8th AGORA PALEOBOTANICA MEETING

FIELDTRIP GUIDEBOOK

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Cover picture:

Alethopteris pennsylvanica var. pyrenaica WAGNER 1968, from its type locality in Ogassa

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1. FOREWORD AND HISTORICAL OVERVIEW

In this guidebook we present the pre- and post-meeting field trips of the 8th Agora Paleobotanica Meeting celebrated in Bellver de Cerdanya (Catalonia, Spain) from the 5th to the 8th of September 2023. The two palaeobotanical localities visited are among the most famous fossil plant sites from Catalonia.

Pre-meeting fieldtrip. This excursion will be devoted to the Upper Carboniferous (uppermost Pennsylvanian) from Ogassa, in the Eastern Pyrenees. The first mentions on fossil plants in Ogassa, also reported to as Surroca, for the name of the coalfield, were made by Spanish geologists and mining engineers already by the mid-19th Century. Until the early 20th Century, palaeobotanical studies were mainly focussed to the biostratigraphy of fossil plants to understand the complicate geology of the coalfield. In contrast to most European coalfields, the Pyrenean Carboniferous has been submitted not only to the end phases of the Hercynian Orogeny in the Latest Caboniferous, but also to the Alpine Orogeny in the Eocene and Oligocene, which results in discontinuous and verticalized coal seams rendering difficult the exploitation. The coal mines from Ogassa were in the decades of 1880-1890 among the first 3 most productive of Spain, with an average extraction of 3500-4500 Tm/year (Fig. 1.1), and even a railway connecting Sant Joan de les Abadesses, near Ogassa, with Barcelona was constructed to transport the Pyrenean coal to the Catalan capital, where it was mainly used to feed the steam machines of the famous Catalan textile industry (Fig. 1.2). Coal mining was done in galleries and lasted until approximately the beginning of the 20th Century, when the gallery mines were closed. After the Spanish Civil War (1936-1939) coal mines were mainly exploited in small opencast mines for local use until the decade of 1960'. The remains of these pit mines are the outcrops we will visit. Still now, the mining village of Ogassa preserves very much of the ambiance of the old times, since the village itself could not be modified until year 2000, when the coal companies finally agreed to sell the ground and buildings to the Ogassa inhabitants (Fig. 1.3).

Some of the first palaeobotanists who helped in determining the fossil plants from Ogassa in the early 20th Century were French, particularly R. Zeiller, P. Bertrand or M. Dalloni. Later most publications devoted to the fossil plants from Ogassa continued to be focused on systematic palaeobotany (e.g. W.J. Jongmans, R. Wagner, C. Alvarez-Ramis, C. Diéguez, Gómez-Alba) and even included the description of new taxa with type localities in the basin. More recently other subjects of emerging interest such as the plant taphonomy, palaeoecology and biogeography are beginning to be developed too (e.g. Martín-Closas and coll.). The uppermost Carboniferous plant-bearing localities of Ogassa are significant in that they provide one of the few South European intramontane and completely freshwater settings in the crossroads between Gondwana and Laurasia.

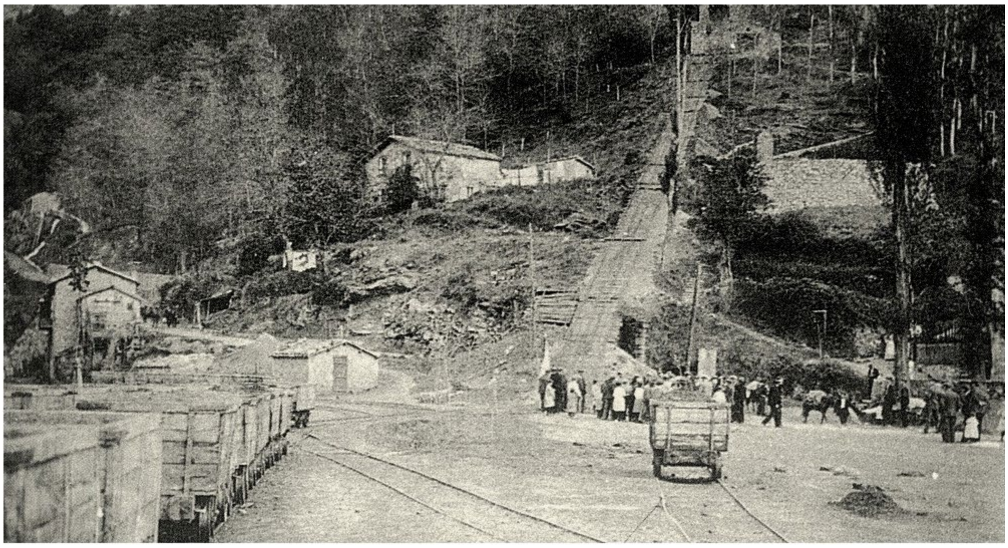


Fig. 1.1. Coal mining activities in Ogassa, in front of the Dolça Mine, by the beginning of the 20th Century. Source: Postcard

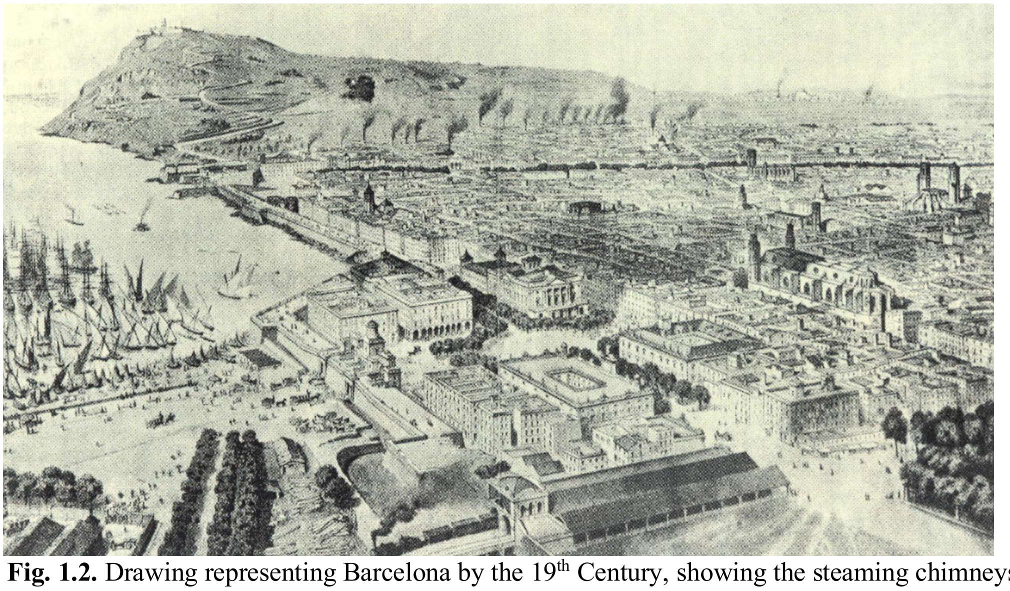


Fig. 1.2. Drawing representing Barcelona by the 19th Century, showing the steaming chimneys of the Poble Sec factories, fed mainly with the Ogassa coal. Some of these chimneys have been preserved for memory. Source: Postcard

Fig. 1.3. Old miner's apartments in the main street of Ogassa, by 2007.

Post-meeting fieldtrip. This excursion will be devoted to the upper Miocene fossil plants from the La Cerdanya Basin, also in the Eastern Pyrenees. The first study on these plants was done by a French author, Prof. L. Rérolle from Montpellier, in 1884-1885. His monograph focused on systematic palaeobotany and provided a strong base to later works until today. During the mid-20th Century there was a second pulse in the study of fossil plants from La Cerdanya, started with J.F. de Villalta and M. Crusafont (Catalan Institute of Paleontology, Sabadell), the PhD thesis of Menéndez-Amor (Complutense Univ. of Madrid) and the first study on palynology of the Miocene from La Cerdanya by S. Jelgersma (Univ. of Utrecht). Studies on the systematic palaeobotany of the Miocene plants continued up to now. It is worth mentioning the studies on megaplant remains by C. Alvarez-Ramis (Complutense Univ of Madrid), A. Sanz de Siria (Catalan Institute of Paleontology, Sabadell) and, especially, the PhD thesis (1995) and further studies by E. Barrón from the Complutense University of Madrid. Palynology was mainly developed by the PhD of Bessedik, from the Univ. of Montpellier and also by E. Barrón.

In 1986 the study of the Miocene of La Cerdanya had a new impulse with the Degree Thesis from E. Roca from the University of Barcelona who drew for the first time a general palaeoenvironmental reconstruction of the Miocene basin, based on facies analysis and regional geology. This thesis allowed to understand better the basin's paleogeography and evolution, and in consequence, the plant paleoecology. As a result of this new impulse, paleobotanical publications began to deal mainly with more conceptual subjects, such as taphonomy, palaeoecology, paleoclimate or paleoaltitude. (e.g., papers by Barrón and coll. from Museo Geominero, Madrid, and C. Martín-Closas and A. Tosal from the Univ. of Barcelona).

La Cerdanya palaeoflora is significant for European palaeobotany in that it provides a unique example of an intramontane vegetation of the Late Miocene in South Europe, to be compared with most other localities from lowlands, generally coastal settings. Another important and unique aspect from the Miocene flora of La Cerdanya is that it includes several endemic species, particularly of aquatic plants, such as the diatom *Aulacoseira ceretana* or the water chestnut *Trapa ceretana*, which justifies the main subject for discussion of the present AGORA meeting.

2. PRE-MEETING FIELDTRIP TO THE UPPERMOST PENNSYLVANIAN OF OGASSA

Geological setting

The ancient Surroca-Ogassa coalfield belongs to the Castellar de N'Hug - Camprodon Basin, which is the easternmost of the Pyrenean late Hercynian basins described by Gisbert (1986). These basins were narrow intramontane grabens following a strike-slip fault, formed within the Hercynian Range after the main compressive stages. The studied basin contains a succession of latest Pennsylvanian (Stephanian C local stage) and Permian rocks, organised in three stratigraphic units limited by sedimentary unconformities, the Transition Unit, the Lower Red Unit and the Upper Red Unit. The sedimentary record studied during the fieldtrip belongs to the Transition Unit. This unit, up to 250 m thick, holds the Carboniferous - Permian boundary and the transition from a flora dominated by lycopsids, sphenopsids and ferns to a flora dominated by conifers and seed plants, hence the name. It is represented locally by an alluvial conglomerate followed by fluvio-lacustrine sandstone, shale and coal with subordinated volcanic rocks.

A depositional model for the basin during the sedimentation of the Transition Unit was developed by Broutin and Gisbert (1985). According to this model the basin was elongated in shape and probably endorheic. 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. 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 upper Carboniferous and Permian succession of Ogassa was strongly involved in Alpine structures of the most internal part of the Pyrenean Chain, mainly during Eocene times (Fig. 2.1). Several rock slices (thrusts) including Devonian limestone, lowermost Caboniferous chert (called "lydite") and Upper Carboniferous conglomerate, sandstone, shale and coal were piled up repeatedly and folded altogether, forming the so-called "Serra Cavallera antiformal stack" (Muñoz et al., 1994). Because of this important Alpine deformation and thrusting, the Pennsylvanian-Permian units are disconnected from each other rendering the correlation of today's outcrops difficult. In this fieldtrip we will visit three different outcrops belonging to two of these slices, which correspond to the Can Camps mine and the Faig mine respectively.

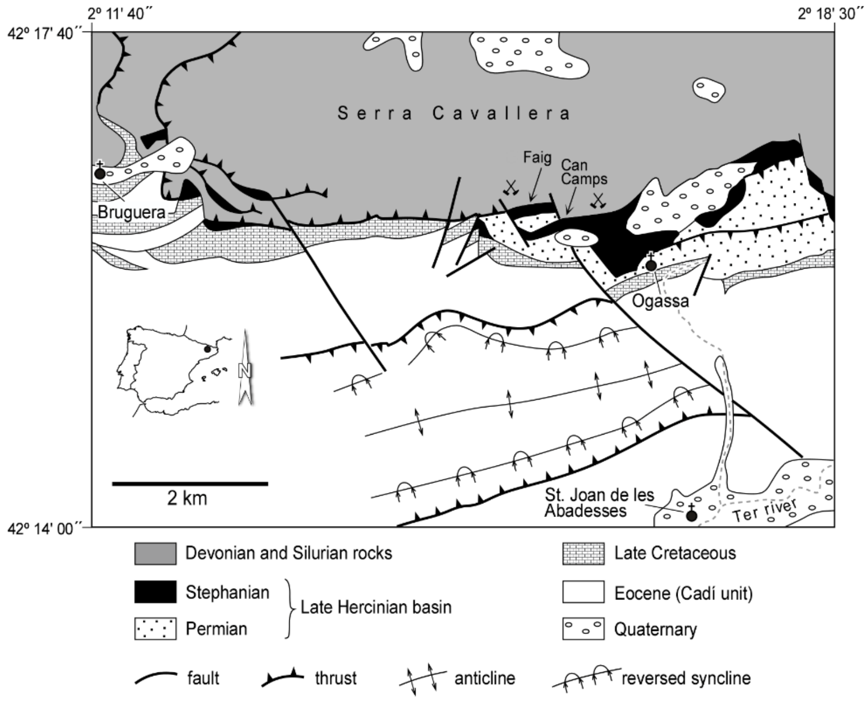


Fig. 2.1. Simplified geological map of the area studied. From Martín-Closas and Martínez-Roig (2007), modified from Muñoz et al. (1994).

Palaeobotanical Setting

The Latest Pennylvanian (Stephanian C) flora of the Surroca-Ogassa coalfield was already documented in the late 19th Century, when the mining district was active. A first summary of fossil plant remains was provided by Faura i Sans (1913), who reported about 20 taxa, determined in part by R. Zeiller (Paris). Later, Dalloni (1930) provided a new list compiled by P. Bertrand (Lylle). These early studies were summarized by Jongmans (1951). Detailed taxonomic studies were not available until the second part of the 20th Century. Wagner (1968) described *Alethopteris pennsylvanica* var. *pyrenaica*, which is one of the most abundant plant remains 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. (1969, 1971). The flora documented by these authors was assigned to the Stephanian-C (Uppermost Pennsylvanian, according to Heckel and Clayton (2006). Diéguez (1985) studied the polymorphism of *Annularia stellata* and recognized two morphotypes in the Surroca-Ogassa coalfield. A revision of the flora from Ogassa, housed in the Museu de Ciències Naturals from Barcelona, by Wagner (2004) evaluated the number of taxa to 45 morphospecies (Table 1).

Although the paleoecology of Carboniferous plants from the Pyrenean basins was already outlined by Broutin and Gisbert (1985), it was not until the study by Martín-Closas and Martínez-Roig (2007) when the precise paleoecology of the plants from the Ogassa wetlands was analysed, based on combined sedimentological and taphonomical analyses. Here we provide an overview about the results of this study in the two mines visited during this fieldtrip.

The Can Camps Mine section

The opencast mine of Can Camps, shows an up-to-60-m-thick succession, bounded by faults both at the base and at top. The stratigraphic succession begins with conglomerates and follows with up to 35 m of siltstone with intercalated coal and two volcanic layers (Fig. 2.2). The top of the series is formed by rippled sandstone beds.

(1) Basal conglomerate. Massive conglomerate beds occur at the base of the section, in outcrops of difficult access. They show a matrix supported fabrics. Clasts of variable size, up to 20 cm in diameter, are mostly angular and formed by Lower Carboniferous black cherts (lydite). These beds 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-orogenic Hercynian rocks bordering the basin. The fining-upwards small sequences intercalated with the former facies may indicate the occurrence of fluvial deposits in relatively more distal areas of these alluvial fans.

Table 1. List of latest Carboniferous species from Ogassa stored in the Natural History Museum of Barcelona, according to Wagner (2004):

Lycopsids
Sigillaria brardii Brongniart Wagner
Sigillaria polygonalis Vetter
Sigillaria cf. *ovata* Sauveur
Lepidostrobus sp.
Stigmaria ficoides Sternberg

Sphenopsids
Calamites cruciatus Sternberg
Calamites suckowii Brongniart
Annularia mucronata Schenk
Annularia sphenophylloides (Zenker) Gutbier
Annularia stellata (Schlotheim) Wood
Asterophyllites equisetiformis (Schlotheim) Brongniart
Macrostachya carinata (Germar) Zeiller
Sphenophyllum oblongifolium (Germar & Kaulfuss) Unger
Sphenophyllum cf. *verticillatum* (Schlotheim) Zeiller

Ferns
Sphenopteris cf. *mathetii* Zeiller
Nemejcopteris feminaeformis (Schlotheim) Barthel
Diplazites longifolius (Brongniart) Göppert
Pecopteris arborescens (Schlotheim) Brongniart
Pecopteris cyathea (Schlotheim) Brongniart
Pecopteris cf. *densifolia* sensu Zeiller non Göppert
Pecopteris jongmansii Wagner
Pecopteris cf. *laxenervosa* Wagner & Lemos de Sousa
Pecopteris robustissima Wagner
Pecopteris spp.
Lobatopteris corsinii Wagner
Polymorphopteris integra (Andrä) Wagner
Polymorphopteris polymorpha (Brongniart) Wagner
Polymorphopteris cf. *subelegans* (Potonié) Wagner
Senftenbergia elaverica (Zeiller) Wagner
Senftenbergia gruneri (Zeiller) Wagner

Seed plants-Pteridosperms
Gondomaria grandeuryi (Zeiller) Wagner & Castro
Odontopteris brardii Brongniart Cyclopteris sp.
Alethopteris pennsylvanica var. *pyrenaica* Willière
Barthelopteris germari (Giebel) Zodrow & Cleal
Linopteris gangamopteroides (de Stefani) Wagner
Linopteris neuropteroides (Gutbier) Potonié
Callipteridium gigas (Gutbier) Weiss
Callipteridium zeilleri Wagner
Taeniopteris multinervia Weiss
Dicksonites decorpsii (Zeiller) comb. nov. (basionym Sphenopteris decorpsii)
Dicksonites plueckenetii (Schlotheim) Sterzel
Oligocarpia leptophylla (Bunbury) Grauvogel-Stamm & Doubinger

Seed plants-Cordaitales
Cordaites sp.
Poacordaites microstachys (Goldenberg) Zeiller

Conglomerates are generally devoid of plant remains. However, sandstone and siltstone beds intercalated with them contain 2-3 m-long and 30 cm-wide logs associated with abundant cordaitalean leaves (*Pachycordaites* type) and seeds (*Cardiocarpus* sp.) (Fig. 2.3, 1-2). 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 different organs of the same plant group suggest that the cordaitalean assemblage is parautochthonous in distal alluvial fan facies and represents the most abundant vegetation in those settings.

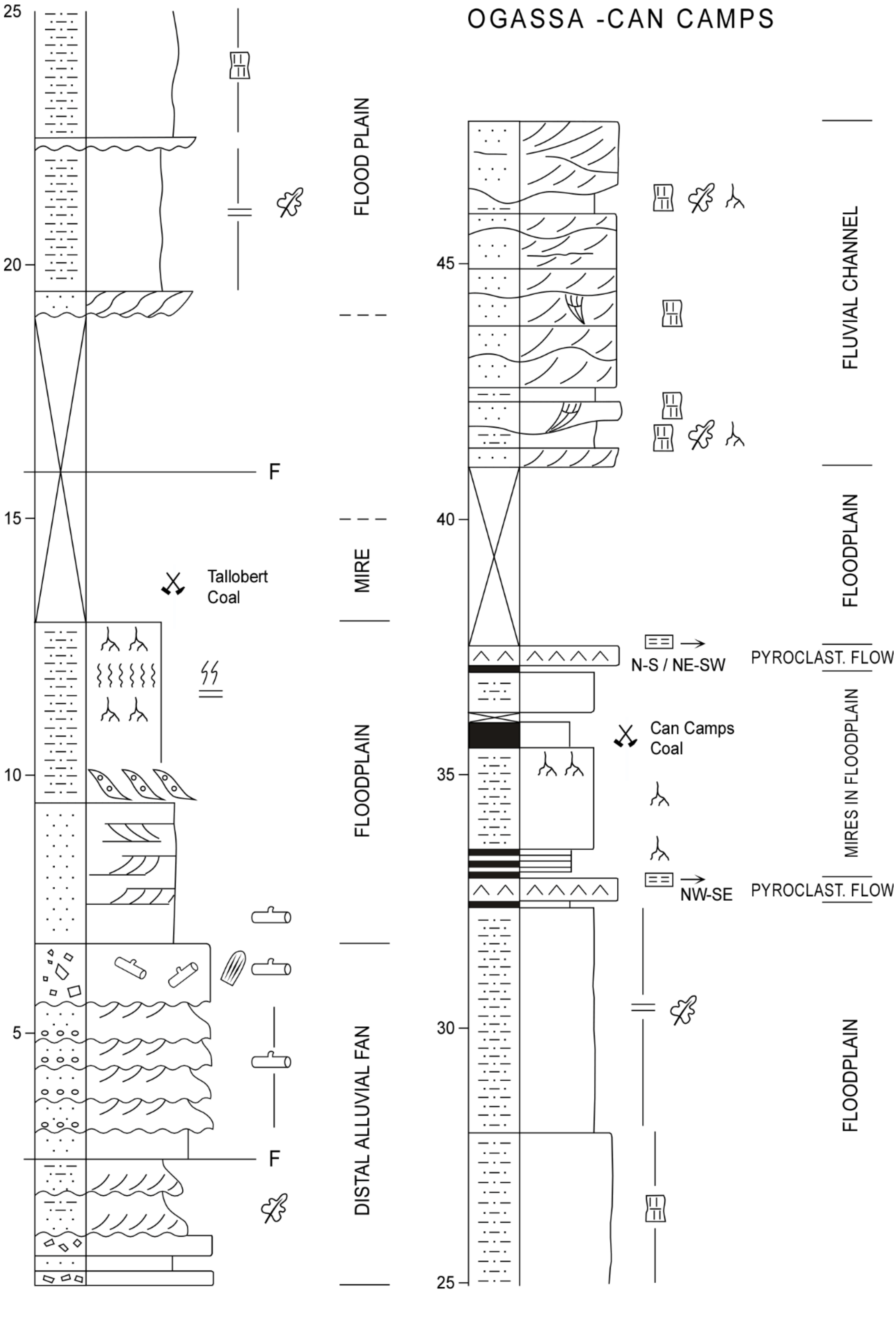


Fig. 2.2. The Can Camps section (from Martín-Closas and Martínez-Roig, 2007). See legend in Fig. 2.5.

(2) Intermediate Siltstone. Dark grey, even-laminated siltstones and shale form the thickest deposits of the Can Camps section. The monotonous siltstone succession is interrupted by a few 10 to 50 cm-thick and a few meters-long lenticular bodies of coarse sandstone showing planar crossbedding and ripple-marks.

Laminated siltstones and shales 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 deposition in standing, anoxic water, generally without bioturbation, resulting in a shallow lacustrine-like environment. Cross-bedded, lenticular sandstone would correspond to small channels that provided some drainage to this floodplain.

Siltstone contains the largest diversity of plant remains in the sections studied. In the Can Camps mine the most abundant remains correspond to *Polymorphopteris polymorpha(=Pecopteris polymorpha)* foliage with subsidiary and smaller fragments of pteridosperm foliage (*Odontopteris, Linopteris…*) and cordaitalean remains (*Pachycordaites, Cardiocarpus*). Some floodplain horizons, generally of fine sandstone, are very rich in compressed sphenopsid remains including abundant *Calamites suckowii* and well-articulated *Annularia stellata*. More rarely these remains are associated with *Asterophyllites*, *Sphenophyllum oblongifolium, Calamostachys and Macrostachya*.

Plant remains in floodplain deposits are all parautochthonous or allochthonous since no rooting structures were observed. At Can Camps marattialean tree-ferns appear to be the plants that grew closest to the floodplain, taking into account large and well-articulated specimens, while sphenopsids would grow near the small channels providing drainage to the floodplain

3) Coal. Two coal seams are intercalated in the siltstone succession of Can Camps, corresponding to the Can Camps and the Celobert seams (the latter also called Tallobert, both terms meaning open-cast in Catalan) respectively. Only the siltstone underlying the Celobert coal is available after extraction and will be studied in Stop 2, while the Can Camps coal is still available near Stop 1.

The siltstone at the base of the Celobert coal shows abundant and well-articulated *Stigmaria ficoides* compressed rooting structures, suggesting that the coal would correspond to a tree lycopsid peat mire (Fig 2.3,3). Laterally, the siltstone corresponding to the coal seam base shows abundant cylindrical and contorted burrows, about 1 cm in diameter, preserved in siderite. These biogenic structures indicate that parts of the lycopsid swamp, probably the edges of it, hold oxygenated water, allowing an aquatic burrower fauna to thrive.

4) ***Volcanic rocks.*** Two 50-70 cm thick, greyish and compact layers of fine-grained cinerite occur by the middle of the Can Camps section, interrupting the siltstone and coal succession. These cinerite beds were formed by deposition of volcanic ash. The top of the layers shows abundant compressed and oriented logs of *Sigillaria brardii,* ranging between 30 cm and 1 m in width, and interpreted to be deposited after a *Sigillaria* swamp was swept away by a burning ash cloud (Fig. 2.3, 4-5). More detail is provided in the description of Stop 3.

5) ***Rippled sandstone at top of the section.*** Up to 6 m-thick, medium- to coarse-grained, rippled sandstone constitutes the top of the succession at Can Camps. Sandstone beds are 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 rippled sandstone itself is attributed to deposition within an active fluvial channel. The intercalation of relatively thin layers of fine-grained deposits is attributed to deposition of suspended load in quiet-water conditions after a flooding event, when the river channel was transformed into a sluggish channel that allowed the wetland vegetation to develop.

Fluvial sand dunes are crossed by abundant erect pith casts of *Calamites suckowii*, suggesting in situ growth (Fig. 2.4, 1-2), while radial rooting structures associated to abundant *Pecopteris* foliage (*Pecopteris polymorpha* = *Polymorphopteris polymorpha*) occur in the intercalated siltstone (Fig. 2.4., 4-5). More detail will be provided in the description of Stop 1.

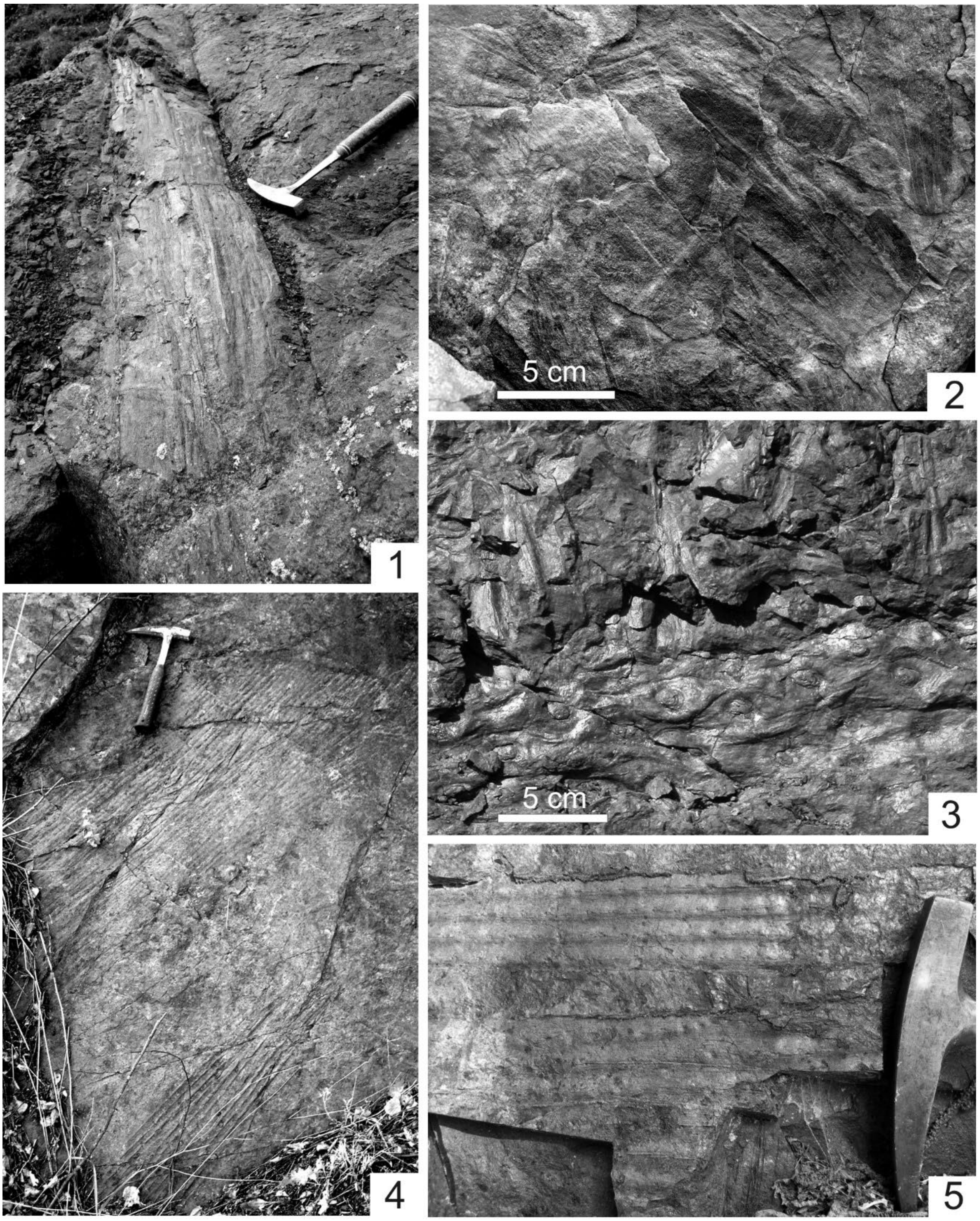


Fig. 2.3. Plant remains from Ogassa (from Martín-Closas and Martínez-Roig 2007). (1) Large log attributed to a cordaitalean tree in debris-flow deposits at the base of the Can Camps section. (2) *Poacordaites* leaves associated to presumed cordaitalean trunks. (3) Detail of in situ *Stigmaria ficoides* at the base of the Celobert seam. (4.) Large *Sigillaria brardii* logs oriented on top of the upper cinerite at Can Camps. (5) Detail of *Sigillaria brardii* on top of the lower cinerite layer.

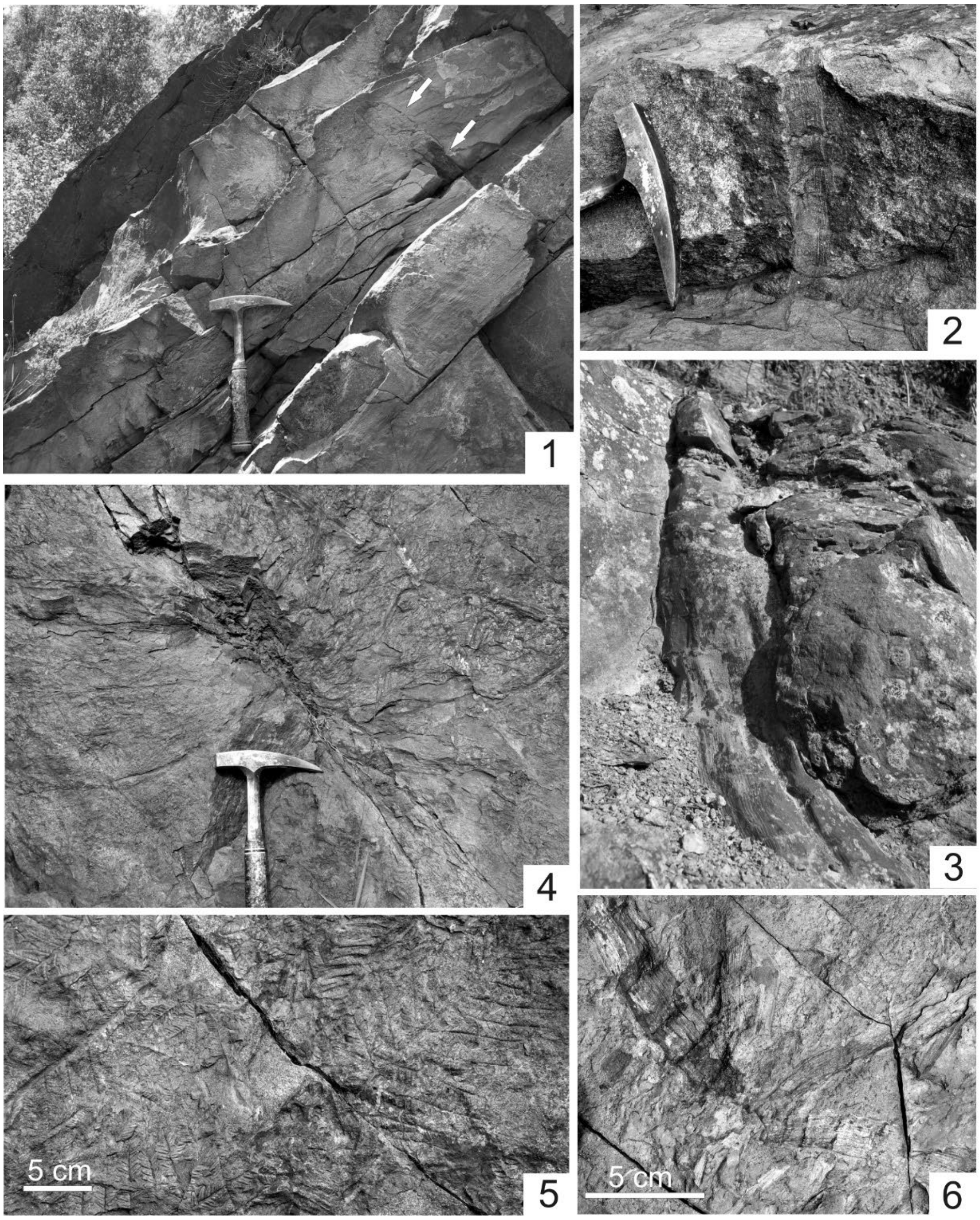


Fig. 2.4. Plant remains from Ogassa, continued (from Martín-Closas and Martínez-Roig 2007). (1) Fluvial sandstone at top of the Can Camps section showing undulating bedding with *Calamites* sp. pith cast crossing sedimentary structures (arrows). (2) Impression of *Calamites* sp. pith cast across the 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 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 at top of Can Camps section.

The Faig Mine section

In the opencast mine of Faig, the Upper Carboniferous succession begins with a conglomerate, which is covered by 15 m of red cinerite (tonstein). The main part of the series is formed by 30 m of siltstone, shale and coal passing upwards to sandstone. The top is formed by a 15 m thick volcanic conglomerate (Fig. 2.5.).

1) ***Basal conglomerate***. The basal conglomerate of the Faig mine is poorly exposed. From the lithological viewpoint it appears to be similar to the Can Camps basal conglomerate.

2) ***Volcanic rocks***. Two types of volcanic rocks were identified in the Faig Mine. (a) A sequence of up to 8 m of dark-red fine-grained tonsteins with a granular texture form the characteristic northern wall of the Faig mine. These cinerite are 2-3 m thick massive layers that display 50-cm large, concentric figures of alteration. These deposits were attributed to volcanic ash fall. They are devoid of plant remains.

b) Up to 5 m-thick massive bodies of conglomerate were found at the top of the Faig Mine. Clasts up to 20 cm in diameter are formed by rounded andesite fragments, and are associated with smaller quartz and schist clasts, all floating in a grey tonstein matrix. This deposit is attributed to a volcanic mass-flow formed when the andesitic clasts were still unconsolidated, which explains their rounding. This deposit is also devoid of plant remains.

3) ***Siltstone, shale***. Dark grey, even-laminated siltstones and shale form the thickest deposits also in the Faig mine. In contrast to Can Camps, the Faig mine siltstones bear abundant siderite nodules. The siltstone succession is interrupted by lenticular beds of coarse sandstone showing planar crossbedding and ripple-marks.

As for the Can Camps mine, laminated siltstones are attributed to the deposition of overbank, suspension-load sediment in permanently inundated and poorly oxygenated floodplains that formed a lake-like environment, while lenticular sand beds are interpreted as small channels providing drainage to the floodplain. 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.

In the Faig mine the most abundant remains in floodplain facies belong to large specimens of *Alethopteris pennsylvanica* var *pyrenaica*, sometimes associated with *Pachytesta* seeds. More detail about the plant assemblage is provided in the description of Stop 4.

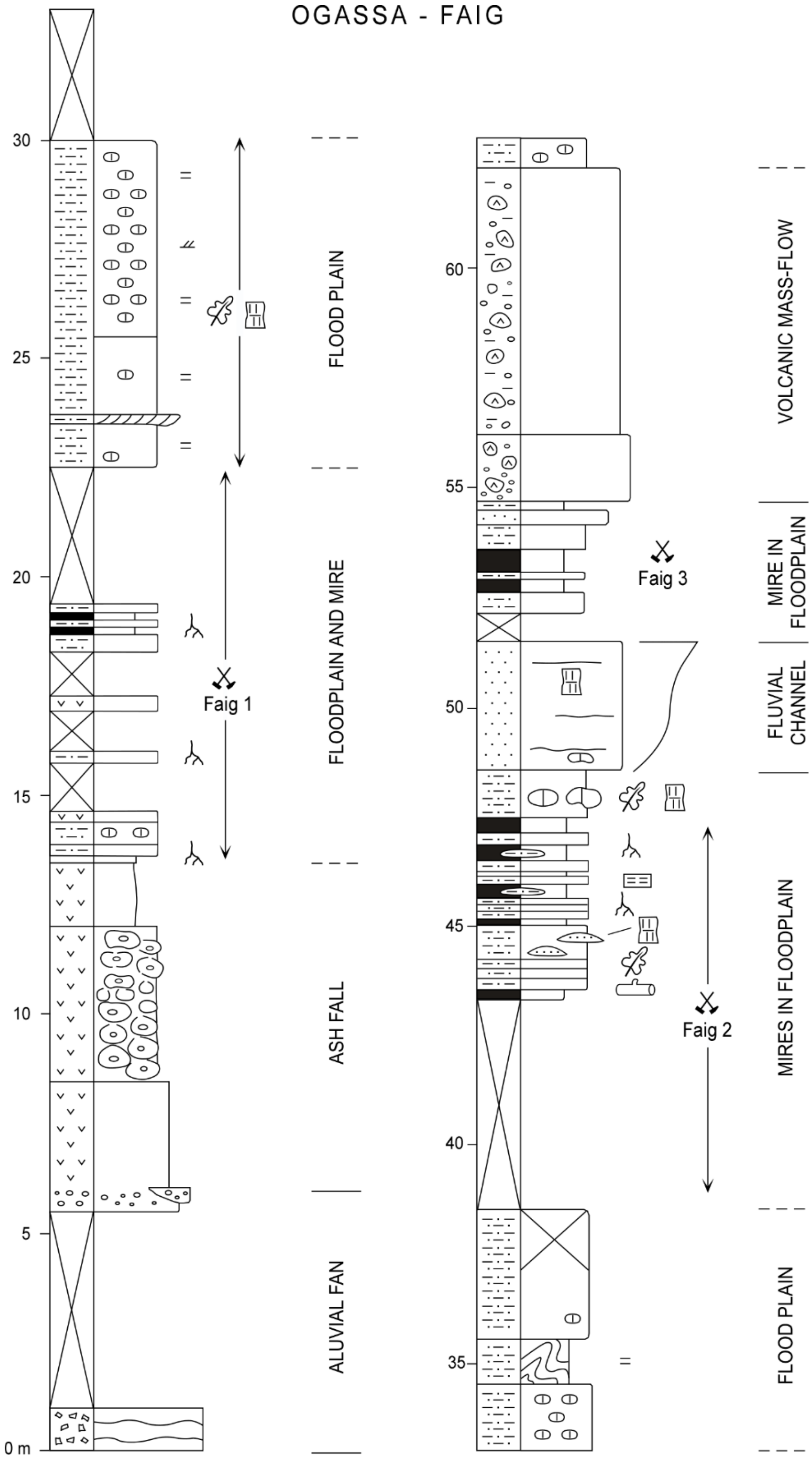


Fig. 2.5. The Faig Mine section (from Martín-Closas and Martínez-Roig 2007).

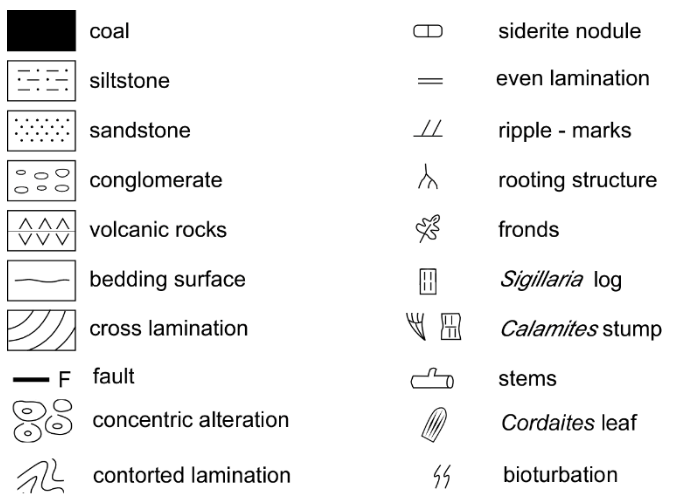


Fig. 2-5 (continued). Legend of Figures 2.2 and 2.5.

5) ***Coal***. In the Faig mine there are three coal bearing intervals, which correspond to the three pits excavated for coal extraction, Faig- 1, Faig-2 and Faig-3. Only Faig-2 pit still preserves several up to a few decimetres thick coal seams that provide accessible coal bases and roof shales for study. The top of the available coals is planar and may contain abundant clastic partitions which 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. 1995).

Plant remains at the base of coals is formed exclusively of *Stgmaria ficoides*, as observed in the Can Camps mine. Roof shales of the Faig mine were analysed quantitatively by point-quadrat counting and show a clear succession of lycopsid remains (extremely decorticated lycopsid bark attributed to *Sigillaria,* along with *Stigmaria ficoides* and *Cyperites* sp., followed in floodplain facies by sphenopsids and pteridosperm remains (Fig. 2.6.). This succession was the rule in similar depositional and palaeogeographic contexts, especially, in the Graissessac Basin, Montagne Noire (Martín-Closas and Galtier 2005). These authors showed that the presence of *Stigmaria ficoides* in the coal base and abundant *Sigillaria brardii* remains in Type B roof shales may indicate that the peat itself was formed by the growth and accumulation of the remains of this species. In Ogassa the evidence does not allow for such a conclusive interpretation, because the lycopsid bark in roof-shales does not bear definite taxonomic characters and also because the coal contains a number of spores belonging to other lycopsids. About 10% of *Densosporites* could be related to *Omphalophloios* according to Wagner (2004).

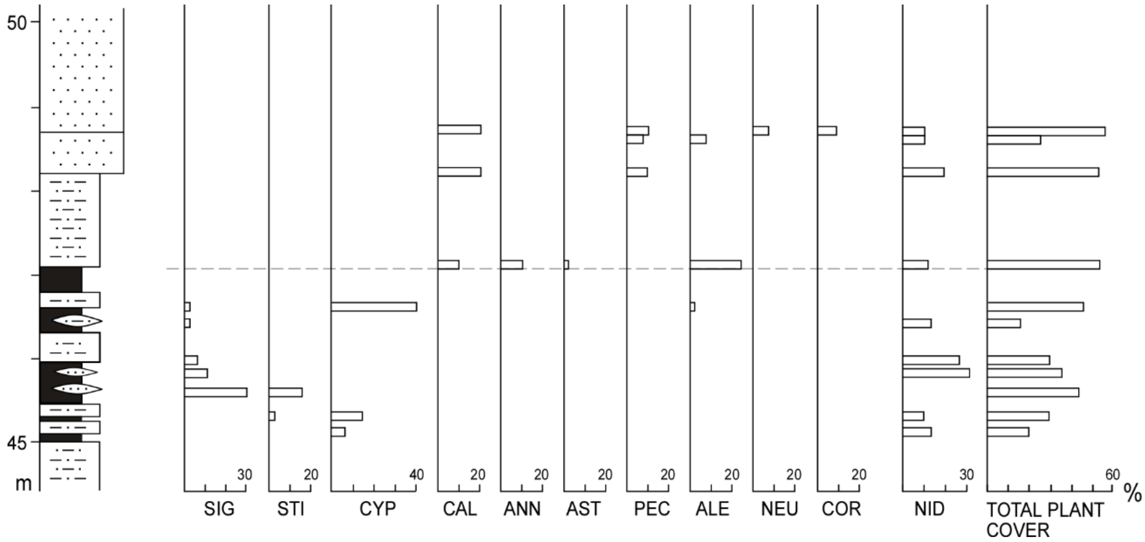


Fig. 2.6. Point-quadrat counting of plant remains in floodplain siltstones of the Faig mine (from Martín-Closas and Martínez-Roig 2007). SIG *Sigillaria*, STI *Stigmaria*, CYP *Cyperites*, CAL *Calamites*, ANN *Annularia*, AST *Asterophyllites*, PEC *Pecopteris*, ALE *Alethopteris*, NEU *Neuropteris*, COR *Pachycordaites*, NID Non-identified remains.

6) ***Sandstone.*** The upper part of the Faig Mine succession shows a 7 m thick lenticular bed of medium- to coarse-grained, sandstone with irregular bedding that contains towards the top a thin intercalation of floodplain shale and coal. The base of the sandstone is planar but clearly erosive on underlying beds.

This sandstone has been attributed to a fluvial channel. In contrast to Can Camps, this channel would have been filled completely during high energy hydraulic regimes, since no traction sedimentary structures occur.

The Faig fluvial sandstone is crossed by erect pith casts of *Calamites suckowii*, like in Can Camps (Fig. 2.4, 3). They show features considered by Gastaldo (1992) to be indicative of regenerative growth after burial such as vertical increase in the pith-cast diameter, or distorted stems.

Palaeoecological model of the Ogassa wetlands

Martín-Closas and Martínez-Roig (2007) proposed a palaeoenvironmental reconstruction of the Ogassa plant communities based on combined sedimentological, taphonomic and palaeoecological analyses (Fig. 2.7). 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 top of two cinerite deposits sweeping away a forested swamp. Lake-like floodplains were generally devoid of vegetation except for the growth of isolated stands of *Calamites suckowii* in relatively better drained areas. *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 floodplain horizons of the Faig Mine. Its habitat is subject to a certain degree of interpretation, since no rooting structures were found associated with foliage or axes of this species. However, well-articulated foliage of this species together with seeds of the *Pachytesta* type were abundant in floodplain shales immediately overlaying the coal seams Faig-1 and Faig-2 and are interpreted as parautochthonous there (Fig. 2.7). 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 *Odontopteris* sp. and the leptosporangiate fern *Nemejcopteris feminaeformis (=Pecopteris feminaeformis)*. Cordaitaleans are difficult to characterise palaeoecologically in Ogassa. Evidence from parautochthonous remains suggests a habitat in distal areas of alluvial fans.

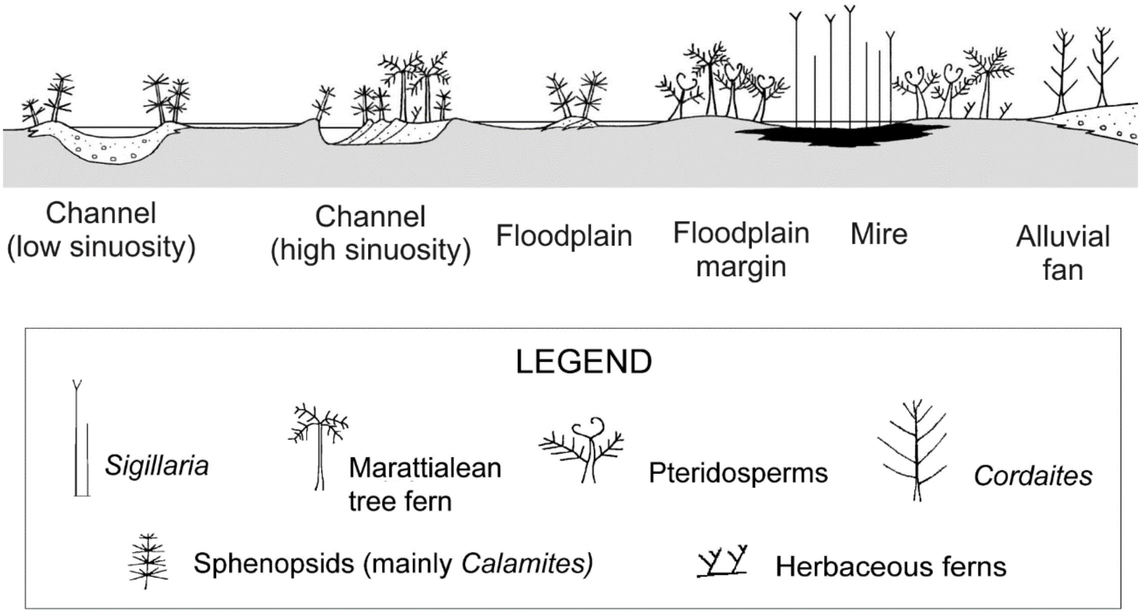


Fig. 2.7. Reconstruction of Uppermost Pennsylvanian wetland vegetation from Ogassa (from Martín-Closas and Martínez-Roig 2007).

The Ogassa-Surroca plant communities show most similarity with the communities described in the Graissessac Basin, Languedoc by Martín-Closas and Galtier (2005) and in the Erillcastell basin, Eastern Pyrenees, Catalonia by Tosal et al. (2022). In comparison with Graissessac a similar habitat was found for *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 Pennsylvnian of the Illinois Basin (United States) by Dimichele and Phillips (1994). Other species which are abundant in Ogassa, such as *Alethopteris pennsylvanica* var. *pyrenaica* and the leptosporangiate fern *Nemejcopteris feminaeformis*, were not found in Graissessac.

In comparison with Erillcastell, many plants show a similar habitat. This is the case of calamitaleans and cordaitaleans. Also, *Sigillaria brardii* grew in both basins in peat mires, laterally related to floodplains but Ogassa differs because this plant was not found growing also in riverine settings, which is general rule in the uppermost Pennsylvanian of Erillcastell and in other basins, e.g., in Nova Scotia (Falcon-Lang and Scott 2000). Marattialean tree ferns (*Polymorphopteris polymorpha*) also show relatively different distributions in Ogassa and Erillcastell, being more affine to floodplain margins than to riverine habitats in the latter basin. Pteridosperms were rare in Erillcastell and thus difficult to relate to a specific habitat.

The intramontane plant communities from the uppermost Carboniferous of Ogassa and other South European basins can be also compared with coeval wetlands from lowlands bordering the Hercynian Range, and generally paralic in nature (i.e. coastal and brackish). A well-documented example of these wetlands is provided by Dimichele and Phillips (1994) in the Illinois Basin (USA). The North American lowland basins differ basically from the intramontane South European basins by the complete absence of *Sigillaria* in peat mires, and its substitution by marattialean tree ferns. In contrast, another South European paralic setting, described in the latest Stephanian of Puertollano (Ciudad Real, South Spain) by Wagner and Álvarez-Vázquez (2015), showed large tree lycopsid swamp forests, in that case belonging to genus *Omphalophloios*.

In sum, the latest Pennyslvanian plant communities of Ogassa contribute to document the diversity of South European intramontane wetlands in terms of composition and plant distribution. They also provide evidence to document that some species, such as *Sigillaria braardii* and *Polymorphopteris polymorpha*, showed unusual plasticity in their habitats soon before their final extinction near the Carboniferous – Permian boundary in Europe.

Description of stops

STOP 1. LOWER OPENCAST MINE OF CAN CAMPS

Location. This small mine is located halfway from the small road from the house of Can Camps (an old miner house now transformed into a rural hotel) to the Can Camps pass.

Objective. Study of plant assemblages in fluvial facies.

Description. This outcrop shows a succession of grey sandstones intercalated with grey siltstones of the Transition Unit. The sedimentological features are exceptionally well-preserved for a Carboniferous Pyrenean outcrop. Sandstones are organized in sets of megaripples with undulated upper surfaces. Siltstones are rich in more than 1 m long *Calamites suckowii* stems, while some upright stems of the same plants cross the sandstones (Fig. 2.4, 1-2). Compressed *C. 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. 2.4, 6). Large portions of the marattialean tree fern foliage *Polimorphopteris polymorpha* (=*Pecopteris polymorpha*),. Several brush-shaped rooting apparatuses, about one meter in diameter are associated with this foliage (Fig. 2.4., 4-5). Associated and less-abundant pteridosperm pinnules belonging to *Alethopteris*, can be also observed in siltstones too. Laterally, in an outcrop just below the main outcrop, with similar facies but with a difficult access, pinnules of *Sphenopyllum oblongifolium* are abundant.

Rippled sandstones have been attributed to fluvial hydraulic sand dunes preserving the undulated dune shape. Siltstones correspond to deposition in the same channel during low-hydraulic regimes. This outcrop gives the clue to interpret the habitat of both *C. suckowii* and *P. polymorpha* in the Ogassa wetlands. The upright *C. suckowii* stems in hydraulic sand dunes suggest active growth of these tree sphenopsids within the fluvial channel. Compressed *C. suckowii* axes radiating from a central point may correspond to the branching of erect buried axes after regeneration, indicating in situ growth. Large brush-shaped root systems are attributed to marattialean tree ferns, which associated to well-articulated foliage, suggest autochthony of these plants near the channel margins.

STOP 2. UPPER OPENCAST MINE OF CAN CAMPS ("CELOBERT DE CAN CAMPS" OUTCROP)

Location. Small mine located about 100 m above the former mine.

Objective. Study of plant assemblages in peat mire facies

Description. The Celobert outcrop corresponds to the base of an important coal seam after exploitation. The bed surface, dipping about 45º south, is completely covered by *Stigmaria ficoides* axes and rootlets. Some of these structures radiate from a central rounded depression, which may correspond to the tree stump.

These fossils have been attributed to the pioneering plants that would develop into the tree-lycopsid mire that provided the peat precursory of the overlying coal. No other remains have been found in this bed suggesting that only tree lycopsids inhabited the peat mire. The possible stumps from which *Stigmaria* axes radiate were probably compressed within the overlaying coal, which indicates continuity between the *Stigmaria* soil and the overlaying original peat.

STOP 3. UPPER OPENCAST MINE OF CAN CAMPS (OUTCROP BESIDE THE DEBRIS OF THE MINE)

Location. Outcrop near a debris pile, below the Celobert mine. A small path has been arranged for the present visit.

Objective. Study of cinerite deposits with fossil plants.

Description. A succession of two cinerite beds intercalated with shale and coal can be observed. These beds are covered by large impressions of *Sigillaria brardii* logs, with different diameters, some of them ca. one meter across. The stems show preferential orientation, which is NW-SE for the lower bed and N-S to NE-SW orientation for the upper cinerite (Fig. 2.3, 4-5). Charred plant remains are found within the cinerite. Laterally equivalent outcrops of difficult access show the irregular base of these cinerites with abundant porosity.

The origin of this deposit has been attributed to a *Sigillaria braardi* peat mire swept away by a burning cloud of volcanic ash. The large lycopsid trees living in the swamp fell and were oriented by the fast-moving ash cloud, which finally embedded them. The burning ash made the water of the original peat boil and produce, by degasification, the enormous porosity in the contact between the cinerite and the underlying coal. Owing to the distinct orientation of the *Sigillaria* logs it can be deduced that different volcanoes produced each cinerite deposit. The composition of the assemblage together with the observations of previous stop indicate that these *Sigillaria* peat mires were monospecific. Different diameters of the *Sigillaria* logs suggest that the peat mire was a mature rather than a pioneering community.

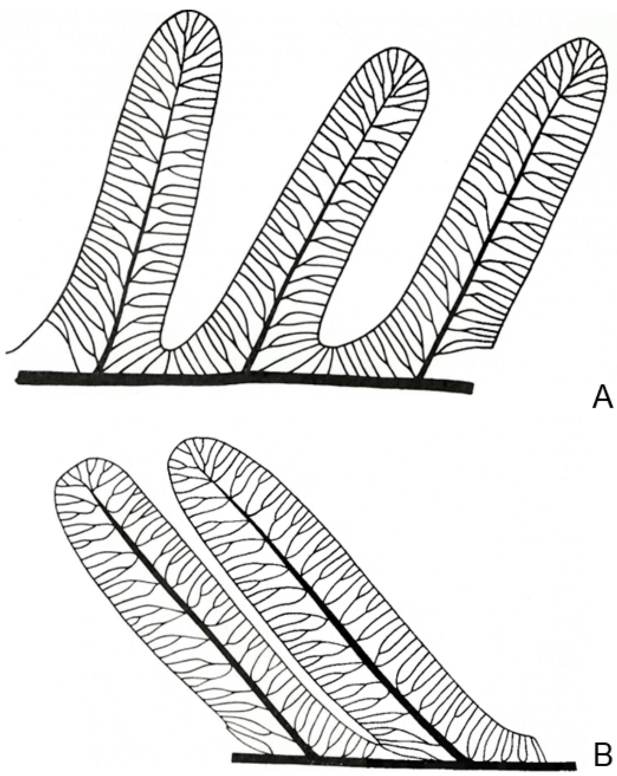
STOP 4. ENTRANCE TO THE FAIG MINE

Location. Mountain track road going from Can Camps Pass to the Faig Mine and further away to the Maus prairies. The Mine entrance is at 1400 m a.s.l.

Objective: Study of plant assemblages from floodplain to lacustrine deposits.

Description. This outcrop shows a succession of dark grey, finely laminated siltstone and shale. The plant assemblage is rich in *Alethopteris pennsylvanica* var. *pyrenaica* WAGNER 1986, originally described from the Upper Carboniferous of Ogassa (Surroca coalfield). This variety is mainly distinguished from the nominal variety by displaying more elongated pinnules and a venation pattern with two dichotomies, the first of which starts close to the main vein (Fig. 2.8). This outcrop could be designed as a neotype locality since the exact type locality was not indicated in the protologue. Associated to this medullosacean plant there also large *Pachytesta* seeds and a varied, but less-abundant array of other plant remains, such as *Pecopteris polymorpha (= Polymorphopteris polymorpha), Pecopteris feminaeformis (= Nemejcopteris feminaeformis*), *Odontopteris* sp., *Calamites suckowii, Annularia stellata, Pachycordaites* sp.…

The deposits have been attributed to deposition in permanently inundated floodplains forming shallow lacustrine-like environments. The preservation of the lamination and the abundant organic matter suggests anoxic bottom conditions. No rooting structures were found in these deposits suggesting that all the remains deposited there are either parautochthonous or allochthonous. However, the abundance of *A. pennsylvanica* var. *pyrenaica*, with a high degree of articulation and associated to other organs putatively from the same plant, such as the *Pachytesta* seeds, suggest that this



plant grew very close to the permanently inundated floodplain.

Fig. 2.8. Comparison between the pinnules of *Alethopteris pennsylvanica* s.s. (A) and *A. pennyslvanica* var. *pyrenaica* (B). Size of pinnules ca. 2-3 cm long. From Wagner (1968).

3. POST-MEETING FIELD TRIP TO THE LATE MIOCENE OF LA CERDANYA

Geological seting

La Cerdanya is certainly one of the Pyrenean valleys with a more distinct geographical identity. It is oriented from northeast to southwest, even east to west in some parts, i.e., perpendicular to and much larger than most of the narrow and shadowy valleys of the same mountain range. These peculiarities have their explanation in the geological origin of the Cerdanya valley, which resulted from the action of a large strike-slip fault, called La Tet fault (Fig. 3.1). This fault obliquely cut the eastern Pyrenees, from La Seu d'Urgell, in Spanish Catalonia, to the Rosselló, in French Catalonia, about 11 million years ago, in the upper Miocene. Over 4 million years, the blocks on both sides of the fault moved laterally and the resulting stresses caused a subsidence of the ground, several hundred meters in depth (Cabrera et al. 1988). Consequently, a tectonic graben was formed where the sediments accumulated, forming what is known as a pull-apart basin. This type of basins is characterized by (1) an elongated shape, (2) a strong asymmetry in the sediment thickness, being much thicker close to the fault than opposite to it, and (3) the occurrence of internal thresholds which compartmentalize the basin in subbasins with distinct depositional environments. In La Cerdanya basin, two main subbasins were defined, the Puigcerdà subbasin to the northeast and the Bellver subbasin to the southwest, separated by the Tossal d’Isòvol threshold.

The sedimentary infill of the La Cerdanya Basin has been separated in two different stratigraphic units of different ages and bounded by an angular unconformity (Cabrera et al 1988). The lower part, known as Lower Neogene Unit, was deposited during the Tortonian, approximately equivalent in non-marine facies to the regional stage Vallesian, ca. 11 Ma. During the deposition of the Lower Unit, three geographical and environmental belts were differentiated in La Cerdanya basin, according to Cabrera et al. (1988) (Fig. 3.2):

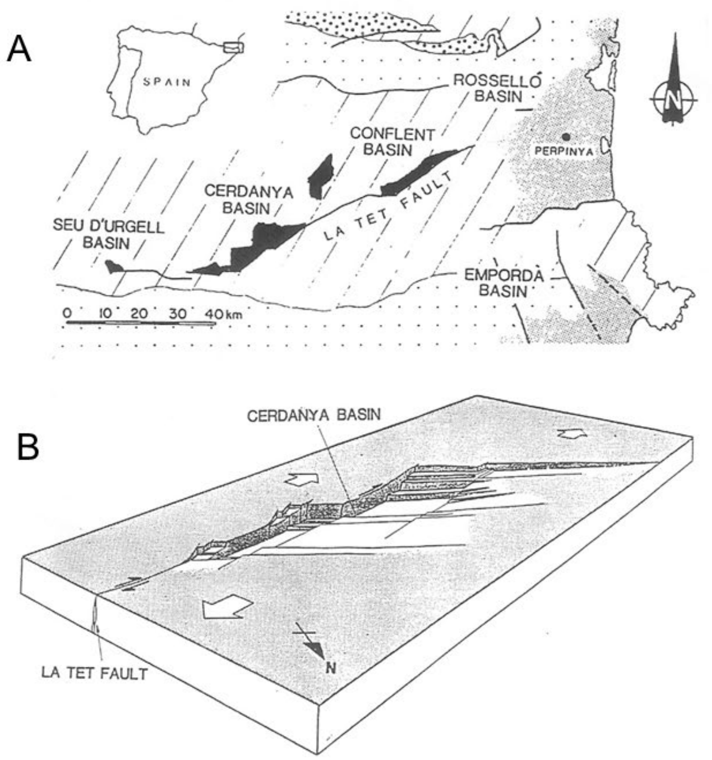


Fig. 3.1. Structural setting of La Cerdanya Basin A. Simplified geological map of the Eastern Pyrenees showing the La Tet fault with the rosary of Miocene basins, including La Cerdanya Basin formed by the activity of this fault (from Cabrera et al., 1988). B. Sketch of the basement of la Cerdanya Basin showing basin asymmetry and internal compartmentation (from Roca, 1986) in horsts and grabens.

- (1) An alluvial to fluvial system in the area occurred in the northeastern Puigcerdà subbasin, from Alp to Sallagosa/Saillagouse.
- (2) A marshy area occurred in the southwestern part of the Puigcerdà subbasin, located mainly near Prats i Sansor, Sanavastre and Das.
- (3) The Bellver sub-basin, occupied mainly by a large lake.

In this field trip we will visit the deposits of these three palaeoenvironmental belts of the basin, the fluvial sediments in Stop 1, the wetland deposits in Stop 2 and the lake deposits in Stop 3. In the latter two depositional environments fossil plant remains are common.

During the latest Miocene or Messinian (in non-marine facies the equivalent regional stage is called Turolian), the Upper Neogene Unit was deposited (Fig. 3.2). This unit was confined mainly to the Bellver subbasin. Most deposits of this subunit are conglomerates from alluvial fans but also finer sediments from fluvial to lacustrine facies have been recorded. This field trip will be only devoted to the Lower Neogene Unit.

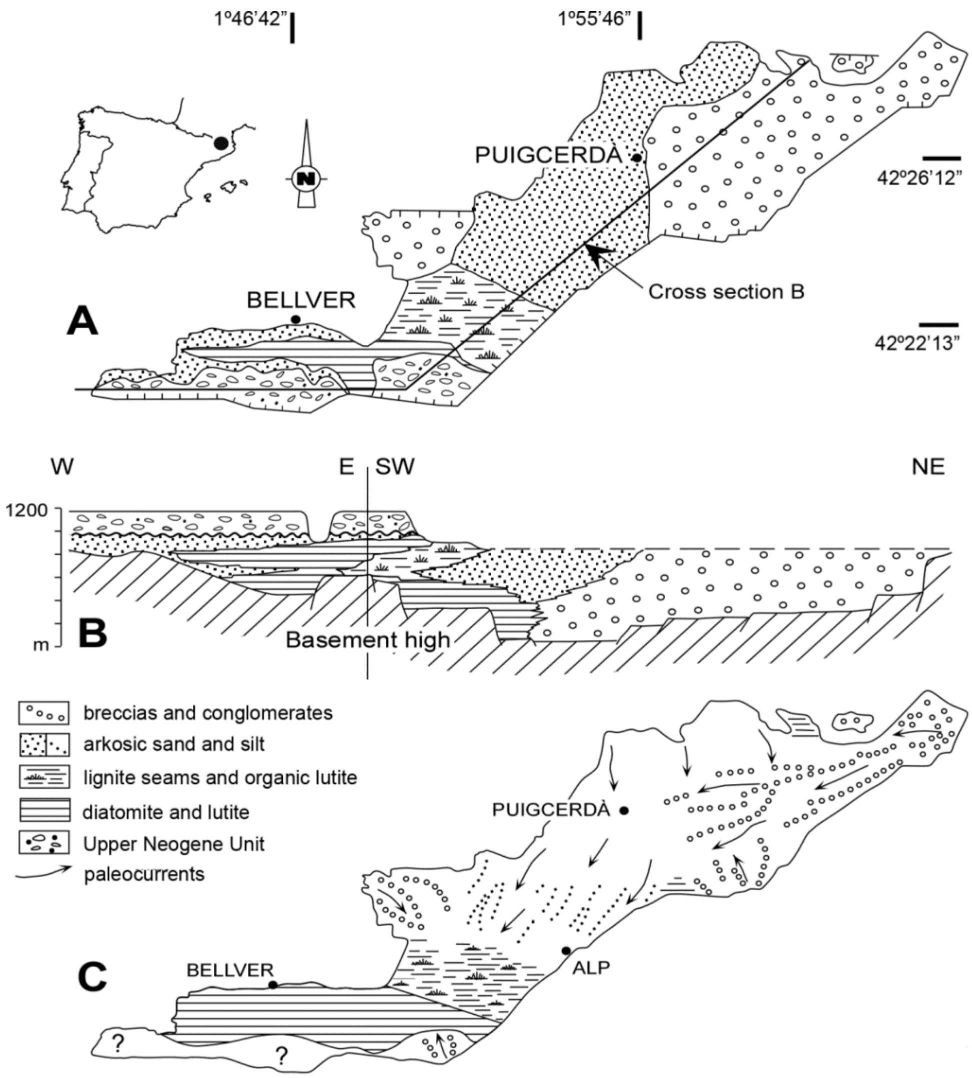


Fig. 3.2. Geological map and sedimentological setting of the La Cerdanya Basin (modified from Cabrera et al., 1988). A. geological sketch of the Neogene deposits from the La Cerdanya Basin. B. Cross section along the main axis of the basin. C. Sedimentological interpretation of basin's palaeogeography during the maximum lacustrine extension in the upper Miocene (Tortonian).

The fluvial network of La Cerdanya Basin

During Tortonian (Lower Neogene Unit), most of the Puigcerdà subbasin was occupied by an alluvial to fluvial system draining from the basin margins to the southwest. Two types of alluvial to fluvial systems were defined by Cabrera et al. (1988).

- (1) Alluvial fans with granite source area in the of the Puig Pedrós and Carlit massifs, to the north of the basin (Fig. 2). The alteration of the granite in a climate that was much warmer and humid than today, supplied mostly silts and sand (arkoses), i.e., sediments with a high content in feldspars, to the river network. These sandy fluvial systems coming from granite source areas had their deltas either directly in the paleolake of Bellver, in the wetlands surrounding it, or merged with other rivers in the central parts of the basin.
- (2) Alluvial fans with metamorphic-rock source-areas in the Puigmal Massif, to the East of the basin (Fig. 3.2). This type of rock, when altered, supplied to the river network conglomerates, coming from the alteration of shales and schists.

Both types of alluvial to fluvial sediments were at the end mixed in the central area of the basin (Fig. 3.3). The finer floodplain sediments show edaphic features of hydromorphic soils, indicating that the fluvial areas were periodically flooded and drained, which corresponds well to a seasonal climate. We know almost nothing from the plants living in these floodplains, but the mammal remains thought to thrive there, show that both open grasslands intercalated with woods occurred.

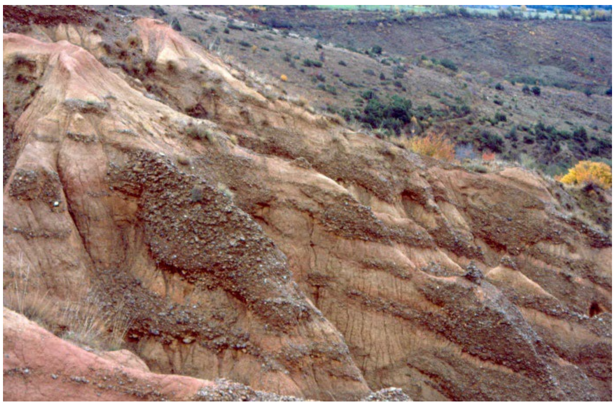


Fig. 3.3. Outcrop at Les Guilleteres near the village of Meranges showing conglomeratic lenses corresponding to sections of fluvial channels, filled in by schist clasts, surround by finer sediments corresponding to floodplain silts.

The wetlands surrounding the lake

Until the mid of the twentieth century, the economic activity of the people of the area located between Prats i Sansor, Sanavastre, Das and Alp was divided between agriculture and coal mining. The coal from the upper Miocene of La Cerdanya belongs to the group of the lignite, it has a low calorific value and gives off a large amount of ash and volatile materials when burnt (Closas, 1948). This coal was exploited for local consumption, in narrow galleries during the 19th and early 20th Century, and later in small pit mines that were active until the decade of 1980'. Only one of these mines is still visible today near Sanavastre, where it has been protected because it contains a small lake fed by groundwater that allows migrating water birds to rest (Fig. 3.4). The coal-bearing sequences were formed by compaction of peat deposited in a wide wetland belt surrounding the lake of Bellver in its northeast side.

These wetlands represented in fact the deltas of rivers that reached the lake, coming from the Puigcerdà sub-basin. A geochemical study of the coal components, as well as the fossil remains of the plants found in the intercalated clay, suggest that the remains precursory of the peat were non-woody stems (Permanyer et al. 1998), probably of plants related to reed families Poaceae and Sparganiaceae. As documented both by plant megaremains and pollen, apart from the reeds, the Cerdanya wetlands contained abundant hydrophytic plants and a well-developed riparian vegetation, which will be studied into more detail in Stop 2.

Coal miners found the quite well-preserved skeletons of a large number of mammals in the coal bearing sequences, allowing us to know about the vertebrate fauna that inhabited both in the extensive river floodplains from the Puigcerdà subbasin as in the wetlands themselves (Golpe-Posse, 1981).

Fig. 3.4. Field picture of the outcrop of Sanavastre, as seen in 1992, showing the intercalation of lignite and clay coarsening upward to sand. To date the lower part of the section is almost covered by debris.

Among the most frequent mammal remains found were the bones and teeth of a primitive horse, *Hipparion catalaunicum*, which lived in grassy meadows and open forests in floodplains and wetland margins. It was a pony-sized horse, but more graceful than ponies in appearance. Among other characters, it is also distinguished from modern horses by having three fingers. Other prominent herbivores were deinotheriids and gomphotheriids, both from the elephant family. Deinotheriids (*Deinotherium laevius*) were similar in size to modern elephants but with their lower defences curved towards the ventral part. It is believed that they lived in open spaces, such as grasslands. Gomphotheriids (*Tetralophodon longirostris, Gomphotherium angustidens*) were smaller than modern Indian elephants. They had short, almost straight, shovel-shaped upper and lower defences, which were adapted to dig into the muddy soils of marshy areas in search of tubercles on which they probably feed. In wetter meadows of river plains there was also the rhinoceros with two species (*Dicerorhinus schleiermacheri, Aceratherium incisivum*). The riverbeds had a very characteristic inhabitant, the beavers, represented by abundant remains belonging to two species (*Chalicomys jaegeri* and *Palaeomys castoroides*). On the margins of the valley there were wooded areas where eer (*Euprox dicranioceras*) and wild pigs (*Microstonyx major*) similar to Asian babirusas lived. The remains of a strange extinct mammal with longer forelimbs than the hindlimbs, *Chalicotherium grande*, have also been found. It is believed that this animal fed on the leaves of the higher branches of trees, such as the today's giraffe. The only large predator found so far is *Amphicyon major*, another strange extinct mammal of intermediate appearance between a bear and a wolf. Apart from these large vertebrates, there were also abundant small mammals, such as rodents (Agustí and Roca 1987).

The paleolake of Bellver

The "Batllia de Bellver" (Bellver large municipality) is not only different from other parts of La Cerdanya by historical reasons (for example it belongs to a different Spanish province than Puigcerdà), but its peculiarities already started in the deep geological past. Not only this part of the basin is where the La Tet fault produced a stronger subsidence, but it was also palaeogeographically separated from the remaining of La Cerdanya by a tectonic threshold already in the Miocene (Cabrera et al., 1988). This horst, called Tossal d'Isòvol, is represented today by an alignment of hills, almost crossing the valley (Fig. 3.2) This set of factors caused a lake to form in the area surrounding Bellver that the structural threshold, like a dam, isolated from the fluvial sediments arriving from the Puigcerdà subbasin.

The paleolake of Bellver has been classified as a deep, meromictic lake (Fig. 3.5). Its waters went rarely mixed, so that the oxygen from the surface rarely reached the lake bottom and biotic activity was there generally limited to anoxygenic bacteria. Therefore, the remains of plants and animals that accumulated at the bottom of the lake underwent less biodegradation and have given rise to exceptionally well-preserved fossils, especially leaves and insects. Periodically the lake bottom was oxygenated for a short time enabling for the development of a poor benthos of small annelids and ostracods.

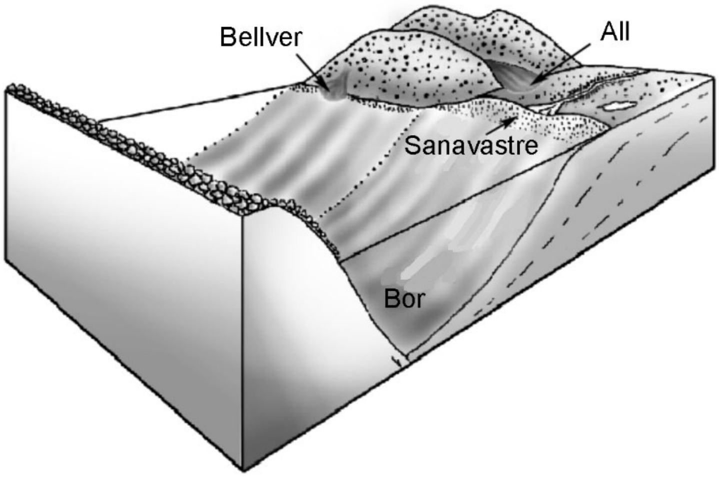


Fig. 3.5. Reconstruction of the paleolake of La Cerdanya, showing deeper water to the South, close to the active fault (from Martín-Closas and Delclòs, 2007)

Another very important character of that lake was the high organic activity in the water column, which resulted in the accumulation of hundreds of meters of silica skeletons belonging to diatoms, forming a diatomite, especially in the central lacustrine facies, whereas in the lake margins the bottom sediment was terrigenic clay. A single fossil species of a planktonic diatom, apparently endemic from the lake, *Aulacoseira ceretana*, was the main component of this diatomite (Haworth and Sabater, 1993). The disproportionate growth of populations of this golden alga, and the formation of sediments from their skeletons of silica, is characteristic of eutrophic lakes. Diatoms, along with another group phytoplanktonic algae, the chlorophyte *Botryococcus*, have the particularity of containing in their cytoplasm droplets of lipids. Once these algae died, sunk to the lake bottom and were buried, these lipids may transform molecularly until becoming hydrocarbons (oil and gas). A geochemical study of the diatomite of La Cerdanya showed that it could have developed into an oil source rock, but diagenetic maturation was not sufficient for final hydrocarbon production (Martín-Closas et al., 2005).

The paleolake of La Cerdanya contained also aquatic vascular plants (Fig. 3.6). The most abundant were the pondweeds, represented by the pondweed *Potamogeton orbiculare*, and the hornwort (*Ceratophyllum schrotzburgense*), more rarely the water chestnut *Trapa ceretana*, which indicate high dissolved phosphorus and ammonium (Martín-Closas et al., 2006). These plants lived on the shores of the lake, along with aquatic invertebrates, such as trichopterans, snails and ostracodes. Aquatic vertebrates, such as fish, may have lived in the La Cerdanya palaeolake too, but their skeletons are rare and partially dissolved (Martín-Closas and Delclòs, 2007). As shown by De las Heras et al. (1989) in a geochemical study, the original calcium phosphate of these bones went dissolved shortly after burial due to acidic pH of interstitial water and became a phosphate jelly. Subsequently, during deep burial, these jellified phosphates precipitated forming irregular nodules that contain inside, beautiful geodes of olive-green crystals belonging to a rare mineral called anapaite [$FeCa_2 (PO_4)_2.4H_2O$]. Apart from La Cerdanya, this mineral is only known from three or four more localities in the World. This explains why vertebrate remains are almost absent in the diatomites.

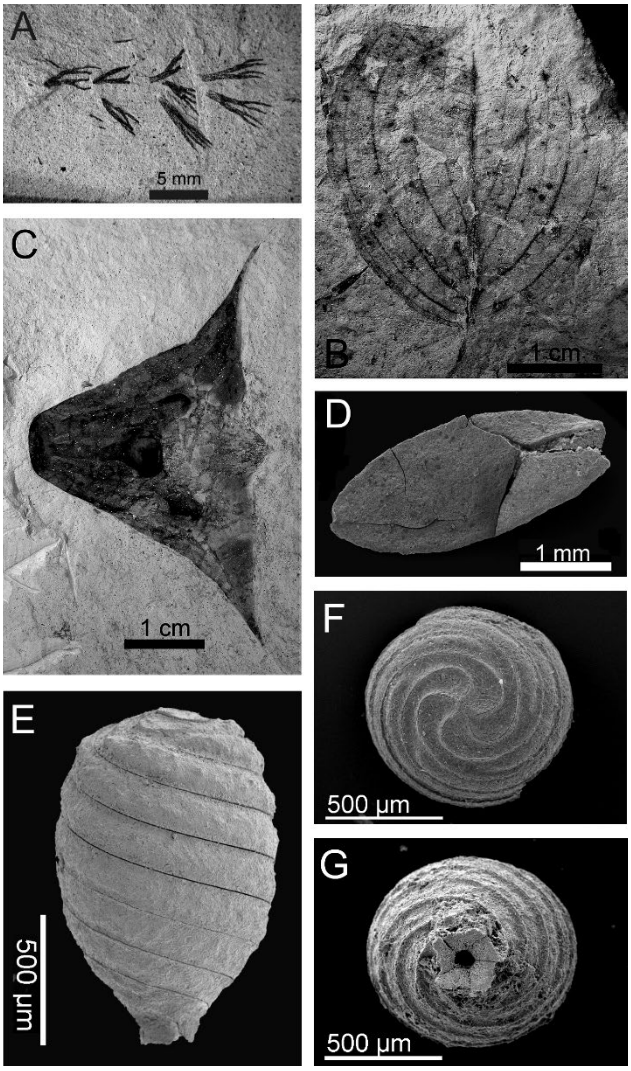


Fig. 3.6. Aquatic algae and vascular plants from the Miocene lake of La Cerdanya A. *Ceratophyllum schrotzburgense*, B. *Potamogeton orbiculare*, C. *Trapa ceretana*, D. *Najas marina*, E-F *Lychnothamnus barbatus* subsp. *megalicarpus*. From Martín-Closas and Delclòs (2007).

But beside the aquatic plants and animals, the diatomites of the Bellver paleolake contain abundant terrestrial plant and insect remains. These fossils were studied since the late nineteenth century starting with the pioneer work of Rérolle (1884-1885) for the plant remains. Dicot leaves of trees growing around the lake are undoubtedly the most abundant plant remains (Fig. 3.7a-c). They were generally transported by the wind and river inlets to the lake (Martín-Closas et al., 2005). Once saturated with water, they sank into the dark and anoxic waters of the lake and settled on the bottom, where they were quickly covered by mud and diatom frustules. Along with these leaves there is also a large amount of fossil pollen. The plant species are typical of beech and oak forests mixed with conifers that grew on the slopes, while the lakeshore was populated by maples, alders, pinaceous and cupressaceous-taxodiaceous conifers and ferns (see Barròn et al., 2014 for an actualized taxonomic list). The forests of La Cerdanya 11 million years ago grew under a warm temperate and seasonal climate. Two leaf-based paleoclimatic studies have determined that the average annual temperature in La Cerdanya was around 11.5ºC (Barrón et al., 2016; Tosal et al., 2021). Although at that time the dominant climate in Catalonia was subtropical, La Cerdanya was already located in a mountain range, at an altitude of about 1000 m, similar to the current one (Tosal et al., 2021). However, several thermophilous plants such as the Lauraceae (*Laurophyllum*, *Daphnogene*), Araliaceae (*Aralia*) and even a palm tree (*Sabalites*) grew along with oaks and beeches. Many of the fossil species of trees from La Cerdanya have their closer living relatives in present-day China and Japan. Particularly northern Honshu Island of Japan is the closer climate analogue of the Miocene La Cerdanya (Tosal et al., 2021).

Beside the leaves there are also well-preserved remains of insects that lived around the lake. Remains of ants are very abundant, especially the wings they wore during bridal flights. Also frequent are beetles and bees. Other less abundant insects are dragonflies and termites (Ortuño and Arillo, 1995). All these insects, as well as the feeding traces left by their larvae on the leaves of trees, have also been the subject of abundant paleontological studies (for a synthesis see Martín-Closas and Delclòs 2007).

Fig. 3.7a. Examples of dicot angiosperms found in the Miocene of la Cerdanya (from Tosal et al. 2021). A: *Daphnogene* sp. (MGB 89667-a). B: *Laurophyllum pseudoprinceps* (MGB 89666). C: *Buxus pliocenica* (MGB 89668). D: *Parrotia pristina* (MGB 89688-a). E: *Cercidiphyllum* sp. (MGB 89669-a). F: *Populus tremulaefolia* (MGB 89671). G: *Cassia* sp. (MGB 89672-a). H: Fabales sp. indet. 1 (MGB 89698–1). I: Fabales sp. indet. 2 (MGB 89698–2). Scale bar 1 cm. MGB numbers refer to the collection of fòssil plants from the Museu de Ciències Naturals de Barcelona.

Fig. 3.7b (continued – 1). Examples of dicot angiosperms found in the Miocene of la Cerdanya From Tosal et al. 2021. A: *Zelkova zelkovifolia* (MGB 89674-a). B: *Ulmus plurinervia* (MGB 89675). C: *Quercus drymeja* (MGB 89676). D: *Q. mediterranea* (MGB 89677). E: *Q. hispanica* (MGB 89678). F: *Q. kubinyii* (MGB 89679). G: *Fagus pristina* (MGB 89680). H: *F. gussonii* (MGB 89681). I: *Juglans* sp. (MGB 89682). J: *Carya serrifolia* (MGB 89683). K: *Carpinus grandis* (MGB 89684). Scale bar 1 cm. MGB numbers refer to the collection of fòssil plants from the Museu de Ciències Naturals de Barcelona.

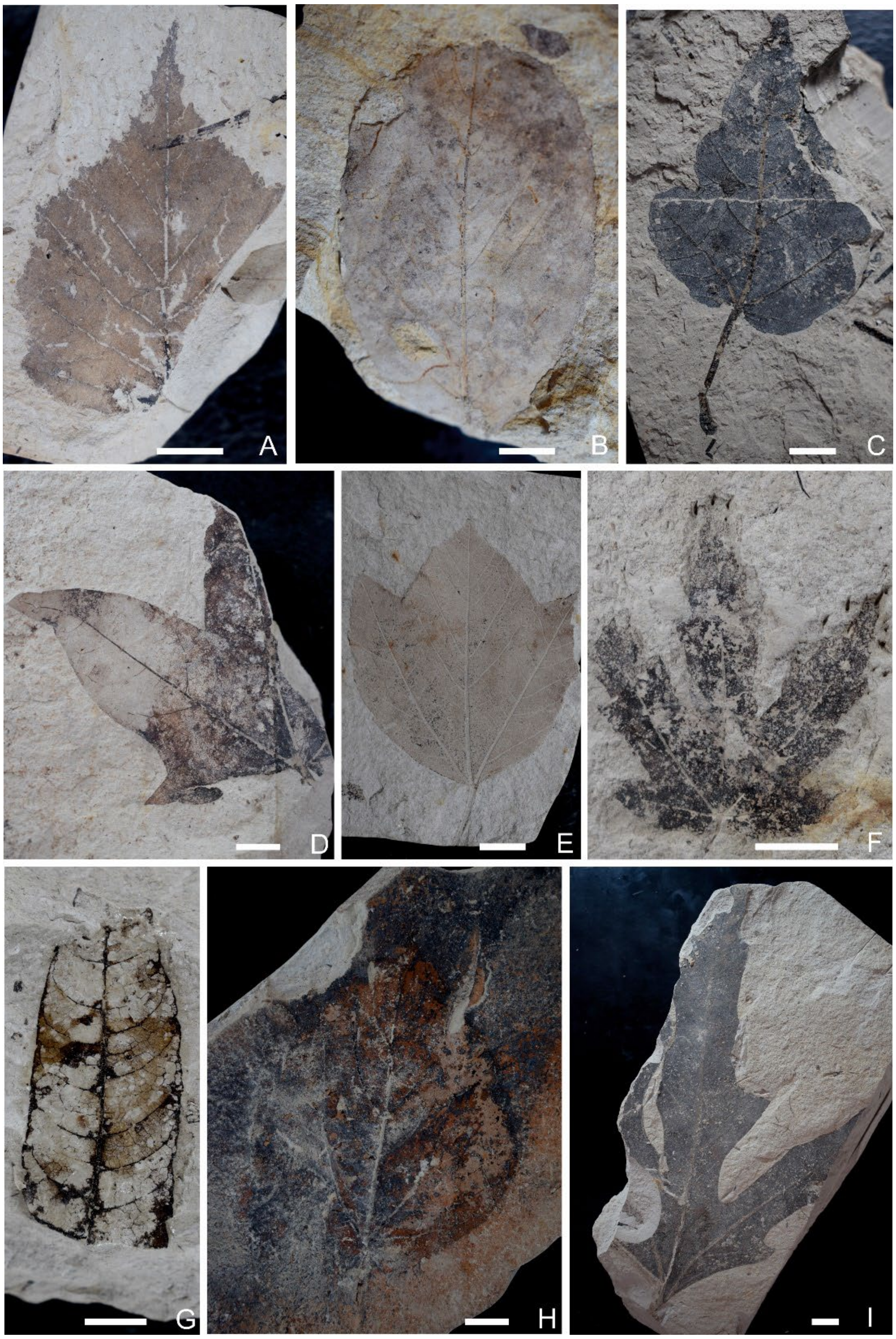


Fig. 3.7c (continued-2). Examples of dicot angiosperms found in the Miocene of la Cerdanya. (from Tosal et al. 2021). A: *Betula insignis* (MGB 89685). B: *Alnus occidentalis* (MGB 89687). C: *Acer tricuspidatum* (MGB 89691). D: *Acer integerrimum* (MGB 89689). E: *Acer pyrenaicum* (MGB 89690). F: *Acer palaeosaccharium* (MGB 89694). G: *Cedrela* sp. (MGB 89695). H: *Tilia vidali* (MGB 89696). I: *Aralia multifida* (MGB 89697). Scale bar 1 cm. MGB numbers refer to the collection of fòssil plants from the Museu de Ciències Naturals de Barcelona.

The final infilling stages of the Bellver palaeolake

The landscape described so far changed according to the tectonic, sedimentary and climatic evolution in the last 10 million years. Thus, the palaeolake of Bellver filled up completely 8 million years ago, before the end of the Tortonian. We know that in the last stages, it was confined near the still active La Tet fault, that is, on the southern margin of the basin, forming an narrow strip that extended south of Bellver. The limnological characters of this last stage of the lake changed drastically. It became shallow, well-oxygenated and alkaline (Martín-Closas et al., 2006). The diatoms disappeared and the charophyte *Lychnothamnus barbatus* subsp. *megalicarpus* associated to *Najas marina* became common (Fig. 3.6 D-G), indicating a shift in water trophism from eutrophic-mesotrophic to mesotrophic-oligotrophic. This important change in the hydrology of the lake suggests that, during its last stages, the lake was mainly fed by groundwater from a calcareous aquifer, probably coming from the Devonian limestones of La Tossa d'Alp - El Moixeró Massif. The last narrow alkaline lake was finally filled in by fluvial arkoses and conglomerates coming from the Puig Pedrós Massif (Fig. 3.8).

The La Tet fault remained then inactive for a few hundred thousand years to have a last pulse at the end of the Miocene (Messinian), about 7 million years ago. In this last basin infilling stage alluvial and fluvial conglomerates from the Upper Neogene Unit were transported to the Bellver subbasin from the southwest (El Cadí Chain). Shallow ponds were formed again with similar biological and limnological features as those described for the end stage of the Bellver paleolake. At the end of the Cenozoic the Segre River ended up making its way beyond the valley and La Cerdanya changed from being an endorheic basin to a well-drained basin connected to the Ebro River, i.e. to the Mediterranean, and subject to erosion, which is today's situation.

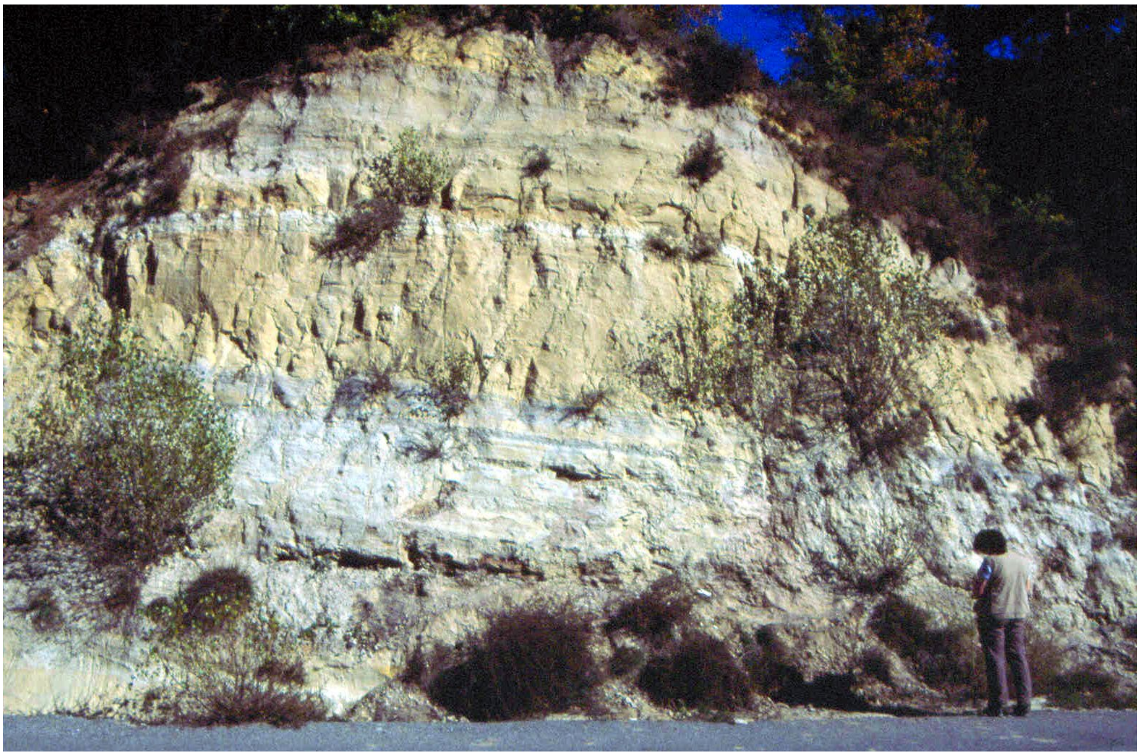


Fig. 3.8. Outcrop near Ridolaina (SW of Bellver) showing the last grey clays corresponding to the last stages of the Bellver lake (bottom of picture), before it was covered by yellow fluvial sand (arkoses), visible on the upper part of this outcrop.

Description of stops

STOP 1: BADLANDS “ESTERREGALLS D’ALL”

Location: This stop is located in the badlands cropping out north from the cemetery of the village of All. The visit follows a signalised nature path. There are several viewpoints with nice views over the southern margin of the graben.

Objective: Introduction to the geology of the la Cerdanya Basin and observation of the alluvial to fluvial facies of the Puigcerdà sub-basin.

Description. From East to West a succession of mountains represent the southern margin of the basin. These are the Puigmal massif, made of Cambro-Ordovician shist, the La Tossa d’Alp - Moixeró massif, made of Devonian limestone, and finally the Cadí chain made of Eocene alveolinid limestone. The La Tet Fault can be recognized by the remains of iron-flats at the hills bounding the southern margin of the basin (Fig. 3.9). Few is visible here from the northern margin of the basin. However, the basement high of Tossal d'Isòvol, subdividing the Puigcerdà and the Bellver Subbasins can be observed to the right.

A number of characteristic facies from the alluvial to fluvial part of the basin can be studied in the outcrop. The sequence shows a coarsening upward trend with fluvial facies at the base and more alluvial facies to the top (Fig. 3.10). Fluvial facies are characterised by small channels filled in by angular clasts made of mottled schists coming from the Puigmal massif. Floodplain deposits are mainly formed by silts with abundant mica and feldspars, characteristic of a granite source area, probably the Carlit massif in the northern margin. Edaphic features of hydromorphic soils, such as vertical decolouration patterns are also visible.

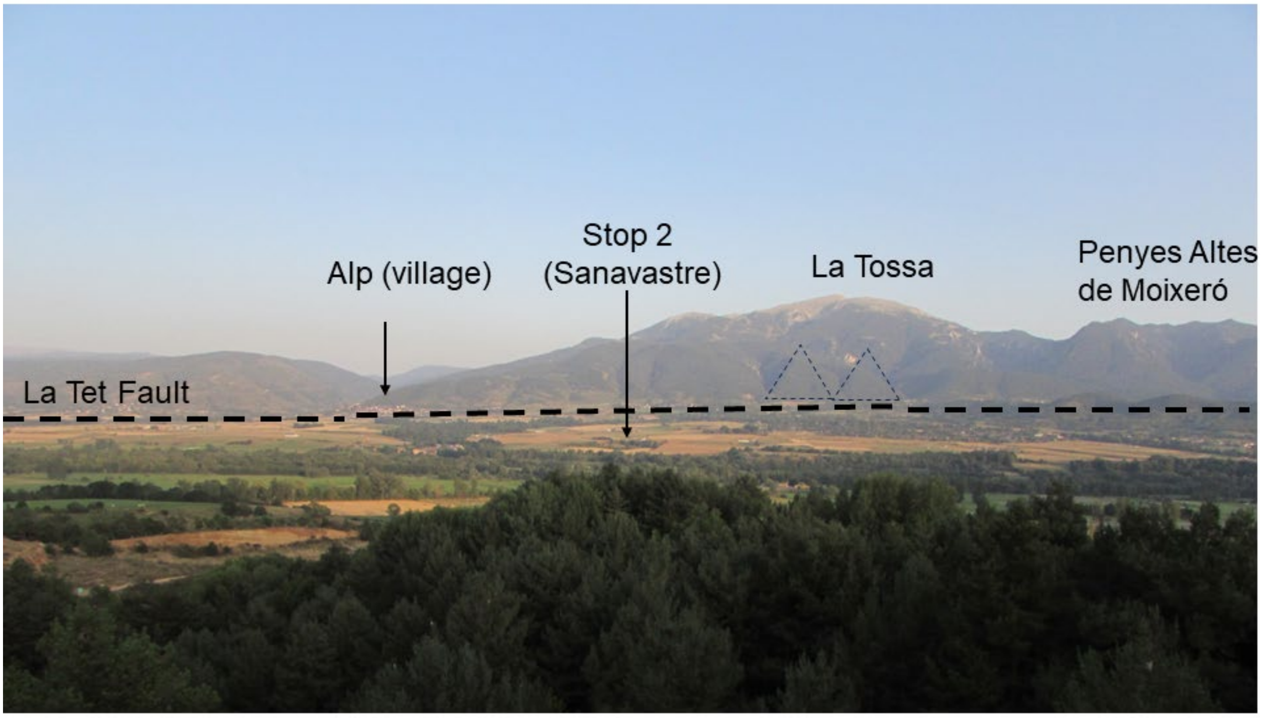


Fig. 3.9. Landscape overview of the southern margin of the La Cerdanya Basin as seen from Stop 1, showing the position of the main fault, and some topographic highs. Two examples of iron-flats are marked with triangles.

Fig. 3.10. Field picture from the Esterregalls d'All outcrop showing sections of fluvial deposits in most of the outcrop, visible by the discontinuous shape of the conglomeratic beds (sections of fluvial channels). Massive conglomerate at top corresponds to alluvial fan deposits.

STOP 2: OLD PIT MINE OF SANAVASTRE

Location: Small lignite pit mine and pond, west of the entrance to Sanavastre village (Alp municipality).

Description: The coal-bearing succession represents the only outcrop visible to date of the wetland belt of the basin. The succession has been partly covered in the last years by debris and only the upper part of it is still visible. The log shows a thickening and coarsening upward trend with intercalation of up to 1m thick lignite and clay at the base grading to silt and arkose sand to the top, with thin lignite beds (Fig. 3.11). This succession has been interpreted as the infilling of a deltaic pond by a river mouth inlet.

Several palynological and taphonomic studies devoted to this outcrop (e.g. Barrón 1997; Martín-Closas, 1995) allowed to reconstruct the local vegetation. The most characteristic water plant remains are *Trapa ceretana* nuts (Fig. 3.6 C), found at the base of the succession, which represents the neotype locality of this endemic species, as defined by Martín-Closas et al (2006). Abundant stems of reeds represent probably the pond margin vegetation, while abundant leaves of *Osmunda, Acer tricuspidatum* Rerolle and *Alnus* formed probably the leaf litter of the surrounding riparian vegetation (Fig. 3.12). Palynological data complement the water plant assemblage with pollen from water lilies and zygospores of conjugate algae among others.

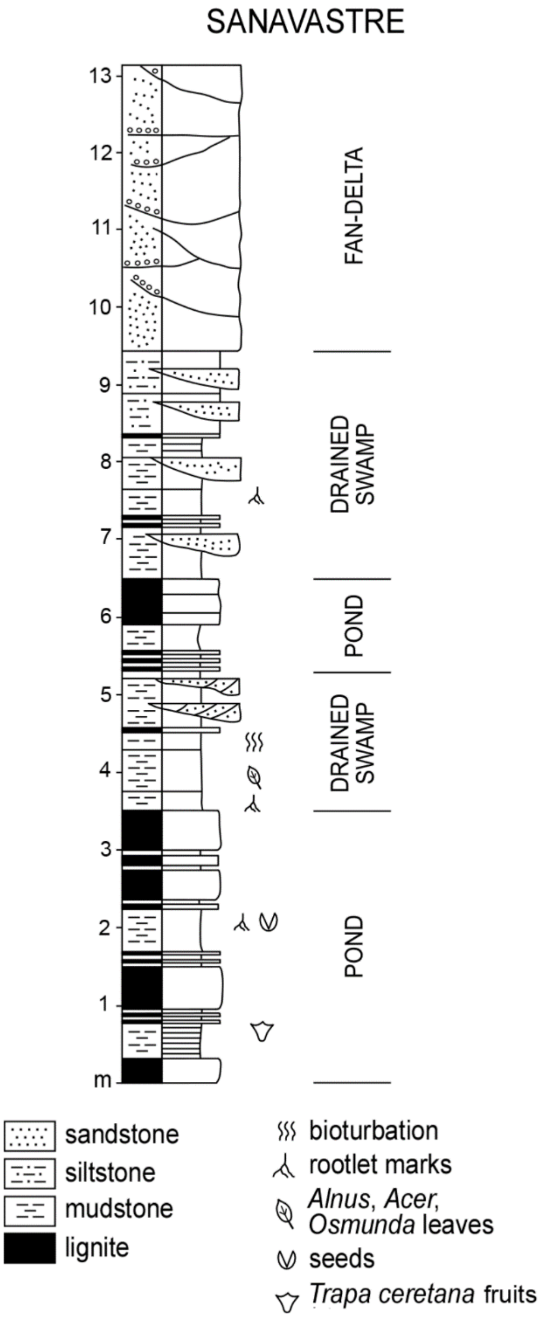


Fig. 3.11. Stratigraphic log of the Sanavastre opencast mine (from Martín-Closas et al. 2006) including at the base the neotype layer of *Trapa ceretana.*

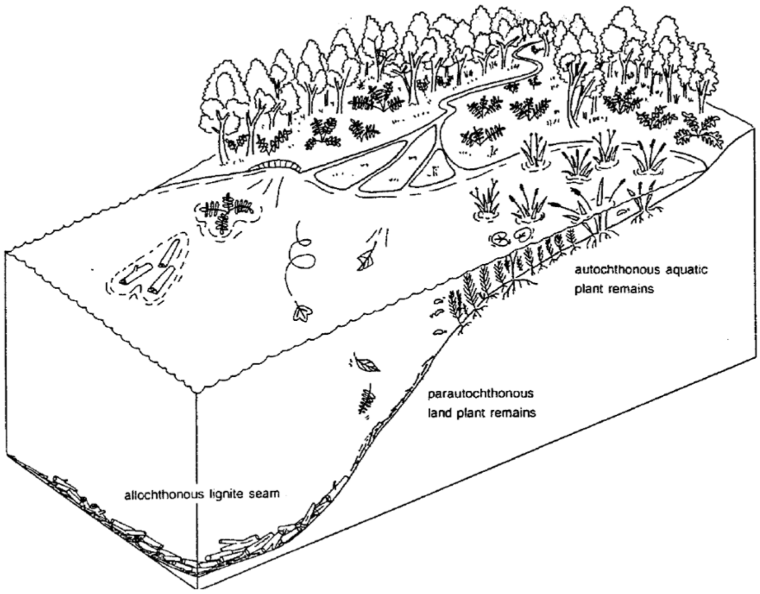


Fig. 3.12. Reconstruction of the vegetation surrounding the pond of Sanavastre. The main taphonomic processes on which the reconstruction is based are marked (from Martín-Closas, 1995).

STOP 3: DIATOMITES NEAR BELLVER (EL CAMP D'EN MIXELA)

Location: Margin of a ravine near the road from Bellver to Pi, where several small pits allow to study the lacustrine facies, otherwise cultivated elsewhere in the basin. The field above the ravine is locally known as Mixela's field (El Camp d'en Mixela). Mr. Mixela was a landlord and farmer from Bellver who was well-known by collecting and gathering all anapaite nodules he found in the surrounding fields (and preventing other people to collect them), since he thought this mineral was of exceptional strategic value, during the 1950' decade.

Description. The outcrop is formed by a monotonous succession of laminated to massive lacustrine clay and diatomite (Fig. 3.13), repeatedly interrupted by ferruginous beds, sometimes associated to anapaite nodules. Laminated clay and diatomite account for the anoxygenic conditions of the lake bottom, hindering bioturbation and enhancing the preservation of plant and insect remains. Ferruginous horizons have been interpreted as formed by iron oxide precipitation when the lake bottom didn't receive any type of sediment.

In this type of facies well preserved dicot leaves and small insect remains are frequent. Quite abundant in the outcrop are *Quercus drimeja, Fagus gussoni, Zelkova ungeri, Carpinus, Acer tricuspidatum*, and more rarely *Laurophyllum* and other thermophilic plant leaves.

Fig. 3.13. Outcrop showing finely laminated diatomite and clay intercalated with iron horizons.

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