximately coeval situations in different palaeogeographic positions within the basin.

4.1. Alluvial fans

Massive conglomerate layers, 1–2 m thick and with lateral continuity of more than 100 m, are found at the base of both the Can Camps and Faig sections (Figs. 2 and 3). The fabric is supported by the coarse sandstone matrix. Clasts of variable size, up to 20 cm in diameter, are mostly angular and formed by Tournaisian–Visean black cherts. Other lithologies include quartz pebbles, microconglomerate clasts from the Lower Carboniferous Culm Formation, and clasts from Devonian Limestone. In the Can Camps mine, these layers are intercalated with microconglomerates, rippled sandstone and laminated siltstone organised in 50-cm- to 1-m-thick, fining-upwards sequences.The massive, matrix-supported conglomerates are interpreted as debris-flow deposits formed in proximal areas of alluvial fans that fed into the pre-Hercynian rocks bordering the Stephanian basin. The fining-upwards cycles intercalated with the former facies may indicate the occurrence of traction deposits in relatively more distal areas of these alluvial fans. Another type of conglomerate, which contains volcanoclastic blocks, occurs on top of the Faig succession (Fig. 3). This layer is attributed to debris flow deposits of an alluvial fan feeding in the uplifted basin margins.

4.2. Floodplains

Dark grey, even-laminated siltstones and shale form the thickest deposits in both sections studied and contain abundant plant remains (Figs. 2 and 3). In the Faig mine, these deposits bear abundant siderite nodules. The monotonous siltstone succession is interrupted by rare, 10- to 50-cm-thick and a few metres long bodies of coarse sandstone showing planar cross bedding and ripple-marks. These sand bodies generally have a concave base and a flat top, but one of them, observed in the Faig mine, has a flat base and a convex top.

Laminated siltstones are attributed to the deposition of overbank, suspension-load sediment in floodplains. The dark colour and preservation of lamination indicate high organic matter content and show that they were deposited under standing, anoxic water, generally without bioturbation. The abundance of siderite nodules in the floodplain deposits of the Faig mine is attributed to high Eh and low pH conditions during early burial. Cross-bedded, sandstone bodies with concave base correspond to small channels that provided some drainage to the floodplain. The lens with a convex top observed in Faig is interpreted as an isolated hydraulic dune within the floodplain.

4.3. Fluvial channels

Up to 6-m-thick, medium- to coarse-grained, rippled sandstone constitutes the top of the succession at Can Camps (Fig. 2). The base of this body is planar on underlying laminated siltstone and is internally organised in sets of megaripples, about 30 cm thick, with planar base and undulating top. Amalgamated sets are separated from each other by 30–40-cm layers of siltstone to fine sandstone with abundant plant remains including rooting structures. The intercalation of relatively thin layers of fine-grained deposits and thick, rippled sandstone is attributed to deposition of suspended load in quiet-water

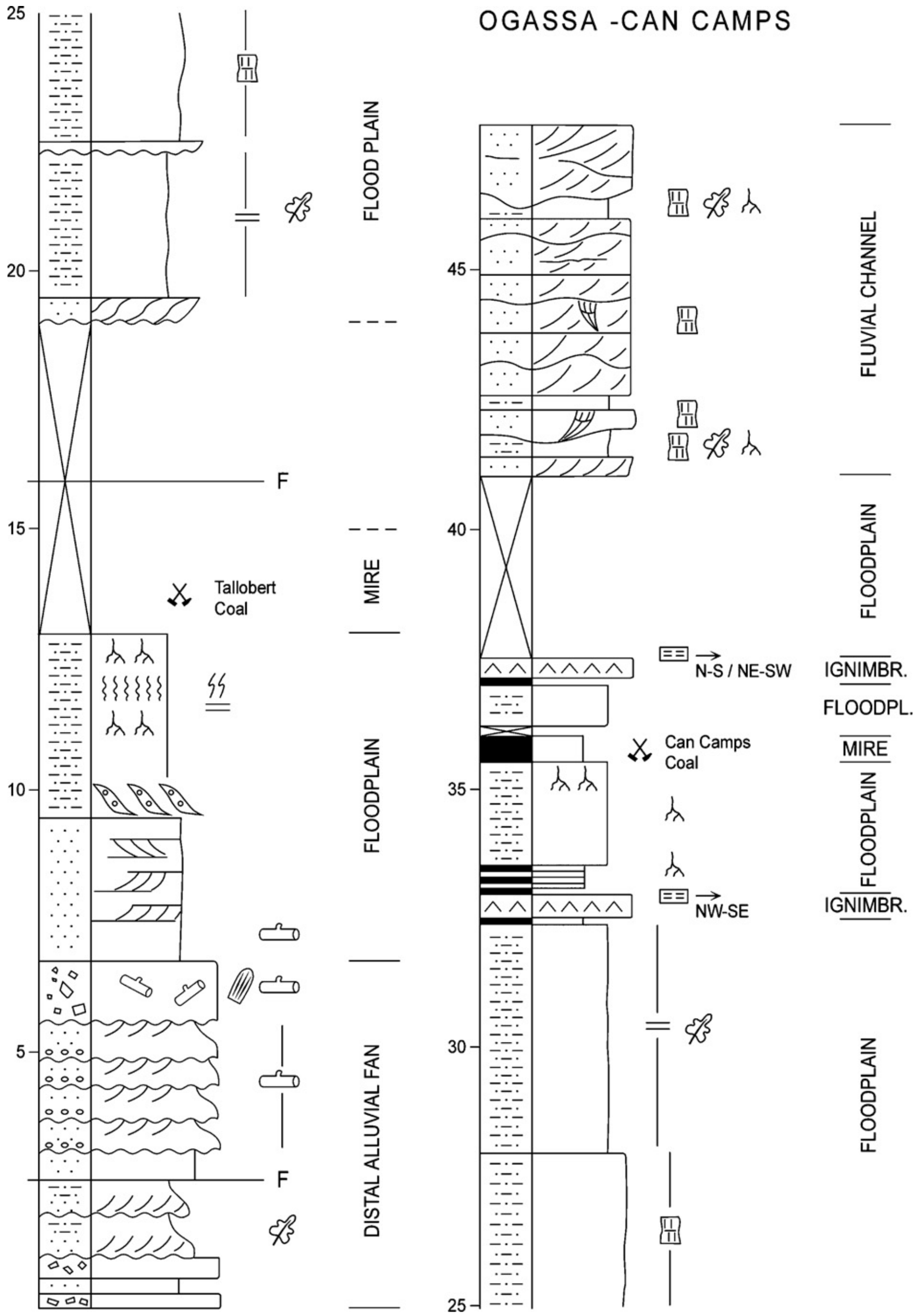
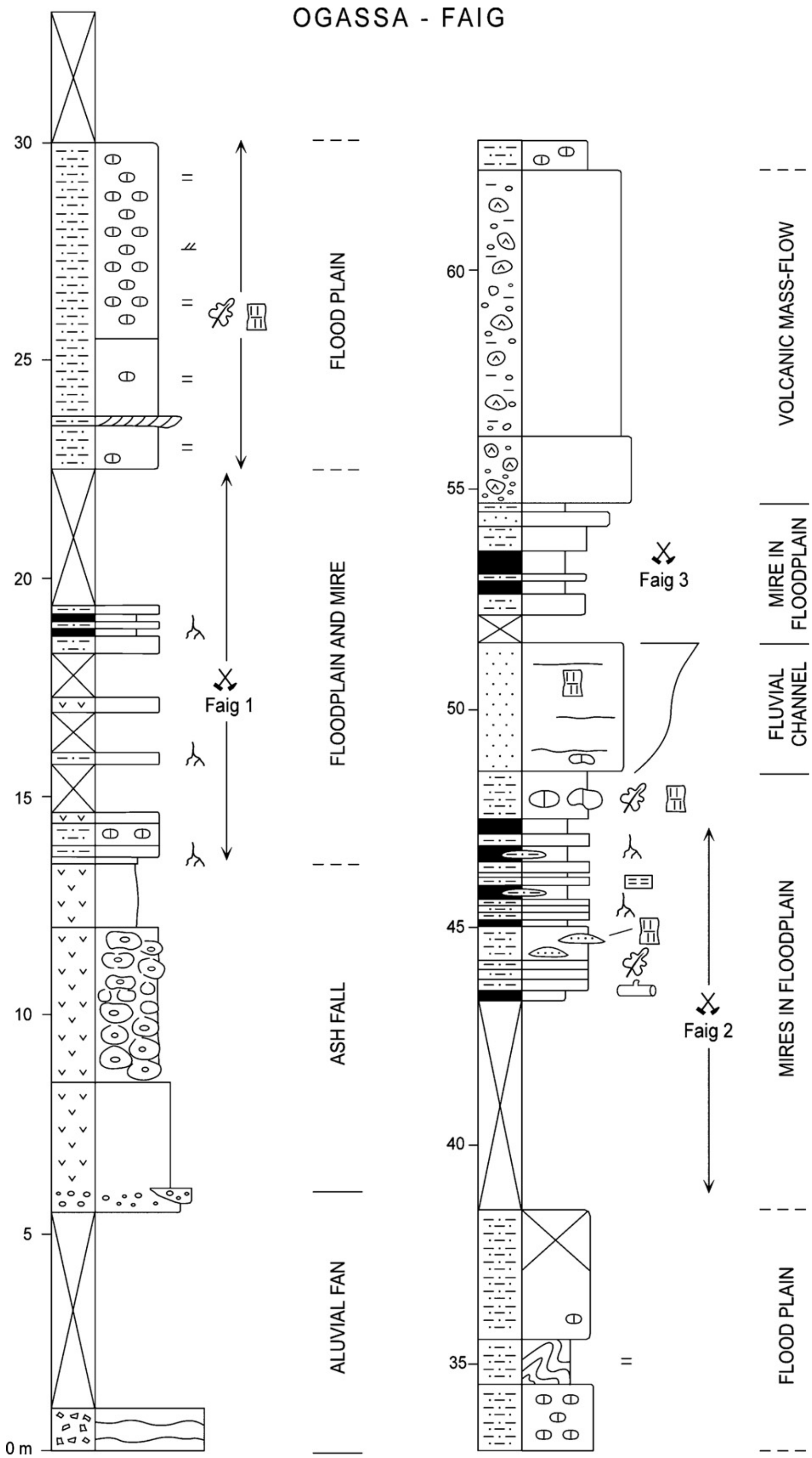


Fig. 2. Stratigraphic log, with interpretation of depositional environments in the opencast mine of Can Camps.
Fig. 2. Série stratigraphique et interprétation des environnements de dépôt dans la mine à ciel ouvert de Can Camps.

conditions after a flooding event. The river channel was transformed during these stages into a low-regime or sluggish channel that allowed helophytic vegetation to develop.

In the Faig mine, the upper part of the succession shows 7 m of medium- to coarse-grained sandstone with irregular bedding that contains towards the top a thin intercalation of floodplain shale and coal (Fig. 3). The base of the sandstone is planar, but clearly erosive on underlying beds.

These sandstone bodies are attributed to the infilling of fluvial channels based on their basal and internal features. The topmost channel at Can Camps displays features of a high sinuosity river, whilst the main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FLOOD PLAIN
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MIRE IN FLOODPLAIN
VOLCANIC MASS-FLOW

channel at Faig may be of low sinuosity. However, the limited lateral continuity of the outcrops hinders a fuller comprehension of their detailed sedimentology.

4.4. Peat mires

The main coal-seams were exploited in gallery, especially during the period 1880–1890, when the mines provided an average of 3500–4500 Tm (up to 6600 Tm) of coal per year and were the third most productive in Spain. It appears that most of the coal seams were 1–2 m thick. However, in particular places, the accumulated thickness of superposed seams reached 14 m. Analyses carried out by Closas-Miralles [7], when the main coal seams were still accessible, indicated a carbon content of 66–83% and a caloric power of 6.3–8.1 kcal.

In the Can Camps opencast mine, there were two main coal seams, the Tallobert and the Can Camps. Only the second is still available for sampling (Fig. 2). In the Faig mine, there are a number of thin (up to a few decimetres thick) coal layers accessible, especially to the top of the section (Fig. 3).

The coal layers were always intercalated in floodplain siltstones. Most coal seams preserve compressed rooting systems on bedding planes at the base of the coal bed, indicating that they were initiated by in situ accumulation of organic remains in peat mires, rather than being formed by allochthonous accumulation of organic debris. In the siltstone underlying the soil at the base of the Tallobert seam, there are abundant cylindrical and contorted burrows, preserved in siderite. These biogenic structures indicate that, before the beginning of the peat accumulation under anoxic conditions, there was a period of stabilisation under oxygenated water in the permanently inundated floodplain. This allowed the aquatic burrower fauna to thrive.

Roof shale was only available for study at the Faig mine since the whole Tallobert seam and the roof shales of the Can Camps seam were extracted during coal mining (Figs. 2 and 3). The top of the available coals in the Faig mine is planar and may contain a number of clastic partitions that pass gradually to the overlying floodplain siltstones and shale. Gradual development of roof shales from underlying coal indicates that they constituted a natural extension of peat mires during their late infilling stages (Type B roof shale of Gastaldo et al. [14]: Fig. 3).

4.5. Volcanoclastic

Two types of volcano-sedimentary deposits were recognized in the studied sections: (Figs. 2 and 3). (1) Cinerites attributed to ashfalls are abundant at the base of the Faig mine. They are generally 2–3-m massive layers of dark-red fine-grained tonsteins with a granular texture. They have 50-cm-large, concentric figures of alteration. (2) Cinerites attributed to pyroclastic flows are 50–70 cm thick, greyish; they consist of compact layers containing abundant, elongated debris of charred wood. They may show internal horizons rich in porosity attributed to degasification. These layers were exclusively found in the central part of the Can Camps section. The top of the layers shows large lycopsid logs.

5. Plant taphonomy and palaeoecology

Rooting systems that give a precise knowledge of the plant habitat in the Stephanian wetlands of the eastern Pyrenees, by comparison with depositional environments, are available in a number of layers. Other plant remains are either parautochthonous or allochthonous and the understanding of their habitat is subject to a certain degree of interpretation.

5.1. Alluvial fans

Alluvial fan conglomerates are generally devoid of plant remains in the basin. However, in Can Camps, the top of some layers is finer in grain size and contains 2–3-m-long and 30-cm-wide logs, associated with abundant cordaitalean leaves (*Pachycordaites* type) and seeds (*Cardiocarpus* sp.). In the absence of structures, characteristic of other Stephanian tree-forming plant groups, the logs are also attributed to cordaitaleans (Figs. 4.1 and 4.2). Other plant remains (pteridosperm foliage debris) are scarce and extremely fragmentary. The abundance of cordaitalean remains, the relatively good preservation of leaves, and the association of a number of different organs of the same plant group suggest that the assemblage of cordaitalean remains is parautochthonous in distal alluvial fan facies.

5.2. Floodplains

Laminated siltstones and shale contain the largest diversity of plant remains in the section studied. In the

Fig. 3. Stratigraphic log, with interpretation of depositional environments in the opencast mine of Faig.

Fig. 3. Série stratigraphique et interprétation des environnements de dépôt dans la mine à ciel ouvert de Faig.

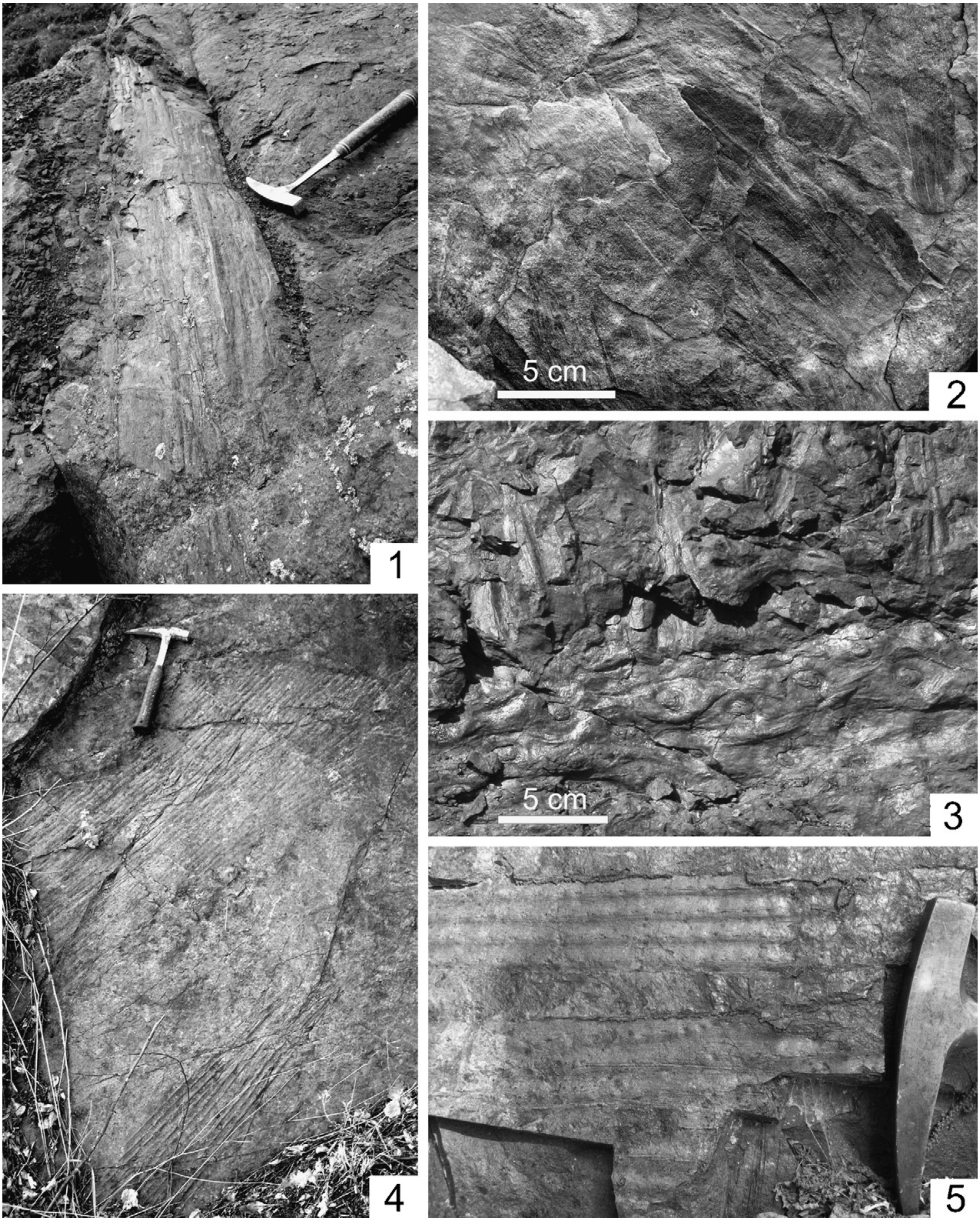


Fig. 4. Plant taphonomic features. (1) Large log attributed to a cordaitalean tree in debris-flow deposits at the base of the Can Camps section. (2) *Poacordaites* leaves associated with presumed cordaitalean trunks. (3) Detail of in situ *Stigmaria ficoides* at the base of the Tallobert seam. (4.) Large *Sigillaria brardii* logs oriented on top of the upper cineritic layer at Can Camps. (5) Detail of *Sigillaria brardii* on top of the lower cineritic layer.

Can Camps mine, the most abundant remains correspond to *Pecopteris* foliage with subsidiary and smaller fragments of pteridosperm foliage (*Odontopteris*, *Linopteris*...) and cordaitalean remains (*Pachycordaites, Cardiocarpus*). In the Faig mine, the most abundant remains in floodplain facies belong to large specimens of *Alethopteris pennsylvanica pyrenaica*, sometimes associated with large *Pachytesta* seeds. Other abundant taxa include well-preserved pecopterid foliage (*Pecopteris polymorpha* = *Polymorphopteris polymorpha*, *Pecopteris feminaeformis* = *Nemejcopteris feminaeformis*) and *Odontopteris* foliage. In both outcrops, some floodplain horizons are very rich in compressed sphenopsid remains including abundant *Calamites suckowii* and well-articulated *Annularia stellata* (Fig. 4). More rarely these remains are associated with *Asterophyllites*, *Sphenophyllum oblongifolium*, *Calamostachys*, and *Macrostachya*. *Calamites* pith casts were found in erect position crossing the cross-laminations of hydraulic dunes in the Faig mine. Lateral rooting structures were emitted by this axis, indicating growth within the dune.

With the exception of this *Calamites* axis, plant remains in floodplain deposits were all parautochthonous or allochthonous since no rooting structures were observed. Medullosan pteridosperms and marattialean tree ferns appear to be the plants that grew closest to the floodplain, especially in Faig, since their foliage is preserved as large and well-articulated specimens, associated with seeds in the case of pteridosperms.

5.3. Fluvial channels

Fluvial sand dunes are crossed by abundant erect pith casts of *Calamites suckowii* in both the Faig and the Can Camps mines (Figs. 5.1–5.3). Some of them show features considered by Gastaldo [13] to be indicative of regenerative growth after burial such as vertical increase in the pith-cast diameter. Compressed *Calamites suckowii* axes were found radiating from a central point in a bedding surface of siltstone to fine-grained sandstone intercalated between sets of rippled coarse sandstone (Fig. 5.6). They may correspond to the branching of erect buried axes after regeneration. These data indicate that *Calamites suckowii* grew isolated within the active sandy channels and eventually colonized the ground during the deposition of channel low-regime deposits.

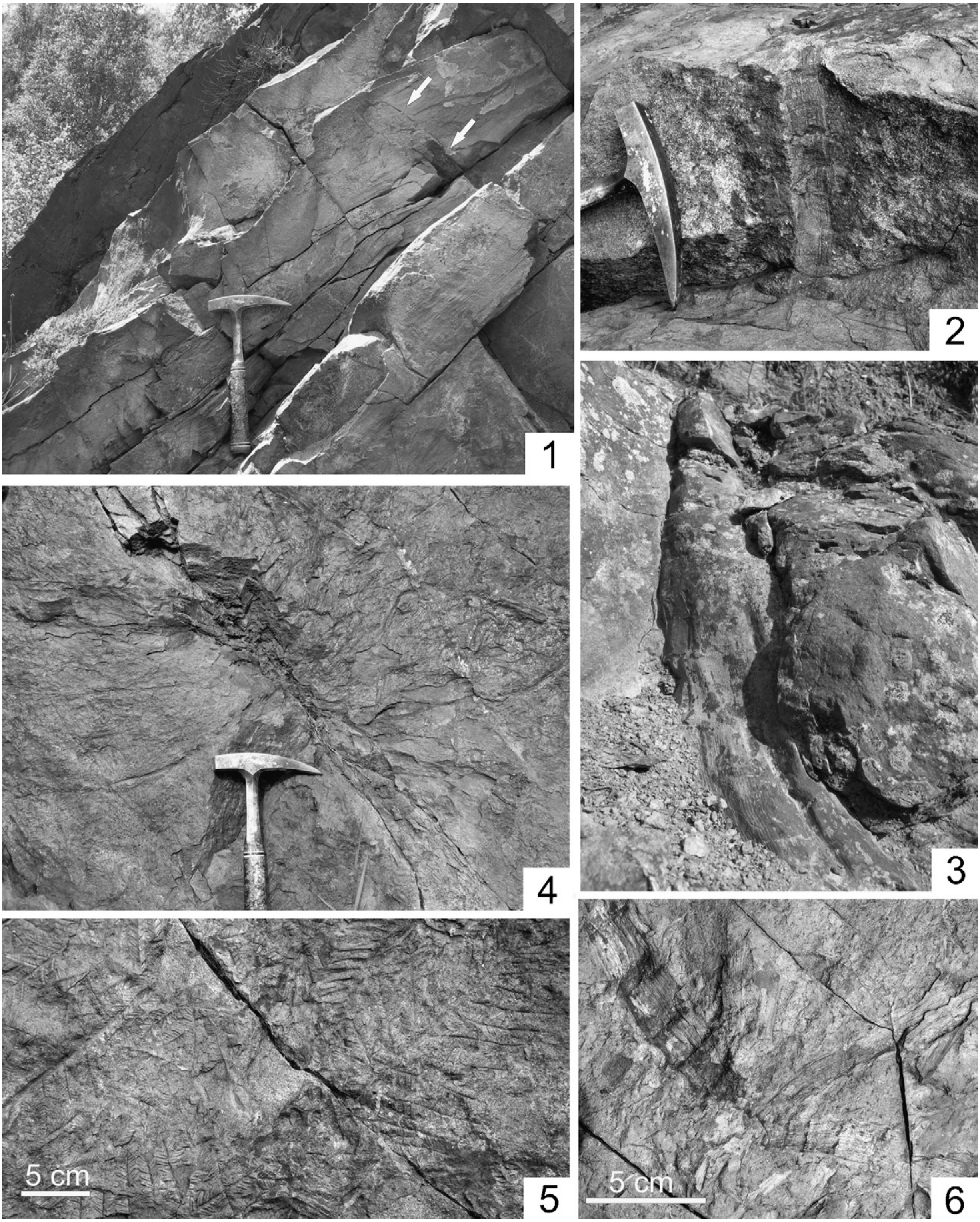
Rooting structures occurred in the same channel low-regime facies. A large structure, 100 cm across, shows a large number of radial impressions of axes, 5 mm to 2 cm thick, with superficial striation (Fig. 4.4). The same bedding plane around this structure is covered by large and well-articulated specimens of *Pecopteris* foliage (*Pecopteris polymorpha* = *Polymorphopteris polymorpha* for authors) (Fig. 5.5). Other smaller rooting impressions, about 50 cm across and without clearly associated foliage, occur in another bedding plane of the same shale facies.

The large rooting structure is attributed to a marattialean tree fern that presumably grew during a low-regime period of the fluvial channel. Other smaller plants, ferns or pteridosperms and the already-mentioned *Calamites suckowii* could have grown along with it in the same deposits.

5.4. Peat mires

The taphonomic information available about peat mires in the Surroca-Ogassa coalfield is relatively scarce, due to the mining out of most of the available coal seams, especially in the Can Camps mine. In the Faig mine, some additional information can be obtained from the study of roof shales of thin coal layers with abundant clastic partitions at the top of the section (Faig-2 seam in Fig. 3). The coal bases of the main coal seams show abundant and well-articulated *Stigmaria ficoides* compressed rooting structures (Fig. 4.3), usually associated with *Cyperites* foliage. Some of these structures radiate from a central rounded depression, which may correspond to the tree stump. This stump was probably compressed within the overlaying coal, which indicates continuity between the *Stigmaria* soil and the overlaying original peat. Roof shales of the Faig mine, analysed by point-quadrat counting (Fig. 6), show a clear succession of lycopsid remains (extremely decorticated lycopsid bark attributed to *Sigillaria*, along with *Stigmaria ficoides* and *Cyperites*), followed in floodplain facies by sphenopsids and pteridosperm remains. This succession was the rule in similar depositional and palaeogeographic contexts, especially in the Graissessac Basin, Montagne Noire (Martín-Closas and Galtier [19]). These authors showed that the presence of *Stigmaria ficoides* in the coal base and abundant *Sigillaria brardii* remains in type-B roof shale might indicate that the peat itself was formed by the growth and accumulation of the remains of this species.

Fig. 4. Caractères taphonomiques des plantes. (1) Grand tronc attribué à une cordaïtale dans un *debris-flow* à la base de la section de Can Camps. (2) Feuilles de *Poacordaites* associées aux troncs de cordaïtales. (3) Détail de *Stigmaria ficoides* in situ à la base de la couche Tallobert. (4) Grands troncs de *Sigillaria brardii* orientés au toit de la cinérite supérieure de Can Camps. (5) Détail de *Sigillaria brardii* au toit de la cinérite inférieure.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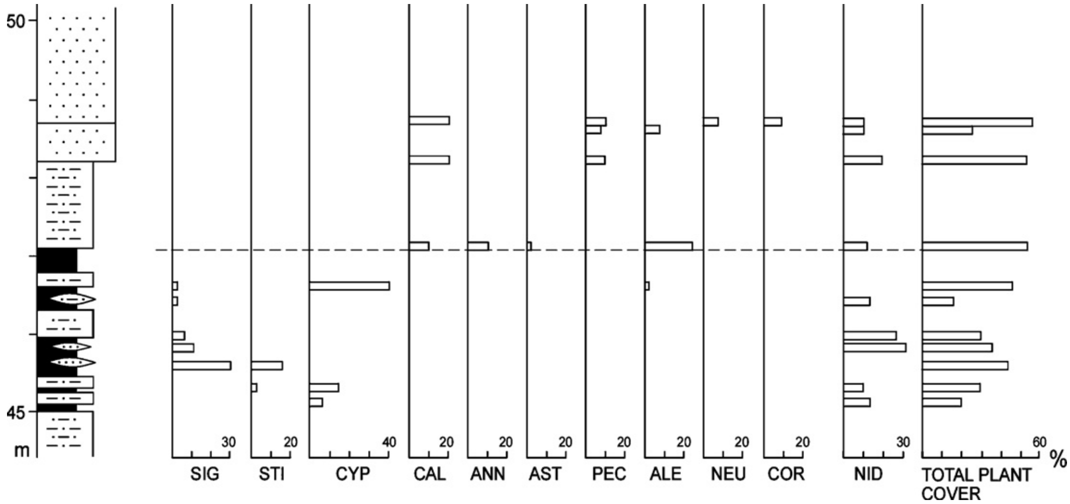

Fig. 6. Point-quadrat counting of plant remains in floodplain siltstones of the Faig mine, following Scott's [21] method. SIG *Sigillaria*, STI *Stigmaria*, CYP *Cyperites*, CAL *Calamites*, ANN *Annularia*, AST *Asterophyllites*, PEC *Pecopteris*, ALE *Alethopteris*, NEU *Neuropteris*, COR *Pachycordaites*, NID Non-identified remains.

Fig. 6. Comptage des restes de plantes dans les sietites de la plaine d'inondation de la mine Faig, d'après la méthode de Scott [21]. SIG *Sigillaria*, STI *Stigmaria*, CYP *Cyperites*, CAL *Calamites*, ANN *Annularia*, AST *Asterophyllites*, PEC *Pecopteris*, ALE *Alethopteris*, NEU *Neuropteris*, COR *Pachycordaites*, NID restes non identifiés.

In Ogassa-Surroca the evidence does not allow such a conclusive interpretation, especially because the lycopsid bark in roof-shale does not bear definite characters and also because the coal contains a number of spores belonging to other lycopsids [2]. Especially significant is the presence of ca 10% of *Densosporites*, a spore that could be related to *Omphalophloios* according to Wagner [26].

5.5. Volcanoclastic events

Two cineritic layers with associated lycopsid logs found in the Can Camps section provide significant information for taphonomic purposes. These deposits lie on thin coal layers and show, on top, abundant compressed logs of *Sigillaria brardii* ranging between 30 cm and 1 m in width (Fig. 4.4 and 4.5). These trunks show a marked NW–SE orientation for the lower layer and a less clear north–south to NE–SW orientation for the upper one. Charred plant remains are found within the cinerite.

The accumulation and orientation of large lycopsid logs on top of the cineritic layers suggest that the assemblage was produced as a consequence of the pyroclastic flow. The difference of more than 45° in the orientation of logs between the two cinerites at Can Camps Mine indicates that the volcanic flux had a different direction in each event. The thin coal layer visible at the cinerite base suggests that the burning cloud swept away peat mire. The monospecific accumulation of trunks suggests that the original forest, swept away by the burning cloud, consisted only of *Sigillaria brardii*. This is significant for our study since it sheds light on the uncertain results obtained from the taphonomic analysis of coal layers. In addition, the different sizes of logs indicate that the forest was not pioneering, but included different stages of growth, which are more characteristic of mature communities.

Fig. 5. Plant taphonomic features (continuation). (1) Fluvial sandstone showing undulating bedding with *Calamites* sp. pith cast (30 cm in height) crossing sedimentary structures (arrows). (2) Impression of *Calamites* sp. pith cast across the same interval of rippled sandstone. (3) *Calamites* sp. pith cast crossing the top fluvial sandstone at Faig Mine. (4) Large radial rooting structure attributed to a marattialean tree fern on shale intercalated with fluvial sandstone at the Can Camps Mine. (5) *Pecopteris* foliage associated with previous rooting structure. (6) *Calamites* stems, radiating from a presumed rooting point on shale intercalated with fluvial sandstone.

Fig. 5. Caractères taphonomiques des plantes (continuation). (1) Grès fluviatile à stratification ondulée avec un moule interne de *Calamites* sp. traversant la lamination (flèches). (2) Impression de moule interne de *Calamites* sp. traversant le même intervalle de grès fluviatile. (3) Moule interne de *Calamites* sp. , haut de 30 cm, traversant le grès fluviatile du toit de la série de la Mine Faig. (4) Structure d'enracinement attribuée à une fougère arborescente marattiale sur schiste intercalé avec des grès fluviatiles de la mine de Can Camps. (5) Feuillage de *Pecopteris* associé à la structure d'enracinement précédente. (6) Tiges de *Calamites* sp. rayonnement à partir d'un point possible d'enracinement dans un "shale" intercalé dans les grès fluviatiles de la mine de Can Camps.

6. Discussion and conclusions

The Stephanian wetlands of Surroca-Ogassa (eastern Pyrenees, Catalonia) occurred in the small Hercynian intramontane basin of Camprodon-Castellar de N'Hug [15]. In stratigraphic terms, they show a succession of alluvial deposits covered by floodplain and fluvial channel deposits with influence of volcanoclastic processes. In these limnic environments, plant communities were characterised based on combined sedimentological, taphonomic, and palaeoecological analyses and a reconstruction is proposed (Fig. 7). Peat mires were grown by lycopsids, mainly *Sigillaria brardii* and perhaps *Omphalophloios*. Evidence for this is provided mainly by taphonomic features of the base and roof shales of coal seams, the spore content in coals and the monospecific accumulation of *Sigillaria brardii* logs on the top of two cinerite deposits sweeping away a forested swamp. Floodplains were generally devoid of vegetation, except for the growth of isolated stands of *Calamites suckowii* in relatively better-drained areas of the permanently inundated floodplain (i.e. sandy, hydraulic dunes). *Calamites suckowii* grew as well within fluvial channels, sometimes associated with *Sphenophyllum oblongifolium*. The calamite regenerated even after repeated burial. Marattialean tree ferns were growing along with calamitean stands in calmed areas of the river channel. Evidence for this was obtained from large radial rooting structures associated with pecopterid foliage (*Polymorphopteris polymorpha* = *Pecopteris polymorpha*) in the same bedding plane. *Alethopteris pennsylvanica* var. *pyrenaica* was the most abundant pteridosperm in a number of floodplain horizons. Its habitat is subject to a certain degree of interpretation, since no rooting structures were found associated with foliage or axes. However, well-articulated foliage of this species together with seeds of the *Pachytesta* type were abundant in floodplain shales immediately overlaying the coal seams at Faig Mine and are interpreted as parautochthonous (Fig. 6). This suggests that the alethopterid pteridosperms were growing in the floodplain margins close to the peat mire. A habitat in the floodplain margins is also probable for the leptosporangiate fern *Nemejcopteris feminaeformis* (= *Pecopteris feminaeformis*) and *Odontopteris*. Cordaitaleans are also difficult to characterise palaeoecologically in Surroca-Ogassa. Evidence from parautochthonous remains suggests a habitat in distal areas of alluvial fans.

In comparison with previous studies of Hercynian limnic wetlands, the Ogassa-Surroca plant communities show most similarity with the communities described in the Graissessac Basin by Martín-Closas and Galtier [19]. A similar habitat was found for lycopsids and sphenopsids (mainly *Sigillaria brardii*, *Calamites suckowii* and *Sphenophyllum*). In contrast, marattialean tree ferns with pecopterid foliage show a relatively different habitat, since in Graissessac they were found colonising the late infilling stages of peat-mires, whilst in Surroca-Ogassa they grew in calmed areas of fluvial channels. Indeed, marattialean tree ferns were already reported to grow in fluvial habitats in the Late Pennsylvanian of the Illinois Basin (United States) by Dimichele and Phillips [10]. Other species are not in common between the two South European Hercynian intramontane basins. Thus, the medullosan pteridosperm *Alethopteris pennsylvanica* var. *pyrenaica* and the leptosporangiate fern

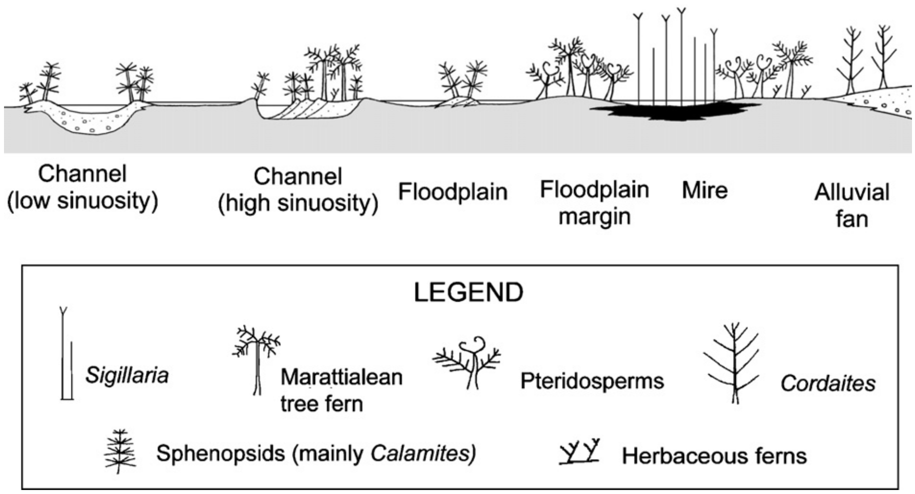

Fig. 7. Reconstruction of Stephanian wetland vegetation from Ogassa.
Fig. 7. Reconstitution de la végétation de marécage du Stéphanien d'Ogassa.

Nemejcopteris feminaeformis, which are abundant in floodplain facies from Surroca-Ogassa, were not found in Graissessac.

In conclusion, the Surroca-Ogassa coalfield provides a new example of Late Hercynian intramontane wetland in southern Europe. Some of the palaeoecological features of the plant communities are comparable to the coeval wetlands from the Montagne Noire, whilst others appear to be different, such as the marattialean-calamitean plant assemblage found growing in low-regime fluvial facies.

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