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Verdeña (Spain): Life and death of a Carboniferous forest community

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Abstract

The remains of a forest of 305 million years ago allow reconstructing its history of colonisation of a coastal sand bar and its destruction by marine flooding due to faulting in a high destructive deltaic setting. Sigillarian trees snapped off just above the rooting bases, whereas woody trees (cordaitaleans?) were uprooted by the unidirectional current, which oriented the fallen logs. This record puts a new perspective on reconstructions of Carboniferous forest mires. ***To cite this article: R.H. Wagner, J.B. Diez, C. R. Palevol 6 (2007).***

Résumé

Verdeña (Espagne) : vie et mort d'un peuplement forestier du Carbonifère. Les restes fossiles d'une forêt ayant existé il y a 305 millions d'années permettent de reconstituer l'histoire de son implantation sur une barre sableuse côtière et de sa destruction par une inondation marine liée à la destruction tectonique d'un système deltaïque. Les sigillaires arborescentes ont été tronquées juste au ras de leur système racinaire, alors que les arbres ligneux (*Cordaites* ?) ont été déracinés par un courant marin unidirectionnel, dans le sens duquel ils se sont alignés après leur chute. Ces nouvelles données autorisent un nouveau point de vue sur les interprétations des tourbières forestières du Carbonifère. ***Pour citer cet article : R.H. Wagner, J.B. Diez, C. R. Palevol 6 (2007).***

Keywords: Carboniferous; Cantabrian; Stratigraphy; Palaeoecology; Taphonomy; Flora; *Sigillaria*; *Cordaites*

Mots clés : Carbonifère ; Cantabrien ; Stratigraphie ; Paléoécologie ; Taphonomie ; Flore ; *Sigillaria* ; *Cordaites*

1. Carboniferous forests: historical

Coal seams in the Carboniferous of Europe and North America are normally found associated with fossil plant remains. Although some coals are simply enrichments in vegetable matter in lake deposits with both inorganic and organic matter, a substantial proportion of coal seams show underlying rootlet beds. These are commonly filled with appendices of *Stigmaria* and other kinds of lycopsid rooting structures. Overlying the coals it is not uncommon to find stands of standing trees, most often lycopsids although stands of *Calamites* also occur.

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There is a substantial amount of literature dealing with standing trees in Carboniferous deposits, and also with the rooting structures of the different kinds of plant involved. One of the first authors to deal comprehensively with these structures was Grand'Eury [4]. This mining engineer was a keen observer and his observations set out in elegant French are still worth reading, well over a century later. Grand'Eury ([5], p.48), working mainly on Stephanian deposits of the Massif Central, in south-central France, wrote that "*les écorces de Lepidodendron, de Sigillaria, de Calamites et de Calamodendron, simples et régulièrement aplaties, produisent une houille admirablement stratifiée que lamellent aussi bien les Aulacopteris que les feuilles des Cordaïtes*". This acknowledged that coals were layered sediments with flattened remains of the organic constituents of shallow lakes and mires. Grand'Eury [5] stated that all coals were entirely of vegetable origin, and sediments of a similar kind to the associated shales. Since then, a wider variety of origins is admitted, although the basic tenets are unchanged.

Grand'Eury [5] made first hand observations of the rooting structures in strata underlying coal seams. In these rootlet beds he distinguished *Stigmaria*, *Stigmariopsis* and *Cordaites* roots. *Stigmaria* was shown as laterally extensive, with a characteristic pattern of rootlet scars (stigmarian appendices), whilst *Stigmariopsis* was depicted as more deeply rooted (i.e. not quite as shallow as *Stigmaria*), and *Cordaites* with roots at a steeper angle ([5], plate 1, fig. 8). Although the picture illustrating these three types of rooting structures is labelled "*Partie inférieure de la couche de la Grille*", near Roche-la-Molière, it would seem that this is a composite picture. Grand'Eury [5] also illustrated the rooting structures of *Calamites*, also underlying a coal seam, and standing trees attributed to *Psaronius* (tree fern) in sandstone (op. cit., plates 2 and 3). Standing *Calamites* trees were illustrated from fine-grained sandstone overlying a coal. Similar observations abound in the literature, with special emphasis on the different position in sedimentary sequences.

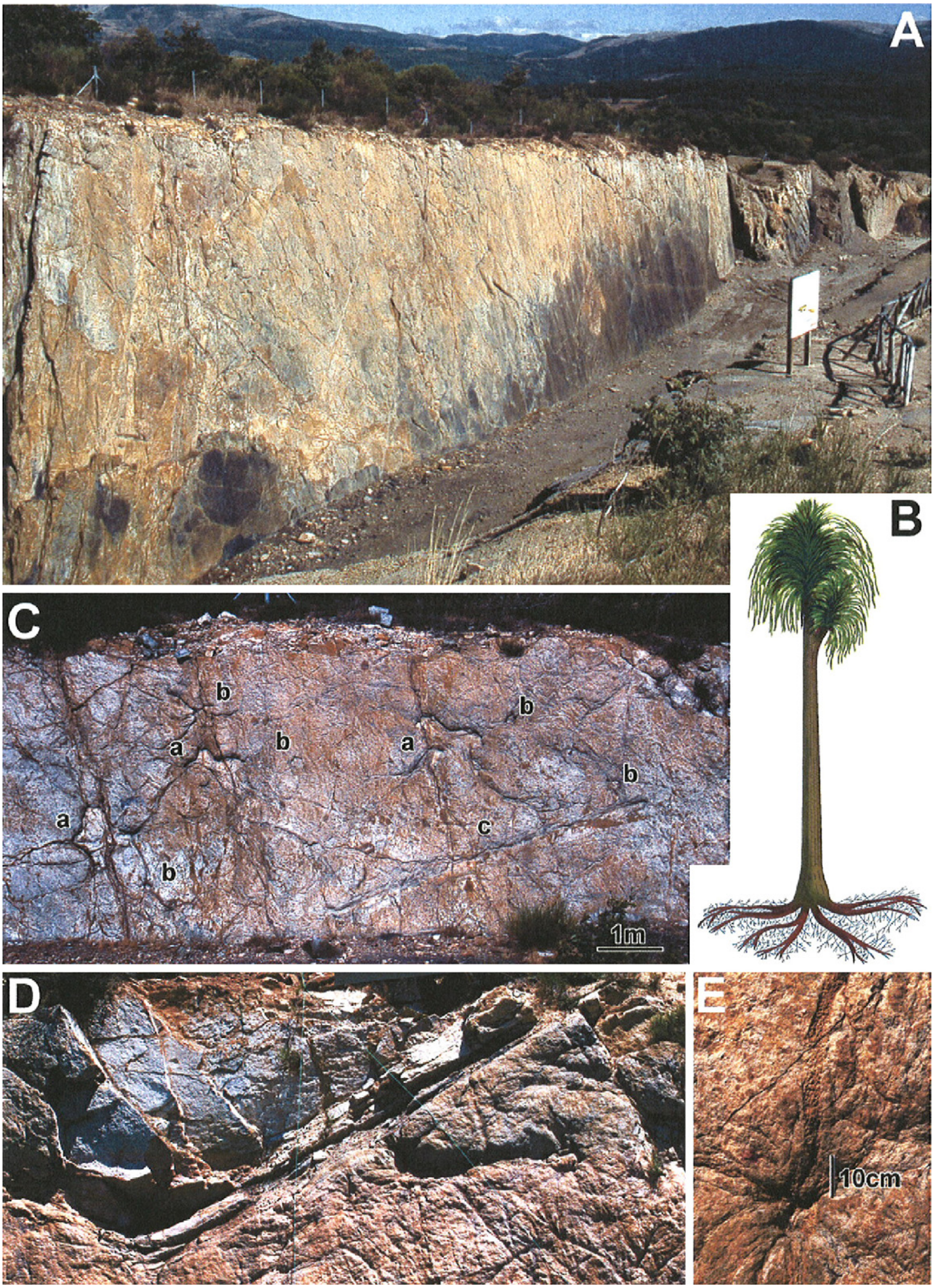
Although Grand'Eury highlighted the various trees with their rather substantial rooting structures, one is also aware of rootlet beds consisting of fern rootlets of a much finer texture. These are increasingly common in Permian strata.

The different elements of Carboniferous forest mires have often been depicted in reconstructions. A compendium of reconstructions was published by Jongmans [10] as a special chapter in the book *Hout in alle tijden* (*Wood throughout time*). This provides a number of interesting pictures, which are often more imaginative than the observational drawings made by Grand'Eury. Worthy of note is a drawing by Unger (in [10] Afb. 1.62) who depicted a Carboniferous forest destroyed by catastrophic flooding. Although usually regarded as a curiosity, the catastrophic destruction of a forest may have been a more common event than is normally acknowledged. Another picture, reproduced by Jongmans, is a diorama from the Geology Museum of the Geological Survey in London. This shows a lycopsid tree with characteristic four cornered *Stigmaria* partially uprooted and broken in half. The inspiration for such a picture is a woody tree, which is the wrong example. Lycopsid trees, possessing little wood, and a large cortical area, can be shown to have decayed rapidly, with tissue collapse and flattening, if preserved in a horizontal position. Lycopsid periderm also provides a leathery surround to hollow trees, and splintering is out of the question. The extensive stigmarian rooting system would remain firmly anchored to the ground or be washed out entirely after separation from the stem. Lycopsid trees were unlikely to topple with the rooting structure attached. In published reconstructions it is a common mistake to depict flat-lying lycopsid trees as cylindrical stems. In fact, these trees are always found in a flattened condition due to the cortical tissue collapsing after rapid decay.

Most of the interest has been centred upon standing forests, that is, upright tree trunks in river overbank deposits, sheet flood sandstones, volcanic ash bands, etc. Less commonly, the reconstruction of Carboniferous forests is based on impressions, the reason being that plant impressions usually relate to drifted, remains with assemblages ranging from allochthonous to parautochthonous and, only very occasionally, autochthonous. With regard to

Fig. 1. Composite showing steeply dipping sandstone (rootlet bed) in abandoned opencast site (**A** above), and, in the middle (**C**), a detail with large first generation stigmarian rooting bases (a), as well as smaller (second generation) rooting bases (b), and a fallen (snapped off) log of a (second generation) cannelate *Sigillaria* (c), as reconstructed alongside (**B**). Below, the imprint of an uprooted woody tree (**D**), and, alongside, the imprint of a second generation stigmarian rooting base (**E**).

Fig. 1. Planche montrant un front de grès escarpé dans une carrière à ciel ouvert abandonnée (**A** en haut) et au milieu (**C**), un détail de l'installation de la première génération des grands systèmes racinaires de type *Stigmaria* (a), ainsi que de plus petits (deuxième génération) (b) et un tronc couché (deuxième génération) d'une sigillaire cannelée (c), telle que reconstituée en (**B**). En bas, empreinte d'un tronc ligneux déraciné (**D**), le long de laquelle on observe l'empreinte d'un système racinaire de lycopside de deuxième génération (**E**).


A
B
C
b
b
a
b
a
b
b
a
c
b
1m
D
E
10cm

the latter, only the plant associations preserved by volcanic ash fall in mires qualify as purely autochthonous. These obviously allow the reconstruction of a local, specialised floral association.

The top surfaces of rootlet beds, when exposed, which is usually due to coal mining activity, may represent the imprints of rooting structures of a local floral community. This quite often consists of stigmarian or similar structures and usually reflects the rooting of a single generation of trees constituting a forest. In the present paper, a special case is described of the imprints of rooting structures showing the successive establishment of two quite separate generations of lycopsid trees with *Stigmaria*, as well as the catastrophic demise of the second generation with the remains of fallen logs [13,20].

2. General description of the Verdeña forest site

Small-scale opencasting for coal in steeply dipping (near vertical) strata of early Cantabrian (earliest Stephanian) age near the village of Verdeña in the mountains of northern Palencia, Cantabrian Cordillera, northwestern Spain, has exposed a wall of 180 m length and 5–12 m in height (Fig. 1A). The exposed rock is a sandstone, underlying the coal that has been stripped off by mining. The top surface of this sandstone, which is a rootlet bed, shows the imprints of rooting structures attributable to *Stigmaria*, and of fallen trees, which are partly the shallow imprints of a lycopsid, identifiable as a cannelate *Sigillaria* in one instance (Fig. 1B and C-c). However, the deeper imprints of stems of a woody tree (cordaitalean?) also occur quite commonly (Fig. 1D). Two sharply different sizes of lycopsid tree bases are found, which clearly represent two separate generations, with a certain spread of sizes for the second generation. In addition, there are small areas of sandstone surface covered by densely arranged markings of what may have been sporelings. These “nurseries” [20] were preserved together with the rooting structures (*Stigmaria*) of the two different generations of lycopsid attributed to *Sigillaria*. The flat-lying stems represented by shallow impressions all belong to the second generation. The stem impressions of the *Sigillaria* and the presumed cordaitalean show a preferred orientation, which has taphonomic significance. It is noted that top surfaces of rootlet beds of the characteristics described for the Verdeña site occur in a number of places throughout the succession of strata in the upper Asturian/lower Cantabrian of northern Palencia. A comprehensive interpretation of the taphonomy of the Verdeña site may well be applicable to other parts of the succession, and will constitute part of the sedimentary history of a basin which combined a high rate of sedimentation (ca 2000 m per Ma) with mixed marine and terrestrial facies (predominantly marine). Small deltaic lobes built out into the basin. Frequent shifts in the position of deltaic lobes may have been accompanied by seismic events, due to downfaulting in a highly mobile tectonic setting, as indicated by the high rate of sedimentation, and the history of catastrophic demise of the Verdeña forest (second generation of lycopsid trees).

3. Palentian Basin

A full description of this basin of latest Westphalian and earliest Stephanian ages can be found in [16,21]. References to the earlier literature are given in these papers. Its stratigraphic succession, adding up to 5500–6000 m, has been logged in detail at 1:100 scale ([15,16], and unpublished data). The geological map of the general area in which the Verdeña site is located (Fig. 2), can be found in [20] as well as in the geological map sheets of Barruelo [19], Camporredondo [11], and Tudanca [12]. Additional information is published in [18].

The Palentian Basin contains the stratotypes of the Cantabrian and lower Barruelian (sub) stages, representing the Lower Stephanian. Its succession commences with Upper Asturian (ex Westphalian D [22]) strata. The total succession correlates with upper Moscovian (Myachkovsky Horizon) and lower Kasimovian [16,17]. Most of this succession is marine, with terrestrial intercalations that increase in importance westwards (op. cit.). The initial basin was located between the villages of Lores and Casavegas (Fig. 2), where basin sags are found in underlying Westphalian D/Myachkovsky strata including a prominent limestone horizon, the Sierra Coriza Limestone. A rapid expansion of the basinal area established a width of ca 60 km, with a considerable palaeotopography with deeply incised valleys on the western side, and a carbonate platform on the eastern side (see [8,9,15]). The carbonate platform had a syn-sedimentary fault with a (reconstructed) north–south strike on its basinal side, separating a predominantly marine but partly terrestrial coal-bearing succession of up to 2300 m thickness from a 90 thick limestone succession on the platform side. This situation lasted throughout late Asturian times into earliest Cantabrian [16]. The 90 m thick platform limestones correspond exactly to the thickness of limestone intercalations in the siliciclastic basinal succession in the immediate vicinity, and represent periods of maximum transgression and quiescence of movements on the syn-sedimentary fault (Los Llazos Fault) separating platform from basin.

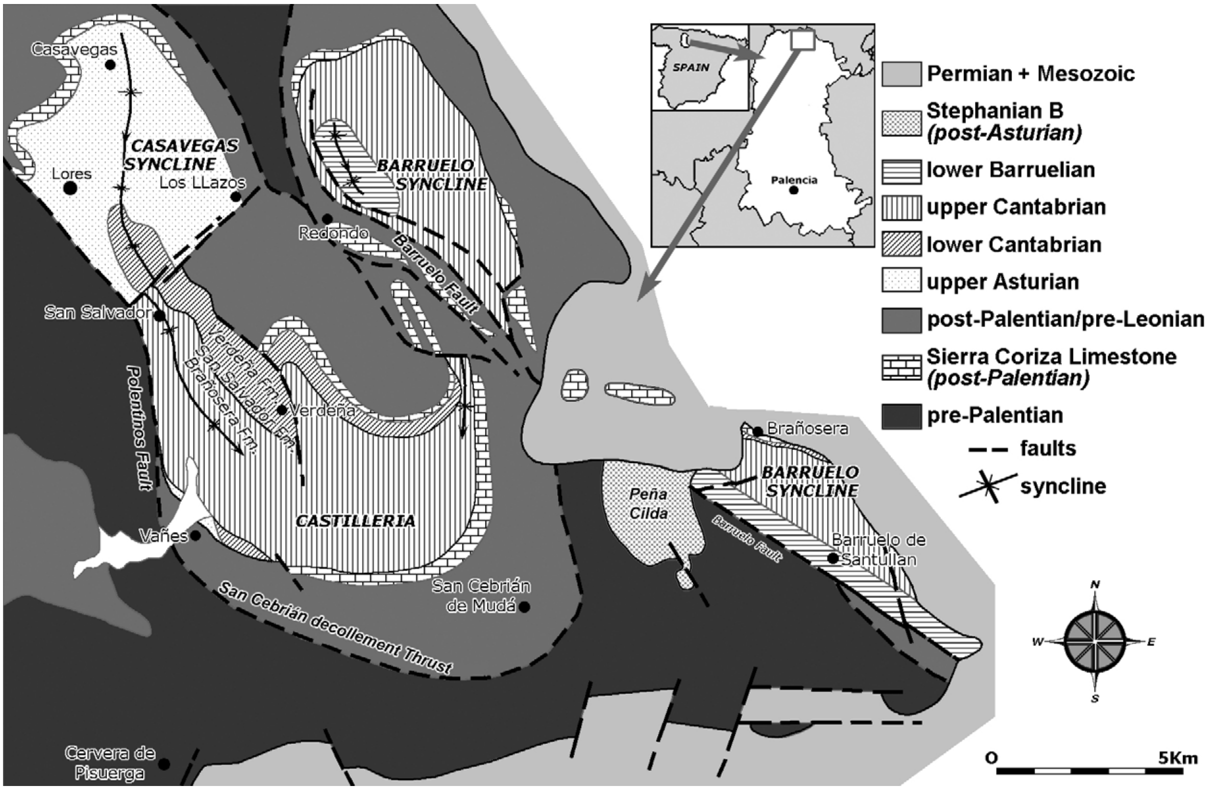


Fig. 2. Geological map showing the distribution of upper Westphalian and lower Stephanian strata of the Palentian Basin in northeastern Palencia province (Spain). Upper Silurian to lower Westphalian strata, deformed during the Palentian tectonic phase (late Langsettian), are shown without detail as pre-Palentian "basement". A small outlier of unconformable Stephanian B deposits at Peña Cildá is shown as well as the Triassic cover (underlain in places by Lower Permian).

Fig. 2. Carte géologique montrant la distribution des couches du Westphalien supérieur et du Stéphanien inférieur du bassin Palentien, du Nord-Est de la province de Palencia. Les strates du Silurien supérieur et du Westphalien inférieur, déformées pendant la phase tectonique palentienne (Langsettien supérieur) sont figurées globalement comme le « socle » pré-Palentien. Une petite butte témoin (« Peña Cildá »), du Stéphanien B discordant, est figurée, ainsi que la couverture triasique (reposant par endroits sur du Permien inférieur).

The carbonate platform split into various parts in Early Cantabrian times, producing several tilted blocks which accumulated siliciclastic successions of various different thicknesses ([16], fig. 12). Finally, a major transgression accompanied a substantial expansion of the sedimentary basin in late Cantabrian (early Kasimovian) times (see also [14]). The upper part of the succession only occurs in the most easterly area, in the vicinity of Barruelo de Santullán (Fig. 2). On the western side of the basin, the known succession reaches only just the level of the late Cantabrian (early Kasimovian) transgression, which is represented by the Brañosera/Taranilla formations. A detailed correlation ([16], fig. 7) shows the various marine transgressive horizons diminishing in importance westwards, where the succession is predominantly terrestrial. Quite spectacular palaeovalleys, up to 300 m deep, were incised on the western and northwestern basin margin in Early Cantabrian times. The preservation of these palaeovalleys has been due to extreme tectonic mobility, regarded as a combination of subsidence on the basin margin and tilting [8]. The local presence of fossil screes suggests steep-sided palaeovalleys. Conglomerate horizons in the palaeovalleys show a mixture of well-rounded quartzite clasts interpreted as fluviatile bed load and angular limestone and other clasts of local origin, which are regarded as barely reworked screes [8]. The spectacular dimensions of the palaeovalleys occurring on a mobile basin margin, and the presence of large volumes of well-rounded quartzite pebbles and boulders, suggest a nearby, rather substantial palaeotopography, with a well-developed fluvial system draining a mountainous hinterland. The eastern and western margins of the Palentian basin are thus quite well known, with marine transgressions coming in from the east and northeast. On the southern side the folded sediments of the Palentian Basin are covered by unconformable Cretaceous and Tertiary strata, and the southern basin margin is conse-

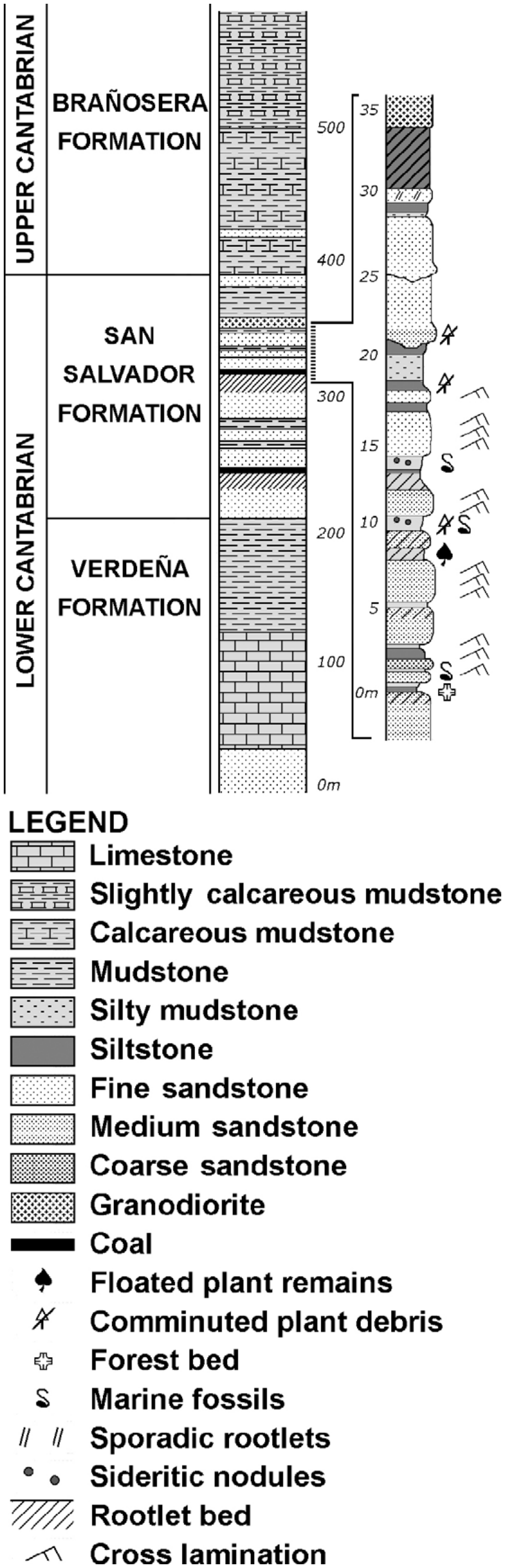


Fig. 3. Generalised stratigraphic column showing the deltaic San Salvador Coal-Bearing Formation in between the entirely marine Verdeña and Brañosera formations. The rootlet bed with imprints of rooting bases and fallen trunks is in the middle part of the San Salvador Formation.

Fig. 3. Colonne stratigraphique composite, montrant la formation deltaïque houillère de San Salvador, encadrée par les formations marines Verdeña et Brañosera. Le niveau à radicelles, avec empreintes de bases racinaires et troncs tombés, se situe dans la partie médiane de la formation San Salvador.

quently unknown. The northern basin margin is caught up in tectonic deformation in the Liébana and Valdeón areas, south of the Picos de Europa.

The sedimentary succession in the Palentian Basin consists, on the whole, of coarsening upwards deltaic sequences. Given the high rate of sedimentation and the general evidence of tectonic mobility, it seems likely that the deltaic sequences are tectonically controlled, with the abandonment of deltaic lobes being due to seismic events (faulting) as well as delta shifting. Although there is considerable evidence of sea level changes in Pennsylvanian times, with glacial/eustatic cyclothems developing on the relatively stable continental platforms (e.g., [6]), it is unlikely that the eustatic effect played a detectable role in generating the sedimentary sequences in the Palentian Basin, which are essentially due to deltaic processes linked to syn-sedimentary tectonic movements [18].

The coarsening upwards deltaic sequence that terminates with a sand bar providing suitable conditions for the establishment of a coastal forest as represented in the Verdeña site is illustrated in Fig. 3. It forms part of the San Salvador Formation in the upper part of the lower Cantabrian (Fig. 3). This is overlain by the transgressive Brañosera Formation, of late Cantabrian age. The high tectonic mobility of the Palentian Basin plays an important role in the history of the Verdeña forest described below.

4. Impressions of rooting bases and fallen tree trunks

Fig. 1A shows the wall of the opencast site representing a steeply dipping sandstone bed below a thin coal that was stripped off by mining. The top surface of this bed is covered by two different kinds of markings, i.e., the imprints of rooting bases of a lycopsid tree with the characteristic four-cornered aspect of *Stigmaria*, and the impressions of fallen tree trunks. The former show two different generations of lycopsid, with markedly different sizes. The larger size rooting bases, with basal diameters of 40–50 cm, are fairly regularly spaced, at about 2½–3 m distance. The smaller size rooting bases, with diameters of up to 20–30 cm and often smaller (less than 10 cm), are more irregularly distributed, but in such a manner that the larger *Stigmaria* with all its ramifications, are avoided. The significance of such a distribution is readily apparent. Evidently, the older generation of lycopsid tree still had its *Stigmaria* physically in place, even though the corresponding trees had died, thus giving the second generation its chance. This second generation shows markedly different sizes. Its replacement of the first generation must have taken time.

Among the fallen log impressions two different kinds are apparent, viz. shallow imprints and deeper imprints; the latter sufficiently deep for the miners to have scooped out the coal, which was found inside. One of the shallow imprints, a log of c. 5 m length, shows the markings of a cannelate *Sigillaria* (Fig. 1B and C-c). Lycopsids are trees with only a small siphonostele and a large cortical area. The corresponding logs must have decayed quite quickly, with almost total collapse of the tissues of fallen trees, and thus leaving a shallow imprint. The deeper impressions of fallen stems must correspond to a woody tree, not a lycopsid. One of these woody trees was uprooted, with its rooting base still attached (Fig. 1D). None of the lycopsid tree-trunk impressions showed the swollen tree bases; clearly, these stems were broken off above the tree base. Apart from the ubiquitous imprints of lycopsid rooting bases (*Stigmaria*) and the fallen logs, areas covered with small, almost stellate markings occur. These are interpreted as the imprints of lycopsid sporelings. It would appear that these “nurseries” corresponded to small areas clear of the pervasive influence of the stigmarian rooting systems.

The sandstone surface seen on the steeply dipping wall of the abandoned opencast mine displays the upper parts of stigmarian rooting systems where they depart from the stem base. Only very occasionally does the lateral extent of the *Stigmaria* become partially visible (Fig. 1E). For the lateral extent to become fully apparent, one needs preservation of a slightly deeper level where the stigmarian roots dug into the soil. At the Verdeña site, this deeper level is not normally visible. However, in another opencast site, near the village of Lores, at an horizon much lower in the stratigraphic succession, that is, in the upper Asturian (ex Westphalian D), the lateral extent of stigmarian rooting bases is clearly visible (Fig. 4), probably as a result of the top layer of sand having been

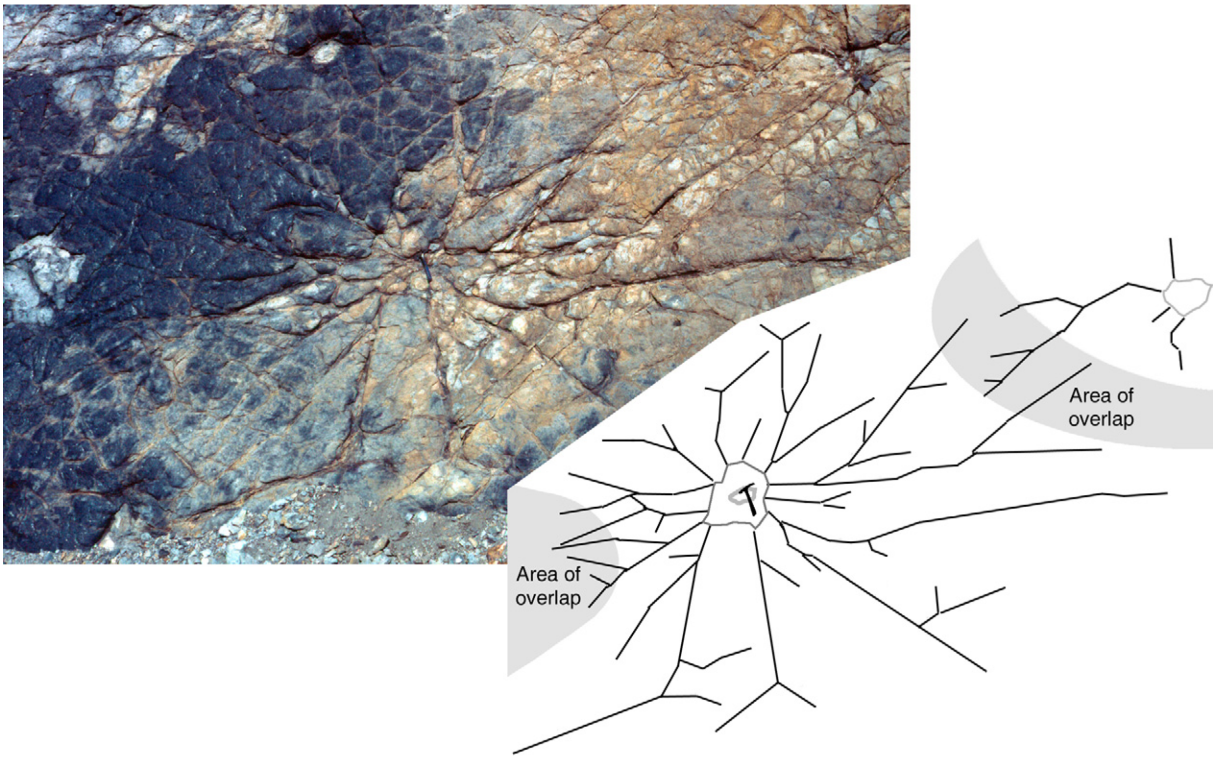


Fig. 4. Imprints of *Stigmaria* showing the lateral extent of rooting systems and the degree of overlap. Locality: abandoned opencast site near the Lores village, Ojosa Formation, upper Asturian.

Fig. 4. Empreinte d’une *Stigmaria* montrant l’extension latérale des systèmes racinaires et de leur degré de chevauchement. Localité : carrière à ciel ouvert, abandonnée, près du village de Lores, formation Ojosa, Asturien supérieur.

removed from the site prior to burial and fossilisation. In this site it is apparent that the laterally extensive, shallow rooting structures (*Stigmaria*) overlapped by approximately one third. This observation allows the affirmation that the spacing of the lycopsid trees (*Sigillaria*) was controlled by the tolerance in overlap of the laterally extensive rooting systems. Since the stems were hardly, if at all, branched, the trees must have stood rather widely apart. The tree height is conjectural and dependent on the taper. Competition between the trees must have been for nutrients. The shallow rooting system shows that water cannot have been a problem. Of course, apart from the acquisition of nutrients, the laterally extensive rooting system also served the purpose of anchoring the tree. The dense array of stigmarian appendices will have been important in this respect.

With a 30% overlap of stigmarian rooting systems, the pioneer generation will have extensively covered the area available for colonisation on the delta lobe. Although sigillarian sporelings were undoubtedly produced at regular intervals by the pioneer generation, these could not grow into trees when the older generation occupied the total ground surface available. Indeed, the similar size of the larger imprints of rooting bases suggests that the pioneer generation grew to full size and was allowed to complete its life span. However, although the pioneer generation may have lived a full life span and thus tended to die at virtually the same time, the individual trees will have lasted longer or shorter. It may be assumed that the sporelings were only given the opportunity to establish themselves permanently when the pioneer generation had died. This is presumably the significance of finding two sharply different sizes of rooting bases. An apparent spread of sizes among the smaller, second generation tree bases imprints may be due to staggering in the demise of large trees of the pioneer generation, and a consequent recolonisation at slightly different times. For the second generation to become established, it needed to avoid the physical spaces occupied by the stigmarian rooting systems of the first generation, which were left in the soil after the trees had died. This would explain the more irregular distribution of the second generation trees (Fig. 1C). Indeed, it is clear that these established themselves in spaces in between major stigmarian axes of the older (first generation) trees. Although data are not quite comparable, the existence of single generation lycopsid stands living a full life cycle and dying at virtually the same time was also observed in Illinois, North America [2].

The impressions of fallen tree trunks are also quite common at the Verdeña site. Most of these trunks were transported as is evident from the general lack of attached rooting structures and a preferred orientation. However, in one case (Fig. 1D), a woody tree shows the imprint of attached roots. This tree also appeared in the same preferred orientation. This suggests transportation of an uprooted tree.

Fallen (transported) logs are only partly of the kind that produced shallow impressions, and of lycopsid origin. Indeed, one specimen shows the markings of a cannelate *Sigillaria*. None of these logs shows the rooting bases attached and they also fail to show evidence of the swollen tree bases. Consequently, it appears that these are the imprints of stems that were sheared off above the level of the swollen base that was connected to the rooting system. It seems likely that this reflects the structural weakness of a lycopsid tree, leaving the rooting bases firmly anchored in the soil whilst the stems snapped off above the swollen bases, at perhaps about half a metre above the soil surface. This behaviour is quite different from that of a woody tree that was more likely to be uprooted due to its greater structural cohesion. Not many (if any) of these woody trees seem to have formed part of the forest community at the Verdeña site. On the other hand, deeply imprinted log fragments are quite common at this site. Most of these are oriented in the same direction as the lycopsid stems, but some shorter ones are at approximate right angles. It could be that these woody trunks suffered more appreciable transport, and that the corresponding trees lived in a different, though nearby site. More about this later.

5. Catastrophic demise of the Verdeña forest

Fallen tree trunks are commonly present on the sandstone surface. Both shallow and deeper impressions are found, as mentioned before. These show a clear orientation, with a spread of about 30°. Occasional, shorter logs, corresponding to woody trees are found at right angles to the preferred direction. Length is variable, up to 5–7 m for the shallow imprints. Only one of these imprints, representing a cannelate *Sigillaria*, shows a small side branch near the tip of a stem with a rounded apex. Presumably, the *Sigillaria* stems were mainly unbranched and only occasionally possessed a small side branch, in the nature of a subequal dichotomy. It is noted in passing that the dichotomous stem apices shown in the classical reconstruction of *Sigillaria* by Hirmer [7] may be the rule in earlier, Westphalian *Sigillaria*, but these appear in a strongly modified form in the Verdeña forest of earliest Stephanian age (see the reconstruction as published in [20], p. 390) (also Fig. 1B).

The width of the sigillarian stem imprints accords well with the diameter of the second generation rooting bases. When the lycopsid forest was destroyed, only the second generation trees were found standing, the inference being that the first generation had died earlier. The deeper stem imprints of a woody tree (*Cordaites*?) are usually shorter and devoid of branches. Might this be the result of longer transport during which the branches were removed? The shorter logs of a woody tree found at right angles to the preferred orientation, suggest that these were rolled into position.

It is observed that small plant debris is notably absent. This is regarded as significant. Whatever agency provoked the catastrophic demise of the Verdeña forest, it cleared the site of litter. It is also observed that both the uprooted woody tree (*Cordaites*?) and the second generation *Sigillaria* stems show exactly the same orientation, suggesting a unidirectional agency. Two possible agencies come to mind, i.e., either a hurricane force wind or a catastrophic flooding event. Hurricane force wind has been adduced in Wnuk and Pfefferkorn [23] for unidirectional lycopsid trunks mixed in with randomly disposed pteridosperm stem remains. The general geological setting of their deposit was terrestrial. Comminuted plant debris was not discussed, but associated foliage remains might suggest the additional presence of CPD. This would indeed suggest wind rather than water. The situation is rather different for the Verdeña site, where the absence of plant litter and the consistent orientation of logs of the two different varieties indicate flooding rather than wind action. In the context of a tectonically mobile deltaic setting, a catastrophic flooding event can only have been of marine origin. A sudden influx of seawater may be explained by the sundering of part of a coastal forest area, as a result of catastrophic downwarp of the delta front, presumably associated with faulting. The strong current will have snapped off the *Sigillaria* trees above the swollen stem bases that were left in situ connected to the firmly anchored rooting systems. The correlation between the stem widths and the diameter of the second generation lycopsid rooting bases suggests a strictly local origin, with only a limited amount of transport for the lycopsid stems.

The woody trees may have come from a more distant area. Not only is there an absence of imprints of rooting structures other than the lycopsid ones, but woody trees may float more easily and suffer longer transport without breaking up entirely. On the other hand, the absence of branches attached to the logs of woody trees suggests a certain amount of breakage as a result of transportation. Perhaps, these trees were cordaitaleans living on the seashore in a mangrove setting, as Cridland [1] suggested on anatomical grounds.

Downfaulting of part of a coastal area would explain a unidirectional current with trees oriented in the direction of the current. A tsunami is out of the question since the backwash would have disorganised the stem remains.

With this scenario the overlying coal bed is likely to have originated in a lagoon, which became established on the site where the lycopsid (sigillarian) forest (and the presumed cordaitaleans on the sea front) were destroyed by a sudden influx of seawater. A forested area would still exist landwards, and this would provide plant debris for an accumulation as represented by the overlying thin, layered coal with a high ash content. Fully marine sediments with crinoid debris and other marine fossils are found overlying the coal. These start off another deltaic sequence. Although not every deltaic sequence in the upper Asturian and lower Cantabrian succession of the Palentian Basin ends with a sandstone colonised by plants, sequences similar to that present in the opencast site near Verdeña are found repeatedly. Even though this site is not unique in the Palentian Basin succession, it is a well-exposed, fully representative example. This splendid example is being conserved under the protection of the Consejería de Medio Ambiente of Castilla-León.

This example of a fossil forest established in a high-destructive deltaic setting that led to its undoing is quite unique in the geological literature. Descriptions of palaeosols with the imprints of lycopsid tree bases do reflect forest dynamics (e.g. [3]), but do not show the special conditions, which could be analysed at Verdeña.

6. Conclusions

(1) The Verdeña forest impression site is a unique example of coastal lycopsid (sigillarian) colonisation followed by complete destruction as a result of marine flooding in the context of a high-destructive delta.

(2) Two sharply delimited lycopsid generations are recognised, as well as "nurseries" of sporelings. The first generation completed a full life span. The second generation, established after the first generation died, was destroyed by the marine flooding event. This catastrophic event snapped off the lycopsid stems above the rooting bases, but uprooted woody trees believed to represent a cordaitalean.

(3) The woody trees (*Cordaites*?) were uprooted and transported as logs without branches. These may well have come from a nearby but different site, nearer the sea shore. The marine transgression would

have affected the woody trees first, sweeping its remains (logs) into the area settled by *Sigillaria*.

(4) This is the first Carboniferous forest community known thus far from a tectonically mobile area in an overall marine deltaic setting.

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