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The coal-bearing, Cenozoic As Pontes Basin (northwestern Spain): geological influence on coal characteristics

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Abstract

Lignite deposits in the Cenozoic As Pontes strike-slip basin (northwestern Spain) were formed as a function of specific paleoclimatic conditions and tectonic evolution of the basin. During the early evolutionary stages, the presence of active normal faults and thrusts inside the basin resulted in two subbasins with distinct differences in sedimentary records, with respect to lignite seam occurrence, thickness, areal extent and lithotype development. In contrast, during the late evolutionary stages the basin was not split and a more homogeneous sedimentary record in terms of coal seam occurrence and lithotype characteristics developed. A total of 26 lignite samples, distributed along the basin infill, were analyzed by organic petrography and geochemistry. All are lignite B (ASTM). The lignites deposited during lower basin infill sedimentation (units 1 and 2) are dark, matrix-rich, mainly huminitic brown coals, with minor bright, liptinitic-rich coal lithotypes. The dark huminitic coals in these units show sedimentological and paleontological evidence of lacustrine influence. Persistent, relatively moderate to low Tissue Preservation Index (TPI) values and high average Gelification Index (GI) values are characteristic of these limno-telmatic coals. Lignites in the upper basin infill (Unit 4) are almost exclusively matrix-rich, huminitic brown coals. Persistent, widespread, low TPI values and variable, but low, average GI values are also characteristic of these telmatic coals. The overall coal petrological data trend (TPI, GI and widespread development or absence of liptinite-enriched lignite layers) recorded from the lower to the upper basin infill units agrees with the stratigraphic and sedimentological data, which show a trend of increasingly drier conditions. Development of bright, liptinite-enriched lignite layers was widespread during the early basin evolutionary stages and was influenced by punctuated water-table oscillations. Sedimentological, petrological and organic geochemical data point to the conclusion that, although the paleoenvironments where peat deposition took place did not undergo dramatic changes, they were affected by distinguishable

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variations (i.e., water hydrochemistry and groundwater-level stability), linked mostly to the evolution of basin morphology (depending mainly on tectonics) and basin water balance.

1. Introduction

The study of coal deposits developed in non-marine fault bounded basins is especially interesting because of the diversity and rapid changes of the controlling factors which influence sedimentation in such settings. Coal sedimentation in fault-bounded basins is usually related to the development of palustrine–lacustrine and/or swamp–marsh areas, where conditions suitable for peat accumulation occur. A wide variety of subenvironmental conditions and sequential trends can develop in this depositional framework because of autocyclic evolution and frequent interrelationships with alluvial systems. In both cases tectonic and/or paleoclimatic allocyclic factors can also exert a large influence and become the major controlling factor.

This paper deals primarily with the study of lignite facies changes recorded in sequences of the small, fault-bounded, Cenozoic, As Pontes Basin, northwestern Spain. Due to tectonic activity, sediments making up the diverse stratigraphic units of this basin were deposited under changing sedimentation/subsidence conditions and evolving basin morphology. The key purpose of this paper is to describe the influence exerted by these changes on the development of main coal facies assemblages. Thus, the sedimentological, petrological and organic geochemical features of some selected coal lithotypes were preliminarily studied with the aim of establishing general evolutionary trends from the lower to the upper parts of the basin infill.

2. Geological setting and basin structure

Several Cenozoic nonmarine basins are located in Galicia, northwestern Spain (Birot and Solé Sabarís, 1954; Nonn and Medus, 1963; Virgili and Brell, 1975; Martín Serrano, 1979; Martín Serrano, 1982; Santanach et al., 1988; Bacelar et al., 1992; Cabrera et al., 1994b). A group of these basins, characterized by rather minor areal extent, is located in northwestern Galicia (Fig. 1). These basins are related to two complex strike-slip fault systems with NW–SE orientation (Santanach et al., 1988; Cabrera et al., 1994b). These strike-slip systems can be included in the wider framework of the Pyrenean–Northern Iberian continental margin region (Mauffret et al., 1978; Boillot et al., 1979; Boillot and Malod, 1988). They record the late stages (mainly late Oligocene to Early Miocene) of compressional tectonic evolution in the westernmost end of this Paleogene–Miocene convergent margin.

Most of the basin infills in the Cenozoic Galician basins consists of terrigenous alluvial deposits (IGME, 1979–1984) but some include thick, workable coal seams, which, in some cases (As Pontes and Meirama basins), have been mined intensively since the 1960s. Up to 280×10^6 t of lignite made up the original workable reserves in the As Pontes Basin.

The late Oligocene–Miocene(?) As Pontes Basin (Nonn and Medus, 1963; Medus, 1965a; Medus, 1965b; Baltuille et al., 1990; Cabrera et al., 1994a; López et al., 1993) is

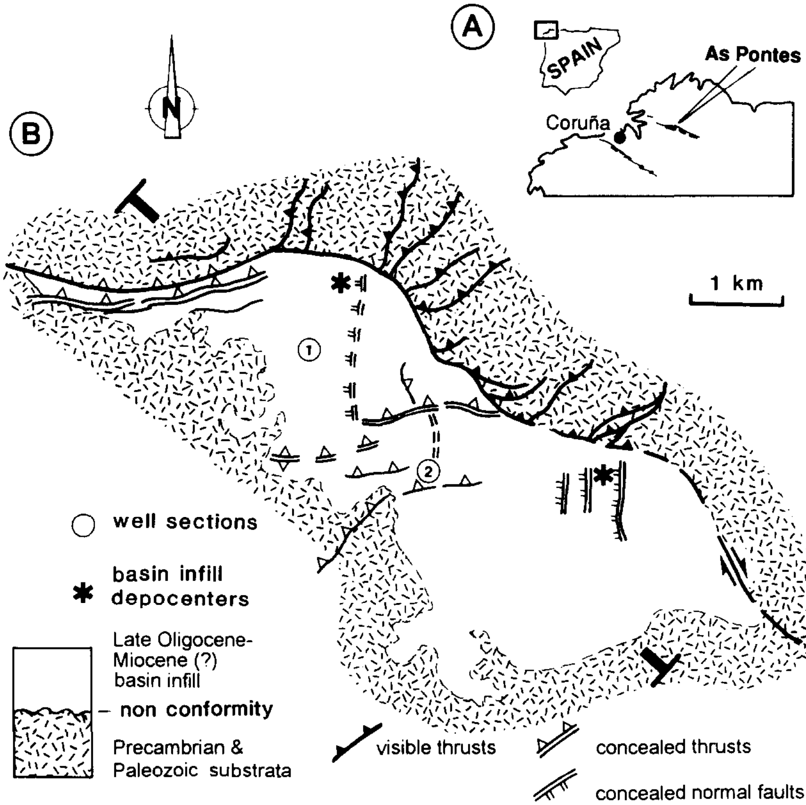

Fig. 1. (a) Location and (b) major geological features of the Cenozoic As Pontes Basin. Note the coexistence of extensional and compressional structures, which acted simultaneously during the earlier stages of basin evolution. Note location of the stratigraphic framework of the basin and of the well sections, which are shown in Fig. 2.

located in the northernmost strike-slip fault system, which lies in northwestern Galicia. This Cenozoic basin is one of the best known in Galicia due to exploration and open pit coal mining activities. The data available on this basin includes approximately 1,300 continuously cored exploration wells and extensive cut trenches. The data resulting from these activities have been stored in a comprehensive data base.

The basin, 7 km long and 1.5–2.5 km wide (Fig. 1), shows a NW–SE orientation, parallel to the strike-slip fault system orientation. It developed as a consequence of the lateral movement along a major fault with two restraining bends (Bacelar et al., 1988, 1992; Cabrera et al., 1994b). The movement along this major fault, caused by north–south shortening, resulted in several compressional structures (thrusts and reverse faults) and normal fault structures, which controlled basin evolution (Bacelar et al., 1988, 1992; Cabrera et al., 1994b; Ferrús and Santanach, 1994).

The basin substrata and surrounding areas consist of Precambrian and Early Paleozoic slates, micaceous schists, quartzites and greywackes, meta-arkoses and gneisses (Manera Bassa et al., 1979), which were deformed during the Variscan Orogeny. The basin is asymmetrical, with substrata dipping gently towards the northern basin margins, where they

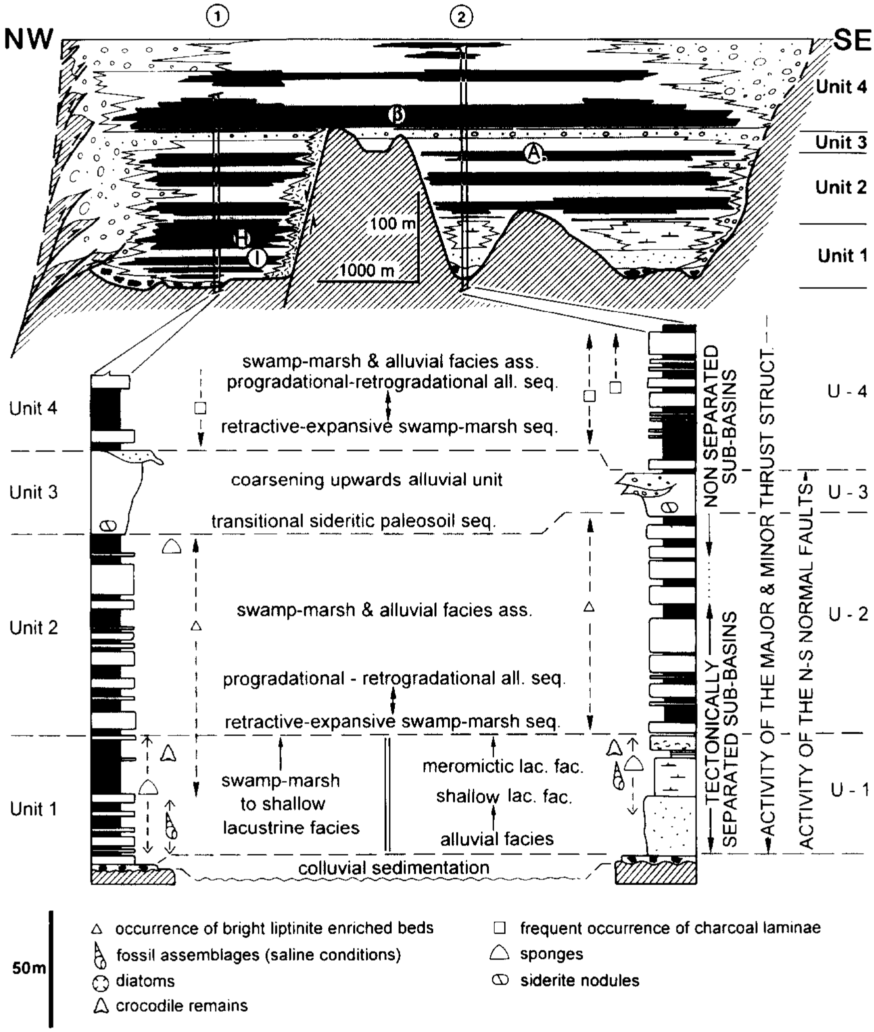

Fig. 2. Stratigraphic framework of the As Pontes basin infill, with indications of major features, sequential trends and relationships with the main tectonic structures. Note the restriction of the lacustrine facies and the liptinite-enriched coal layers to the lower part of the infill. See text for further explanation.

attain a maximum depth (up to 80 m below sea level datum). Whereas the northern basin margins are bounded by tectonic structures, the southern basin edges are defined by the non-conformity between the Precambrian–Early Paleozoic substrata and the base of the Cenozoic basin infill. Subsurface data indicate that the As Pontes Basin is divided by a tectonic threshold into two different subbasins (Fig. 2). Basin infill thickness changes in the diverse basin zones and attains a maximum (about 400 m) near the northern basin margins and decreases towards the southern margin and tectonic threshold. The basin infill is characterized by onlaps, developed towards the southern margin and the tectonic threshold (Fig. 1). Sedimentation ceased in the basin during the latest Oligocene or Miocene. The basin remained quiescent until the late Neogene–Quaternary, when it was subjected to erosion and sediments composing Quaternary fluvial terraces were deposited.

The northeastern tectonic margins show two orientations (E–W and NNE–SSW), which correspond to two distinctive kinds of tectonic structures. The E–W oriented boundaries are mainly related to low angle, gently dipping thrusts, which, subsurface, attain up to 800 m of horizontal displacement in the Cenozoic basin infill (Bacelar et al., 1988, 1992). The NNE–SSW basin edges are mainly related to the activity of reverse faults, which have a noticeable dextral component (Bacelar et al. 1988, 1992). The basin floor shows several irregularities related to minor compressional and extensional structures. The major threshold which divides the basin is bounded to the west by a N–S oriented normal fault and to the south by an E–W oriented thrust (Figs. 1 and 2).

3. The basin infill

3.1. Depositional framework and sequence arrangement

Sedimentation in the As Pontes basin was nonmarine and developed under significant tectonic influence. The sedimentary framework which resulted in the infilling of the As Pontes Basin was formed by alluvial systems, fed from source areas located to the north of the northern tectonic margins of the basin and to the east of the eastern basin margin. It is quite probable that southern contributions also occurred. All source areas were composed of slates, schists and quartzites, which sourced mainly fine to medium sand grains and only minor contributions of gravel (Figs. 1 and 2).

Interpretation of the terrigenous facies distribution suggests that two main alluvial systems contributed to the basin infill and were closely interrelated in the eastern subbasin and in some of the northern basin zones. The main alluvial system, in terms of water and sediment contribution, impinged into the basin from the eastern end and spread fine gravels, sands and mudstones, following a trend broadly parallel to the successive basin axis. In this system the lateral transition from the proximal to the distal-marginal facies, although somewhat abrupt, was gradual and braided fluvial zones developed between the proximal and the terminal alluvial zones. The other alluvial system consisted of an assemblage of coalescent alluvial fans, which were developed along the northern basin margins. These fans were small in size with a radial extent of up to 1 km. In the proximal zones of these alluvial systems, sediments comprising sequences dominated by thick sandy mudstone with minor intercalations of gravels and sandstones were deposited.

The alluvial systems spread and retreated repeatedly, controlled by the changing base level and ongoing tectonic processes along the basin margins. The alluvial systems finally impinged on distal–marginal lacustrine and/or swamp–marsh areas at the front of terminal zones. The areal extent and distribution of these zones and corresponding environments (i.e. lakes versus swamp–marsh zones) changed markedly during successive stages of basin evolution (Fig. 2).

As a consequence, the basin infill of the As Pontes Basin consists mainly of terrigenous sequences which were deposited in alluvial and lacustrine–palustrine zones. These terrigenous facies are related laterally and vertically to lignites deposited in swamp and marsh environments. Lignite-bearing or lignite-dominated successions are well developed further away from the marginal–distal alluvial zones and alternate with, and pass laterally into, terrigenous dominated sequences barren of lignite (Fig. 2).

The terrigenous sequences consist of changing percentages of mudstones, sandy mudstones, arkosic sands and sandstones and quartzose gravels with angular clasts, characterized by very low textural and mineralogical maturity. Whereas the sandy mudstone and sand-dominated coarser facies assemblages developed in proximal and middle alluvial system zones, the mud-dominated facies developed mainly in distal and marginal alluvial and lacustrine zones. Mudstone deposits consist mainly of kaolinite but some deposits include significant percentages of smectites and illites (Medus, 1965a,b; Brell and Doval, 1979). The lignite, barren, terrigenous-dominated sequences display coarsening- and fining-upwards large-scale sequences up to several tens of metres thick. These larger sequences are split into a number of single, mainly fining-upwards sequences up to a few metres thick (Figs. 2–4).

The lignite-bearing sequences display a well established sequential pattern of early increasing and later upward decreasing seam thickness and areal extent (Fig. 2). The lignite-bearing sequences or zones are organized into metre-scale sequences which include two facies: (1) terrigenous-dominated, fining-upwards, which consists of sandy mudstones, sands, sandstones, silts, and mudstones bearing root traces; and (2) lignite-dominated, made up of diverse lignite lithofacies (matrix huminitic dark coal, bright liptinite-rich coals and sometimes xylitic coals). These sequences can be split and assembled into other minor and major order sequences (Figs. 2–4).

In the coal-bearing assemblages the transition between the lutitic–sandy sequential facies and the lignite seams is gradual or sharp. When transition is gradual, intermediate coaly–carbonaceous mudstone facies developed between the coal and terrigenous facies. The stacking up of the elementary sequences and the areal extent and distribution of the terrigenous and lignitic terms are complex, showing reiterative spreading and retreat of the alluvial facies, which can be correlated with the opposite trends of the lignite deposits.

3.2. *Basin infill subdivision and facies assemblages description*

The sedimentary record of the basin usually started with the deposition of discontinuous, lenticular, thin, monomictic breccia levels which sometimes include basal root traces. These deposits record development of colluvial sedimentation, with minor clast reworking and pedogenetic processes. The deposition of breccias took place on the gentle paleotopography of a weathered surface (Fig. 2).

The remaining sedimentary sequences overlie and sometimes onlap these basal deposits. On the basis of the relative development of terrigenous alluvial and palustrine–lacustrine deposits, and bearing in mind the major features of the lignite seams (i.e., areal extent, thickness, lithofacies and major geochemical features), the basin infill can be split into four major lithologic units, with lithologic composition and thickness changes dependent on location (Fig. 2).

3.2.1. *Unit 1*

This lower unit is up to 120 m thick in the western subbasin and is nearly 100 m in the eastern subbasin (Figs. 1 and 2). These maximum thicknesses are attained close to the N–S extensive faults, near the margins of the northern basin. One of the most characteristic

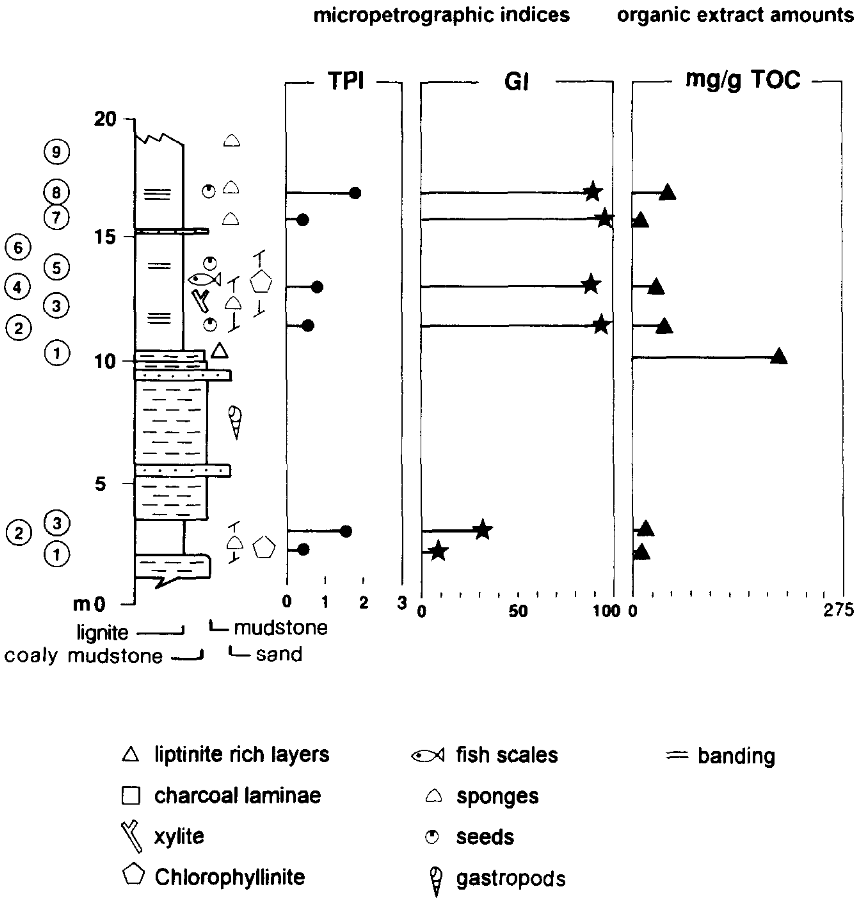

Fig. 3. Sedimentological log of the I seam and the lower part of the H lignite zone in the As Pontes basin (western subbasin), showing major features, variation in the organic matter extract and changes in the tissue preservation (TPI) and gelification (GI) indices (as defined by Diessel, 1992; see micropetrography section for further explanation of these indices). Note the widespread occurrence of fossil remains of limnic organisms. See Fig. 2 for the general stratigraphic location of the lignite deposits.

features of this unit is the diverse facies assemblage recorded in each subbasin, with exclusive development of major coal deposits (the so called 'H zone') in the western subbasin (Fig. 2). The development and areal distribution of the facies in this unit was appreciably influenced by the peculiar basin morphology, defined by the tectonic threshold which separated both subbasins.

Unit 1 in the western subbasin: facies assemblages and coal deposits

In the western subbasin the lower part of this unit is comprised of alluvial and lacustrine green mudstones and marls which alternate, or include sandy deposits and bear bioclastic accumulations of limnic gastropods (Planorbidae, Hydrobiidae), bivalves, ostracods and Charophytes. These lower terrigenous facies alternate upwards with dark matrix rich lignite seams and the whole succession is overlain by the H zone.

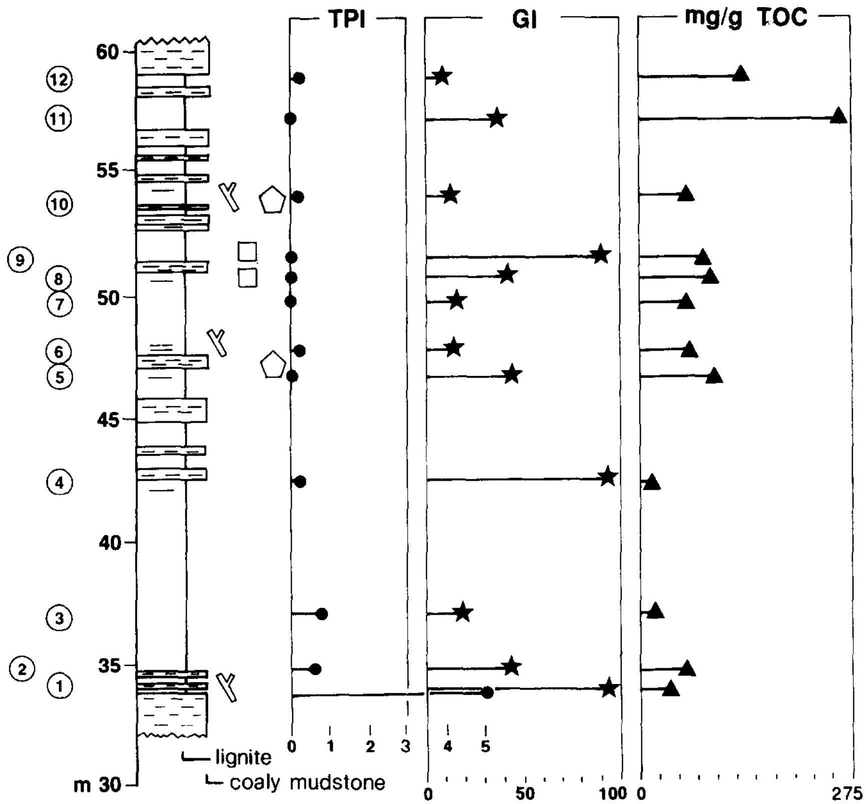

Fig. 4. Sedimentological log of the Beta lignite zone in the As Pontes basin showing major features, the variation in the TPI and GI indices and the organic matter extract. Note the absence of any major trace of paleontological remains of limnic organisms. See legend in Fig. 3 and Fig. 2 for the general stratigraphic location of the lignite deposits.

The H zone (Figs. 2 and 3) is restricted to the western subbasin. It is up to 30 m thick and attains maximum thickness in basin zones neighbouring the present northern margins of the western subbasin. The coal thins towards the southern basin margins, as well as towards the structural high which separates both subbasins. The sequence is made up of the repeated stacking of terrigenous-coal sequences around 1 m thick, with predominant coal deposition in the central and southern zones of the western subbasin. A rapid lateral transition to terrigenous, mudstone–sandstone dominated facies towards the northern basin margins, the western margin of the threshold and the southeastern subbasin margin is also found.

The ash content in the H coal zone ranges between 50% and 20% and is higher towards the margins. Sulphur content (partially contained in sulphides, mainly pyrite) ranges from 4% to 12%, which constitute the highest values present in any seam of the basin.

Two major coal lithotypes are present in the H zone: dominant, dark, matrix-rich, huminitic lignites and minor, distinctive, bright, yellowish liptinite-rich lignites. Sponge spicule laminae have been recorded in several coal seams included in this zone. Some beds in the lower and upper part of the coal sequence bear chert micronodules and macronodules up to

1 m long which have preserved vegetal tissues. As a distinctive feature, several clay or coaly clays intercalated in the H zone show a high content of fossil limnic gastropods (Hydrobia, Lymnaea and Planorbidae). Crocodile (Alligatorinae) and tortoise remains as well as aquatic plant seeds have been recorded in these lacustrine beds, as well as in the immediately overlying and underlying lignite beds. Preliminary palynological data gathered from the H zone (Cabrera et al., 1994a) indicate tropical–subtropical, warm and humid paleoclimatic conditions and the occurrence of a number of plants characteristic of marsh and swamp environments.

Unit 1 in the eastern subbasin: facies assemblages and coal deposits

In the eastern subbasin the lower unit displays a lower alluvial–lacustrine dominated succession (Fig. 2). Lowermost alluvial green greyish sandy mudstones are overlain by cyclical, lacustrine, gastropod-bearing green mudstones which contain magnesium-rich neoformed clays (Sáez et al., work in progress) and whitish dolomitic and calcitic mudstones and carbonate beds (Sáez and Cabrera, 1994). This lower lacustrine assemblage is covered by a few meters of lacustrine clay–carbonate laminites with laminae with a high magnesium calcite content (Sáez and Cabrera, 1994). The uppermost levels of this lacustrine unit consist of bioclastic, sandy and carbonaceous mudstone deposits, overlain by a thin coal seam. The whole sequence also passes laterally into the alluvial marginal facies of the northern basin margin as well as into the alluvial facies in the eastern basin end zone. No coal was deposited in this lacustrine facies assemblage.

Despite the rather diverse facies assemblages deposited in both subbasins, the sedimentary lacustrine facies and biota suggest that meteoric surface and/or phreatic waters which came into the basin system were subjected to diverse degrees of hydrochemical evolution, with diverse increases in solute content. Magnesium-rich clay and carbonate facies, including dolomite and mineral phases with high magnesium calcite contents, carbonate limnic biota (Charophytes and gastropods potentially adapted to euhaline to hypersaline conditions like Potamides) are present in these lacustrine facies. This feature points to the existence of initially carbonate-, calcium- and magnesium-rich waters which in some cases evolved to chloride–sulphate rich, euhaline waters. The relative homogeneity of the lithologic composition of the source areas precluded the possibility of changes in the incoming solute composition. Thus, these features are probably related to a trend of the basin water balance, which was, perhaps, enhanced by closed or restricted drainage conditions (Sáez and Cabrera, 1994). The existence of carbonate- and/or sulphate-rich waters in the basin would account for the rather high sulphide contents in the Unit 1 coals, given the high sulphide activity which would result from the enhanced activity of sulphate-reducing bacteria.

3.2.2. Unit 2

This unit is up to 120 m thick in the western subbasin and is as much as 100 m thick in the eastern subbasin. These maximum thicknesses are attained close to the N–S extensive faults, near the northern basin margins. Unlike the underlying unit, coal deposits were formed in both basins, although relative development was greater in the western subbasin. The uppermost beds of this unit marked the onlap of the tectonic threshold which differentiated both subbasins.

The ash content in the lignite seams in this unit shows average ranges similar to those recorded in Unit 1 coals and is also higher towards the depositional margins. Sulphur content (also partially contained in sulphides, probably pyrite) is also fairly high, but does not attain the highest values recorded in the lower H zone (Fig. 2).

In both subbasins this unit shows similar lithologic features. In the inner basin zones it consists of alternating alluvial sandstones and mudstones and laterally extensive coal seams up to several metres thick. The terrigenous and coal facies alternations make up sequences up to several metres thick. Well developed lacustrine deposits do not occur in this unit but the presence of lacustrine sponge spicule laminae has been recorded in some of the coal seams (i.e., in A seam). The scarce palynological data on the fossil plant associations recorded in this unit indicate the persistence of warm climatic conditions associated with a decrease in the importance of the water-dominated, limnic environments (Medus, 1965a,b; Nonn and Medus, 1963).

Coal lithotypes in this sequence are mainly dark, matrix-rich, sometimes xylitic, huminitic coals. In some places they are associated with distinctive bright, liptinite-rich coal layers. These bright coals, which display root traces, often cap the coal seams but they also alternate with the dark coal facies. Unlike Unit 1, the stacking up of the alluvial coal sequences in Unit 2 usually shows a more equal development of the terrigenous and lignite facies. These sequences never attain the greatest coal sequence thickness recorded in the H zone (Unit 1).

The deposition of this alluvial swamp unit marked a demonstrable change in basin evolution. The absence of open lacustrine facies is a striking feature, together with the conclusion that coal deposition was widespread over the basin except for the threshold area. The whole unit records the repeated spreading and retreat of the swamp deposits with a correlatable retrogradation and progradation of the proximal to middle alluvial and fluvial facies from the northern margin and the eastern end of the basin. The similar facies assemblages deposited in both subbasins, characterized by the absence of carbonate lacustrine sediments, limnic carbonate flora, or gastropods adapted to saline water, suggest that no perennial, open surface water column developed in the basin. Nevertheless, meteoric surface and underground waters entering the basin system could still have evolved towards solute concentrations higher than the original. Moreover, the high sulphide content suggests enhanced sulphate-reducing bacterial activity.

3.2.3. Unit 3

This unit is up to 60 m thick in both subbasins and is exclusively composed of grey sandy mudstones, mudstones and whitish arkosic quartz sands, gravels and sandstones. During sedimentation the threshold which divided the basin was nearly completely overlapped and no coal deposits were formed (Fig. 2).

The whole unit is dominated by proximal to distal alluvial deposits. Coarse-grained facies assemblages, made up of stacked, sandy and pebbly mudstone deposits are present along the northern basin margins, where they are dominant. This proximal facies grades laterally towards the inner basin zones into mudstone-dominated assemblages. A distinctive coarsening- and thickening-upwards sequential trend is displayed by this unit in the central basin zones. More highly sorted sandstone and gravelly channelized facies attain maximum development in the eastern subbasin, since active alluvial braided stream channelized axes impinged into the basin from the eastern end. These channelized sandy and gravelly facies display a multistorey character, with amalgamation and the predominance of vertical infilling in each individual channel episode. Mudstone lenses, related to flood alluvial plain and to channel abandonment episodes, are also present. In several central and southern basin sectors the sandstone-dominated channelized facies assemblage make up the upper part of this unit and erosively overlie the lower, mudstone-dominated deposits. Neither coal deposits nor lacustrine facies are present in this unit but minor hydromorphic paleosol sequences with siderite nodules are frequent in the lower part of the unit, in the transition from the underlying coal-bearing sequences. Recent occurrences of siderite have often been reported from river bogs and marsh deposits (Pye, 1981; Postma, 1977). Siderite occurrences have often been attributed to bacterial diagenesis (Kantorowic, 1985). The conditions necessary for siderite precipitation require high iron and dissolved carbonate activities, low sulphide activity and a reducing environment. These parameters suggest that meteoric waters still underwent a certain degree of solute evolution in the basin system. However, in contrast to earlier situations, groundwaters in the basin were characterized by high carbonate activity, in contrast to the earlier high sulphide activity recorded in units 1 and 2.

The deposition of this major alluvial unit was a significant stage in the evolution of the basin, since coal deposition was prevented. The whole unit records spreading and progradation of the proximal to middle alluvial–fluvial facies coming from the eastern basin end onto the pre-existing palustrine–swampy coal zones.

3.2.4. Unit 4

This unit is up to 180 m thick in the western subbasin and attains a thickness of 140 m in the eastern subbasin. The lower beds of this unit overlapped the tectonic threshold which separated the subbasins. Coal deposition took place over the entire basin, although it was again more persistent in the western subbasin (Fig. 2).

This unit shows similar lithologic features in both subbasins. In the inner basin zones it consists of sequential alternations of 2–10 m of alluvial sandstones and mudstones, and laterally extensive coal seams. No lacustrine deposits are present in this unit and no traces of early diagenetic siderite nodules have been recorded to date.

The lower part of this unit includes the Beta zone, which is the thickest (up to 30–40 m of coal in the western part of the basin and up to 30 m in the eastern part) in the basin (Figs. 2 and 4). The Beta zone is made up of the repeated stacking of 1 m thick terrigenous coal sequences, with predominant coal deposition in the central and southern basin zones and a rapid lateral transition to terrigenous, mudstone–sandstone-dominated facies towards the northern margins and the eastern basin end. Average ash contents in the coal seams of this sequence range between 20% and 30%. They are higher in the zones neighbouring the northern basin margins, with a maximum of up to 40%. Sulphur contents are relatively low in most of the seams (3%) compared with coals in units 1 and 2. Nevertheless, a local maximum of up to 8% is present in some marginal zones of the sequence.

In the upper part of Unit 4 the alluvial deposits become more and more dominant (Fig. 2). Hence the thickness (up to a few metres), areal extent and continuity of the single, lenticular coal seams are rather low compared to the lower part of the unit. The uppermost part of the unit is exclusively comprised of alluvial deposits. Coal seams in this unit are made up exclusively of dark, matrix-rich huminitic coals, which often alternate with distinctive, brittle, charcoal laminae or thin beds up to 0.5 cm thick. Bright, yellowish, highly liptinite-rich coal beds are not extensive.

The available palynological data gathered from the coal seams (Medus, 1965a,b; Baltuille et al., 1990; Baltuille et al., 1992) indicate tropical–subtropical, warm and humid paleoclimatic conditions and the occurrence of a number of plants characteristic of marsh and swamp environments. Nevertheless, a large amount of conifer pollen has been recorded, suggesting the beginning of a change towards more temperate and drier climate conditions (Medus 1965a,b).

The deposition of this last alluvial–swamp unit of the basin marked the final stages and the end of the basin evolution. The absence of well developed lacustrine facies and the fact that coal deposition spread all over the basin make this unit similar to Unit 2. The whole unit also records repeated spreading and retreat of the swamp coal deposits. These areal changes of the marsh–swamp zones were concomitant with retrogradation and progradation of: (1) the alluvial fan facies which spread from the northern margin; and (2) of the channelized alluvial facies impinging from the eastern basin end. Similar facies assemblages were deposited in both subbasins, with no occurrence of either carbonate lacustrine sediments or limnic carbonate flora, which suggests no perennial, open surface water column developed during this stage of basin evolution. Nevertheless, meteoric surface and underground waters entering the basin system could still have provided a high sulphate concentration, as suggested by the fairly high sulphur content, which indicates enhanced activity of sulphate-reducing bacteria.

4. Coal rank, petrography and organic geochemistry: paleoenvironmental significance

The marked changes of the coal seam distribution and coal lithotype assemblages in the As Pontes basin show a distinctive evolution from the lower stratigraphic units (1 and 2) where sulphide-rich, dark, huminitic and bright, liptinite-rich lignites are present and the upper unit (4) where only low sulphide, dark coals are present. These facies assemblage changes took place simultaneously with rearrangements of the depositional framework, which was mainly related to the tectonic basin evolution. From this point of view, the changes in the major lignite facies and corresponding diverse assemblages may be related to the depositional framework changes. Subsequently, probable variations in the major coal features (including macro- and micro-petrography) were sensitive in varying degrees to the tectonic evolution of the basin and/or climatic changes. Therefore, a detailed study may improve our understanding of basin evolution.

4.1. Methods of coal sampling and analysis

Coal samples were taken from several seams in different sections (Figs. 2–4). The seams were not sampled completely but individual samples were taken in accordance with macropetrographical characteristics. The aim of this sampling was to get a first overview of the variety of the coal facies present in the diverse stratigraphic units. The 26 coal samples studied were taken from selected seams in Unit 1 (seams I and lower part of zone H in the

Table 1
General coal quality parameters

Unit No.	Sample No.	TOC (%, daf)	Ash (%, db)	Cal. value (J/g; moist, af)	Cal. value (J/g; daf)	v.m. (%, daf)	W (sat.) (%)	R_r (%)
IV	Beta 12	45.6	53.0	18720	29570	61.9	36.7	0.36
IV	Beta 11	52.4	44.7	19320	32250	(98,4)	40.1	0.36
IV	Beta 10	62.7	20.8	15620	26560	57.4	41.2	0.36
IV	Beta 9	51.1	46.1	15170	27180	74.8	44.2	0.34
IV	Beta 8	57.6	32.7	15010	27150	63.8	44.7	0.36
IV	Beta 7	58.2	30.6	14410	27080	62.4	46.8	0.35
IV	Beta 6	68.0	12.4	15640	28800	59.3	45.7	0.34
IV	Beta 5	58.1	30.6	15670	28330	65.9	44.7	0.39
IV	Beta 4	60.0	15.0	13730	27450	55.5	50.0	0.37
IV	Beta 3	68.4	15.5	15910	29850	59.1	46.7	0.39
IV	Beta 2	58.5	31.8	16120	28230	63.3	42.9	0.35
IV	Beta 1	61.0	6.4	11140	23960	55.5	53.5	0.34
II east	A3	43.2	27.6	12990	23620	60.7	45.0	0.35
II east	A2	59.2	18.4	14520	26790	63.3	45.8	0.33
II east	A1	55.7	17.4	15610	28490	63.3	45.2	0.34
II west	A2	62.7	20.4	15230	28570	63.4	46.7	0.34
II west	A1	55.2	19.1	12840	25220	55.5	49.1	0.36
I	H8	55.1	27.3	15110	27730	68.2	45.5	0.31
I	H7	59.6	14.1	14110	26620	55.7	47.0	0.34
I	H4	56.7	20.2	14340	27310	60.8	47.5	n.d.
I	H2	58.4	17.9	13440	24850	71.2	45.9	n.d.
I	H1	57.5	63.8	(38160)	(45750)	(86.1)	(16.6)	n.d.
I	I2	66.8	14.4	15880	29030	56.9	45.3	0.31
I	I1	67.5	14.1	16110	30520	58.4	47.2	0.35

TOC = total organic carbon; cal. value: calorific value; v.m. = volatile matter; W (sat.) = saturation moisture; R_r = random reflectance.

western subbasin), from Unit 2 (seam A in the eastern subbasin) and from Unit 4 (seam fl in the eastern subbasin).

To avoid oxidation, the coals were freeze dried before further preparation and analyses (Hagemann, 1981).

The macroscopical description (up to $\times 15$ magnification) and the microscopical analyses (up to $\times 625$ magnification) were carried out in reflected white and fluorescent light (blue light excitation). Reflectance measurements were made according to ISO (1984).

The soluble organic matter (extract/bitumen) was obtained by Soxhlet extraction with dichloromethane (24 h). These extracts were further separated into aliphatic-, aromatic- and NSO+ residuum fractions by flash chromatography (Moinelo et al., 1987), using n-hexane, dichloromethane and methanol for elution. The aliphatic fraction was further separated by gas chromatography (SE 54 column, 25 m $\times$ 0.32 mm, temperature program: 80–300°C at a rate of 4°C/min, 30 min at 300°C).

The ash content, gross calorific values, saturation moisture and TOC were determined according to ISO standards (ISO, 1975; ISO, 1976; ISO, 1981). The results of these analyses are shown in Tables 1–3.

Table 2
Microscopical analysis data

Unit No.	Sample No.	min. m. (%)	hum. (%, mmf)	inert. (%, mmf)	lipt. (%, mmf)	HT (%, mmf)	HD (%, mmf)	HC (%, mmf)	TPI	GI
IV	Beta 12	8	75	8	17	15	48	12	0.38	9.38
IV	Beta 11	12	87	2	11	5	68	14	0.09	43.50
IV	Beta 10	8	81	7	12	9	50	22	0.22	11.57
IV	Beta 9	7	90	1	9	6	71	13	0.08	90.00
IV	Beta 8	10	81	2	17	7	58	16	0.12	40.50
IV	Beta 7	11	85	6	9	2	63	20	0.10	14.17
IV	Beta 6	4	91	7	2	19	65	7	0.36	13.00
IV	Beta 5	17	88	2	10	5	61	22	0.08	44.00
IV	Beta 4	15	94	1	5	18	64	12	0.25	94.00
IV	Beta 3	6	92	5	3	43	27	22	0.98	18.40
IV	Beta 2	11	89	2	9	33	38	18	0.63	44.50
IV	Beta 1	3	98	1	1	83	2	13	5.60	98.00
II east	A3	13	73	2	12	24	18	31	0.53	36.50
II east	A2	4	74	1	14	9	42	23	0.15	74.00
II east	A1	5	90	1	9	11	59	15	0.16	90.00
II west	A2	4	98	1	1	10	82	6	0.13	98.00
II west	A1	4	94	2	4	70	16	8	3.00	47.00
I	H8	12	89	1	10	55	13	21	1.65	89.00
I	H7	0	96	1	3	28	52	15	0.43	96.00
I	H4	5	88	1	11	39	17	33	0.80	88.00
I	H2	23	92	1	7	32	41	19	0.55	92.00
I	H1	51	0	0	100	0	0	0		
I	I2	2	95	3	2	59	12	24	1.72	31.67
I	I1	5	89	10	1	24	34	31	0.52	8.90

min. m. = mineral matter; hum. = huminite; inert. = inertinite; lipt. = liptinite; HT = humotelinite; HD = humodetrinite; HC = humocollinite; TPI = tissue preservation index (see text); GI = gelification index (see text).

4.2. Rank

The coals can be classified as lignite B (ASTM) or class 11/12 coal (UN-ECE), according to huminite (ulminite b) reflection, ranging from 0.31% to 0.39% (R_r). For these and the other data quoted in connection with rank, see Table 1. The calorific values indicate the same rank. With a mean of about 15,000 J/g they reach a maximum at 19,700 J/g and a minimum at 11,140 J/g.

Reasonable data are usually obtained exclusively from coals with ash contents lower than about 10 wt%; the coals studied contain up to 63.8 wt% ash and in general contain more than 10 wt%). For this reason, the reflectance data are considered to be the most reliable for the rank determination in this case. The saturation moisture, which varied from 54% to 37% (ash free) indicates a slightly lower rank. Because of the high ash content of the coals, the saturation moisture data vary more than for low ash coals.

Although they are not considered to be typical rank parameters for lignites, the TOC data are in good agreement with this rank classification (Stach et al., 1983). There is no (sys-

Table 3
Geochemical analysis data

Unit No.	Sample No.	Extract (ppm)	Extract (mg/gTOC)	Alkanes (%)	Aromates (%)	NSO + res. (%)	CPI (17–32)
IV	Beta 12	27938	131.2	4.3	8.4	87.3	1.5
IV	Beta 11	72935	265.2	3.3	9.4	87.3	9.4
IV	Beta 10	26264	58.0	3.9	11.9	84.2	5.9
IV	Beta 9	22644	83.6	4.3	9.1	86.6	5.5
IV	Beta 8	34349	92.8	3.9	8.8	87.3	4.9
IV	Beta 7	23329	61.1	5.1	11.1	83.8	4.6
IV	Beta 6	36318	62.5	2.4	23.3	74.3	5.3
IV	Beta 5	34222	93.0	2.7	13.8	83.5	6.2
IV	Beta 4	6544	15.8	9.0	15.6	75.4	0.8
IV	Beta 3	13416	23.5	1.4	3.8	94.8	4.7
IV	Beta 2	20555	55.0	5.2	11.3	83.5	2.8
IV	Beta 1	17377	38.0	2.9	13.6	83.5	4.7
II east	A3	17387	62.3	19.9	28.8	51.3	2.1
II east	A2	55591	130.2	3.5	8.9	87.6	12.8
II east	A1	33206	80.2	6.3	24.9	68.8	2.2
II west	A2	63497	139.9	2.6	23.7	73.7	6.7
II west	A1	9626	24.2	7.5	28.0	64.5	8.9
I	H8	15465	41.1	3.5	12.3	84.2	12.0
I	H7	2247	5.2	2.7	3.9	93.4	2.1
I	H4	11899	28.4	2.4	12.8	84.8	4.5
I	H2	19236	38.0	3.6	16.0	80.4	4.4
I	H1	40171	184.5	3.6	7.7	88.7	3.9
I	I2	5986	11.0	7.6	17.8	74.6	13.7
I	I1	5550	9.9	6.4	24.1	69.5	6.4

NSO + res. = NSO compounds and residuum, e.g. asphaltenes and resins; CPI = carbon preference index.

tematic) change in rank determinable in the coals from the bottom to the top of the basin infill. The low huminite reflection values point to the inference that the basin infill burial temperature was around 35°C and that it did not attain 50°C.

4.3. Macropetrography

Macropetrographically, the coals look more or less homogenous and can be classified as matrix coals and/or mineral-rich coals. They are moderately or not stratified. The stratification is caused by small plant tissues of varying brightness. Large plant organs are not present. Some bright layers are especially eyecatching because the coals of As Pontes in general are medium to dark brown, depending on their degree of gelification.

The bright coals are related to either relatively high mineral (especially clay) contents and/or a relatively high content of lipid-rich matter. These bright coal layers may have been subjected to aerobic degradation, a process by which the most resistant components, liptinite and mineral matter, were relatively enriched (Hagemann and Wolf, 1987). The dark coals are characterized by strongly gelified matrices. It is remarkable that some contain chlorophyllinite (red fluorescing). It can be concluded that the peats making up the coals were deposited under rather wet and alkaline reducing conditions (Jacob, 1964). Charcoal occurrence is often restricted to layers a few millimetres thick, which are especially frequent in the coal seams of Unit 4 and to a lesser degree in Unit 2.

4.4. *Micropetrography*

Coal micropetrographic data can provide information on the paleoenvironmental conditions under which the coals accumulated. The changes in the occurrence and relative dominance of the diverse kinds of maceral components through the coal-bearing successions allow interpretations of the probable environmental trends. Thus, following Diessel (1992) two indices for the environmental conditions of coal deposition can be calculated from the maceral composition. These are the 'gelification index' (GI) and the 'tissue preservation index' (TPI). The GI is dependent upon the continuity of moisture availability, since it relates the amount of gelified (huminite/vitrinite and non-fusinitised inertinite) to fusinitised macerals (fusinite, semifusinite and liptodetrinite). The TPI, although also dependent upon the originally accumulated plant material, is mainly a measure of the degree of humification. Thus, it is related to the subsidence rate by relating macerals displaying preserved tissue structure (e.g., telohuminite and fusinite) to the other huminite and inertinite materials which do not display any tissue structure. Information from the depositional environment can be inferred from the data of these two indices (Diessel, 1992). Apart from this quantitative approach, other indications from petrological observations may provide paleoenvironmental information. Thus, further evidence for the depositional environment is provided by the fact that the plants growing in wet environments have more tiny cuticles than those growing in dry environments (Sitte et al., 1991).

The main maceral group of the As Pontes lignites is huminite with varying amounts of humotelinite, humodetrinite and humocollinite (Table 2). Inertinites are rare and are enriched as inertodetrinite in small layers.

Sporinite, liptodetrinite and a fluorescent mineral–bituminous groundmass (Pickel and Wolf, 1989; 'bituminite in lignites' according to Teichmüller, 1974) are the dominant macerals of the liptinite group, which makes up to 17% (mmf) of the coal. The mineral–bituminous groundmass is especially enriched in the bright lithotypes. Cutinite, fluorinite, suberinite, resinite and chlorophyllinite are also present, but in smaller amounts. Sample H-1 is a clay rich in organic matter, with an ash content of 63.8%. The microscopically identifiable organic material consists exclusively of liptinite macerals.

The amount of liptinite is related to the amount of mineral matter (ash content; see Fig. 5). The amount of liptinite, in general, is higher in coals with a high mineral matter content. The extreme example of this is sample H-1 in which exclusively mineral matter and liptinite (suberinite) are present.

Figured alginite was not found by microscopic analysis. The occurrence of alginite is considered to be evidence for lacustrine depositional environments. However, the absence of alginite is not proof of a non-lacustrine environment because alginite may be present as liptodetrinite or in the mineral–bituminous groundmass. The commonly diminutive size of the cutinites, due to the occurrence of aquatic plants in the coals of the As Pontes basin, is indicative of wet depositional environments. The As Pontes lignites, in general, are char-

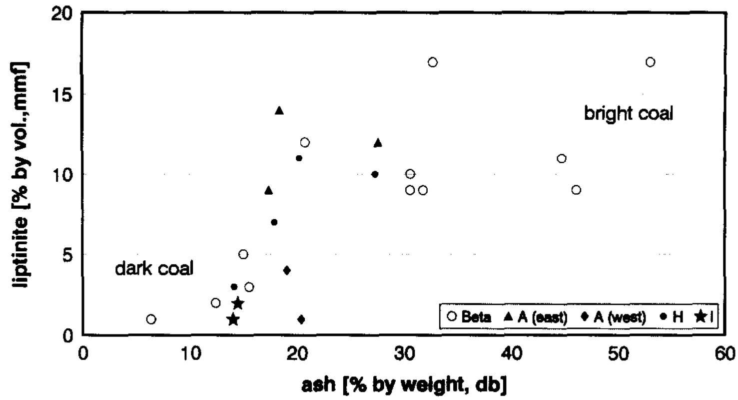

Fig. 5. Ash content versus liptinite content in samples of huminitic lignites from the As Pontes basin. See Figs. 2–4 for the stratigraphic location of coal seams sampled.

acterized by high to low GI values and very low to low or moderate TPI values (Table 3 and Fig. 2).

Some general statements can be made on the basis of the currently available GI and TPI data:

(1) The GI changed through time from rather high (88–96 in H-1 samples and 98 in the lowermost Beta sequence sample) to very low (8.90 in the lower part of the I seam and 9.38 at the upper part of Beta coal-bearing sequence). Probable lateral changes in these indices are the cause of the changing values observed in the samples of the A seam.

(2) Even if the samples analyzed are not representative of the whole coal-bearing sequences, it should be noted that the gelification indices of the coals from the upper part of the basin infill (Unit 4, zone Beta), in general, are lower than those from coal seams in the lower units 1 and 2. The same is true of the TPI index values measured (Table 2).

4.5. Organic geochemistry

The amount of carbon extracted varied from 5.2 to 184.5 mg/g TOC. These variations, as well as the range, are typical of lignite B (Hollerbach, 1985). TOC data are presented in Table 3.

The amounts extracted from lignites were influenced by various parameters, including the degree of gelification, the content of mineral matter (by which the mobility and thereby extractability may be increased), resin content and the degree of degradation (Pickel, 1991; Qi Ming et al., 1994). A major contribution from the non-degraded liptinites, with the exception of resinite, to the extract is not to be expected, in accordance with the low rank of the coals (Khorasani and Murchison, 1988). An increase in the extract amount is thus to be expected in the bright coals in which the mineral matter content and the liptinite content are higher due to secondary enrichment (see above). This relationship is present because the extract amount increases with the mineral matter content and with the abundance of liptinites (Fig. 6).

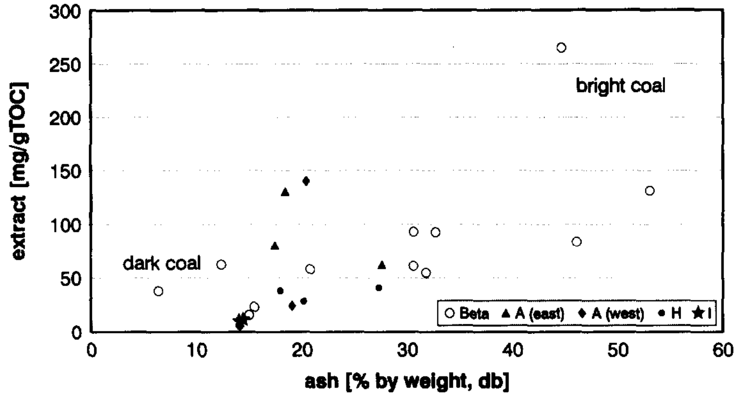

Fig. 6. Ash content versus organic matter extract amount of the huminitic lignites from the As Pontes basin. See Figs. 2–4 for the stratigraphic location of the coal seams sampled.

The proportions of the single bitumen fractions are also typical of lignites (Table 3), with minor amounts of the aliphatic fraction, minor to moderate amounts of the aromatic fraction and a predominant amount of the NSO + residuum fraction.

The Carbon Preference Index (CPI), calculated from the ratio of odd and even n-alkanes present in the aliphatic fraction, is a parameter of coal rank. With values ranging from 1.5 to 13.7, the rank determination given above as lignite B is further supported (Hollerbach, 1980; Philp, 1985). The CPI of sample Beta 4 (0.8) is the only exception. This value is due to the fact that in this sample n-C16 and n-C18 are the predominant n-alkanes (Fig. 7). This can be taken as an indication of algal influence (Blumer et al., 1971). Even though no alginite was found by microscopic analysis, it can be assumed that the liptodetrinite and the mineral–bituminous groundmass were partly from alginite. This coal is a very dark, strongly gelified coal so that a high water level, and thereby the possibility of algal influence, can be inferred.

A typical gas chromatogram of the aliphatic fraction of the As Pontes lignites is shown in Fig. 7 (sample Beta 12). The dominance of odd-numbered n-alkanes over the even-numbered is clear, as well as the maximum of n-alkanes at n-C29. The hopanes (aβ-homohopane and $\beta\beta$-homohopane) indicate bacterial influence (Dehmer, 1989). Bacterial contributions in the As Pontes lignite deposits are also evidenced by the existence of several characteristic maxima (450, 505, 545 and/or 655 nm) in the fluorescence intensity curves of the dichloromethane extracts (samples H1 and H2, Beta 3 and Beta 6), which indicate the occurrence of carotenoids derived from sulphate-reducing bacteria cell walls. The method of spectral fluorescence measurements of the extracts has been described by Hagemann and Hollerbach (Hagemann and Hollerbach 1981; Hagemann and Hollerbach, 1986).

With the exception of sample Beta 4 (see above and Fig. 4) the gas chromatograms of the other samples look very similar. It is quite interesting to note that only tiny traces of diterpenoids (which indicate a major gymnosperm influence) appear in the aliphatic fractions. In the light of this result angiosperms seem to be dominant contributors. These results complement earlier data on the organic geochemistry of the As Pontes coals (Martín et al., 1986; Cubero et al., 1987; González Vila et al., 1987) which confirmed the existence of noticeably higher terrestrial plant, and probable bacterial and algal, contributions.

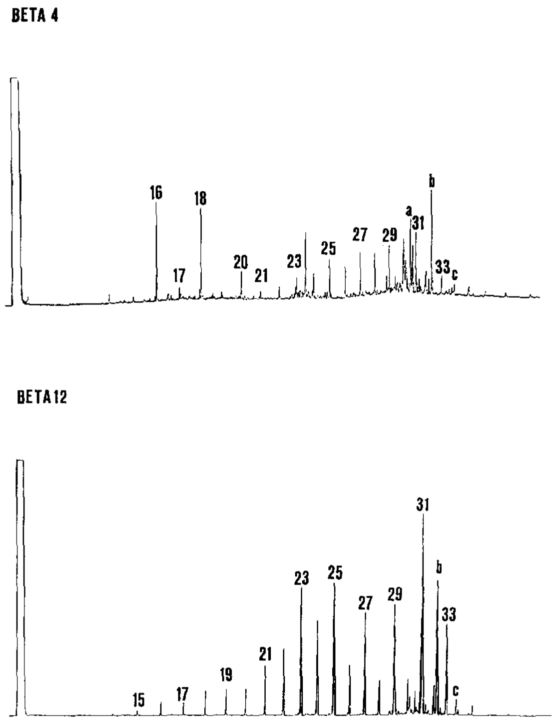

Fig. 7. GC traces of the aliphatic fraction of samples Beta 4 and Beta 12; a = hop 17(21) en; b = 17a, 21β homohopane; c = 17β, 21β homohopane, 15–33 = n-alkanes. See Fig. 4 for stratigraphic location of these samples.

4.6. Paleoenvironmental interpretation

These preliminary petrological and geochemical data warrant the following conclusions:

(1) The As Pontes lignites were deposited under paleoenvironmental conditions ranging from wet to slightly drier conditions (telmatic or limno-telmatic; i.e. intermittently to permanently flooded) according to the changing low to high GI values.

(2) The lowering and increasing of the GI values recorded from the bottom to the top of the coal seams studied and sequences show that the groundwater level was relatively steady during coal accumulation in some cases (i.e., in the lower part of the H zone seam). In other cases it was subjected to repeated rises and falls (e.g., the spiky profile of the GI in the Beta zone sequence) or to a single rising or falling trend in single seams (e.g., I and A seams respectively). Moreover, these data suggest that peat deposition commenced under conditions of rapid (e.g., A seam and Beta seams) or more gradual (e.g., I seam) water table rises.

(3) As mentioned above, the coal depositional environments changed and were subjected to pulses of rapid rises and falls in the groundwater level but they became (more or less gradually) drier during deposition of the lower units 1 and 2 to the upper Unit 4. This conclusion fits well with, and is also supported by, the sedimentological and paleontological data which characterize the lignite deposits and associated facies in each of the stratigraphic units of the basin.

(4) High GI values, combined with high TPI values recorded in some samples (for instance Beta 1) suggest that coal sedimentation took place in telmatic swamps under relatively high subsidence/sedimentation rates.
(5) High GI values, combined with low or moderate TPI values (e.g., samples Beta 4 and Beta 9 and H2, H4 and H7) suggest that sedimentation developed:
(a) either in telmatic–limno-telmatic swamp areas under conditions of relatively low subsidence/sedimentation rates or lowering groundwater table; or
(b) in treeless, open marsh areas, with major contributions from open marsh and limnic plant communities.

According to the sedimentological features of the associated facies and the palynological and paleozoological data (Medus, 1965a,b; Cabrera et al., 1994a; López et al., 1993), the first possibility could be the most likely for Beta 4 and Beta 9, whereas the second is more suitable for H-2, H-4 and H-7.

(6) Low GI values combined with very low TPI values, as recorded in most of the samples from the Beta seam, suggest peat accumulation in intermittently dry swamps from aerobically decomposed autochthonous plants under low subsidence/sedimentation rates.

5. Coal accumulation conditions and basin evolution: changes in the coal assemblages

5.1. Climatic and tectonic conditions

Substratum paleoweathering (Brell and Doval, 1979); fossil palynomorph assemblages (Nonn and Medus, 1963; Medus, 1965a,b; Baltuille et al., 1990, 1992; Cabrera et al., 1994a); fossil plant leaves (López et al., 1993); and crocodile remains (Cabrera et al., 1994a) recorded in the basin suggest that warm and humid, tropical–subtropical conditions were dominant during most of the early basin infill sedimentation. Carbonate–clay rhythmites accumulated in the lacustrine environments of Unit 1 point to the existence of a seasonal paleoclimate, with changes in precipitation and/or wind regime. A probable trend to more temperate, drier conditions might have developed (Medus, 1965a,b) during the generation of the upper basin sequences (units 3 and 4). Characteristic marsh–swamp plant taxa have been recognized in the diverse parts of the basin infill. Taxodiacea (*Taxodium-Glyptostrobus*) and aquatic plants characteristic of open subaquatic and marsh environments (*Nymphaea*, *Potamogeton*, *Stratiotes* and *Typha*) are present in the lower part of the basin infill (Cabrera et al., 1994a). The subsequent relative development of these communities in the sedimentary area varied as a consequence of the tectono-sedimentary and climatic changes which affected the basin.

As has been shown by the geometric relationships between the stratigraphic units and the tectonic structures in the basin (Fig. 2), tectonic activity persisted throughout the evolution of the basin, although the active structures were not always the same in the successive evolutionary stages (Bacelar et al., 1988, 1992). In the early evolutionary stages the active tectonic structures (N–S normal faults and E–W to NNE–SSW thrust slices and reverse

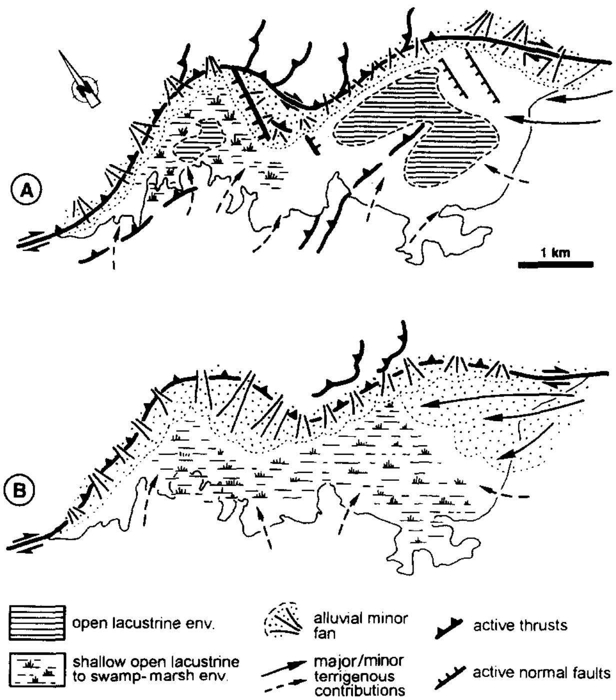

Fig. 8. Major evolutionary stages of the As Pontes basin. Note changes in the depositional framework (mainly the declining development of lacustrine environments) and basin morphology (the increasing communication between the eastern and the western parts of the basin), both of which were directly linked to tectonic evolution.

faults) gave rise to poorly connected depositional zones separated by a threshold. Both zones could be subjected to relatively variable sedimentation/subsidence rates.

Moreover, during these earlier evolutionary stages the basin morphology, controlled by tectonic activity, gave rise to a depositional framework where the peat-accumulating swamp–marsh zones were frequently related to or evolved to shallow lacustrine–palustrine environments. In these systems the basin waters were subjected to diverse degrees of solute concentration and sometimes became enriched in carbonate and sulphate and slightly alkaline. These features explain the very high sulphur contents recorded in the coals of the lower basin infill (Fig. 8).

Cyclically arranged sandy mudstones, mudstones, dolomitic mudstones, coaly bioclastic facies and even carbonate–clay rhythmites were deposited in the lacustrine environments in the eastern subbasin (Sáez and Cabrera, 1994) but major coal seams did not form there (Bacelar et al., 1988, 1992). In contrast, only minor, shallow lacustrine deposits and major, swampy marsh coal deposits (mainly the H zone) developed under this situation in the western subbasin. Most of these coal seams in the western subbasin display features which indicate that some were deposited under the persistent influence of very high groundwater levels and/or under shallow subaqueous conditions (i.e., open-water marshes less than 2 m deep). Some of these features include the higher average GI and the presence of laminated accumulations of aquatic plant seeds, *Nymphaea* palynomorphs, sponge spicule laminae, intercalations of thin, limnic, gastropod-bearing mudstones and alligator remains. Nevertheless, no cannel or boghead coals have been found, to date, in the western subbasin. These findings suggest that the subaqueous environments were not persistent or wide enough to trigger the widespread deposition of these characteristic subaqueous coal facies.

Bright, liptinitic-rich coal deposits also developed in the main western subbasin H lignite zone. This points to the conclusion that occasional water-table rises or falls triggered the aerobic degradation of peat and/or organic-rich deposits. This degradation was possibly enhanced by the neutral or slightly alkaline character of the waters in the basin system. Water-table changes could have been caused either by a temporary decrease in tectonic subsidence or by changes in the basin water balance, linked to climatic changes or tectonically induced drainage changes in the basin or in source areas. As a result, the lignites deposited during the earlier evolutionary basin stages (Unit 1) are mainly dark, huminitic, matrix- and sulphur-rich brown coals, associated with minor, bright, liptinite-enriched coal layers. Persistent, relatively moderate to low TPI values and generally high GI values characterize these limno-telmatic coals.

The geometric relationships between stratigraphic units 2 and 3 and the tectonic structures show that, during the later stages of basin evolution, tectonic activity persisted but normal fault activity was decreasing; in the end only minor E–W to NNE–SSW thrust slices and reverse faults remained active along the northern basin margins (Bacelar et al., 1988, 1992). During these intermediate stages the early tectonic threshold, which split the basin into two subbasins, was totally overlapped. As a consequence, during these stages of evolution, the basin subdivision resulting from tectonic activity became progressively less pronounced and gradually more interconnected. During the subsequent stage of basin evolution (i.e., during sedimentation of units 2 and 3), perennial, open, inner lacustrine environments with neutral or slightly basic waters did not develop. In some cases, the terminal alluvial facies were related either to swamp–marsh peat-accumulating zones (Unit 2) or to terminal, mud-dominated, poorly drained marshes without peat accumulation (Unit 3).

Coal seams developed in Unit 2 display paleontological (i.e., the occurrence of sponge spicules) and facies features (high sulphur contents and some very high GI values) which indicate that they were deposited under very high groundwater levels or subaqueous conditions. Nevertheless, temporary falls in water-table level (tectonically and or climatically induced) still persisted and helped form widespread, aerobically degraded, bright coal beds. The lignites deposited during the sedimentation of Unit 2 are mainly characterized by dark, huminitic, matrix-rich brown coal, also associated with minor bright liptinitic rich coal facies. Coals in this assemblage show less sedimentological and paleontological evidence of lacustrine influence, which was conspicuous in the underlying Unit. Relatively moderate to low TPI values and generally high GI values are characteristic of these limno-telmatic coals.

The subsequent stages of basin evolution were characterized by a somewhat more stable situation with tectonic activity mainly restricted to thrusting on the northern basin margin. Coal facies development and spreading was more homogeneous during these phases of evolution.

During the last stage of basin evolution, the geometric relationships between Unit 4 and the tectonic northern basin margin show that tectonic activity persisted there but normal N–S trending faults were inactive (Bacelar et al., 1988, 1992). As a consequence, during this late evolutionary stage (i.e., during sedimentation of Unit 4), the basin morphology resulting from tectonic activity was gentler and gave rise to a more homogeneous depositional framework. No perennial lacustrine environments with neutral or slightly basic water developed and the terminal alluvial facies were related mainly to terminal, mud-dominated, poorly drained, alluvial flood plains and swamp–marsh peat zones. Coals in Unit 4 are characterized by the nearly exclusive occurrence of dark, huminitic, matrix-rich brown coal. Very persistent and widespread low TPI values and variable, generally low GI values are also characteristic.

The coal seams developed in Unit 4 display features which indicate that some of them were deposited under very high groundwater level conditions (see, e.g., punctuated, very high, GI values in some beds of the Beta coal zone). Nevertheless, low water-table levels (tectonically and or climatically induced) persisted and a great deal of the peat accumulation which gave rise to the Beta coal zone took place, in general, under relatively lower groundwater level conditions than those of units 1 and 2. However, these low water tables did not result in the widespread generation of aerobically degraded bright coal beds. This could be explained by:

(1) more steady sedimentation/subsidence rates, which prevented noticeable water table falls and rises like those recorded in units 1 and 2;
(2) a more steady basin water balance, linked to climatic or paleodrainage conditions;
(3) the absence of evolved, carbonate–sulphate-rich, slightly alkaline waters in the basin system, which could have enhanced bacterial degradation of the huminitic components as far as the extreme diagenetic evolution recorded in the liptinite-enriched coal layers of units 1 and 2.

A definitive interpretation will require further petrological and sedimentological research of the basin.

6. Concluding remarks

Lignite deposits recorded in the Cenozoic As Pontes strike-slip basin (northwestern Spain) were formed due to early, favourable, warm–humid, tropical–subtropical paleoclimatic conditions which later evolved into slightly drier and cooler conditions. The main features of these lignites resulted from the tectonic evolution of the basin, due to the influence of tectonics on the sedimentation/subsidence rate and on the basin morphology.

No significant rank differences have been observed between the lower and upper lignites and all are lignite B (ASTM) or class 11–12 coal (UN-ECE) according to ulminite reflectance. These rank data indicate that the burial temperature which affected the basin infill was lower than 50°C.

During the early stages of evolution, movement of normal faults and thrusts inside the basin resulted in the formation of a tectonic threshold, which split the basin into two subbasins and probably caused local, temporary, subsidence/sedimentation rate variations. Demonstrable differences in the sedimentary record of both subbasins, including coal seam occurrence, thickness, areal extent and lithotype development, arose during these early stages. In contrast, the late stages of basin evolution were characterized by wider interrelationships between the diverse basin sectors and a more homogeneous sedimentary record in terms of coal seam occurrence and lithotype development.

The lignites deposited during sedimentation of the lower basin infill (units 1 and 2) are mainly dark, matrix-rich, huminitic brown coal, associated with minor, bright, liptinite-rich coal facies. The dark huminitic lignites in these units show sedimentological and paleontological evidence of lacustrine influence. Persistent, relatively moderate to low tissue preservation index (TPI) values and generally high gelification index (GI) values are characteristic of these limno-telmatic coals. On the other hand, lignites in the upper basin infill (Unit 4) are nearly exclusively huminitic, matrix-rich brown coals. Persistent and widespread low TPI values and changing, but generally low, GI values are also characteristic of these telmatic coals.

The overall coal petrological data trend (TPI, GI and the widespread development or absence of liptinite-enriched lignite layers) recorded from the lower to the upper units fits well with the stratigraphic and sedimentological data, which show a trend towards increasingly drier and more stable conditions in the basin. The development of bright, liptinite-enriched, lignite layers was widespread during the early stages of basin evolution, which were influenced by water table oscillations and/or water hydrochemistry changes.

Sedimentological, petrological and organic geochemical data point to the conclusion that, although the paleoenvironments where coal deposition of units 1–4 took place were not very different, they were affected by noticeable variations (i.e., the development of open lacustrine zones, water hydrochemistry and groundwater-level stability), linked mostly to the evolution of the basin morphology (depending mainly on tectonic–sedimentation balance) and the basin water balance (which, in turn, depended on the paleoclimate and on tectonics, through tectonically induced drainage network changes).

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References

Bacelar, J., Alonso, M., Kaiser, C., Sánchez, M., Cabrera, Ll., Sáez, A. and Santanach, P.F., 1988. La cuenca terciaria de As Pontes (Galicia): su desarrollo asociado a inflexiones contractivas de una falla direccional. 2nd Congr. Geol. España (Granada), Simposios, pp. 113–121.

Bacelar, J., Cabrera, Ll., Ferrús, B., Sáez, A. and Santanach, P.F., 1992. Control tectónico sobre la acumulación de lignitos de la cuenca terciaria de As Pontes (A Coruña, NW de España). 3rd Congr. Geol. España and 8th Congr. Latinoamericano de Geol. (Salamanca), Simposios, Vol. 2, pp. 227–238.

Baltuille, J.M., Becker-Platen, J.D., Benda, L. and Ivanovic Calzaga, Y., 1990. A contribution to the division of the Neogene in Spain using palynological investigations. Abstracts 9th RCMNS Congr. (Barcelona), pp. 34–40.

Baltuille, J.M., Becker-Platen, J.D., Benda, L. and Ivanovic Calzaga, Y., 1992. A contribution to the subdivision of the Neogene in Spain using palynology. Newsl. Stratigr., 27(1–2): 41–57.

Birot, P. and Solé Sabarís, L., 1954. Recherches géomorphologiques dans le NW de la Peninsule Ibérique. Mém. Doc. Centr. Nat. Res. Sci., 4: 9–61.

Blumer, M., Guillard, R.R.L. and Chase, T., 1971. Hydrocarbons of marine phytoplankton. Mar. Biol., 8: 183.

Boillot, G. and Malod, J., 1988. The north and north-west Spanish continental margin: a review. Rev. Soc. Geol. Esp., 1(3–4): 295–316.

Boillot, G., Dupeuble, P.-A. and Malod, J., 1979. Subduction and tectonics on the continental margin off northern Spain. Mar. Geol., 32: 53–70.

Brell, J. and Doval, M., 1979. Relaciones entre los sedimentos de Galicia y las alteraciones de su substrato. Interpretación paleoclimática. Acta Geol. Hisp., 14: 190–194.

Cabrera, L., Jung, W., Kirchner, M., Sáez, A. and Schleich, H.H., 1994a. Crocodilian and Palaeobotanical findings from the Tertiary lignites of the As Pontes Basin (Galicia, NW Spain). Crocodylia, Plantae. Cour. Forsch. Inst. Senckenberg, 173: 153–165.

Cabrera, L., Ferrús, B., Sáez, A., Santanach, P.F. and Bacelar, J., 1994b. Onshore strike-slip basins in NW Spain. In: P. Friend and C. Dabrio (Editors), Tertiary Basins of Spain. Cambridge Univ. Press, Cambridge, in press.

Cubero, F., Martín, F., González Vila, F.J. and Verdejo, T., 1987. Composición química de la fracción resina del lignito de Puentes de García Rodríguez. Afinidad, 44: 309–312.

Dehmer, J., 1989. Petrographische und organisch–geochemische Untersuchungen an rezenten Torfen und tertiären Braunkohlen. Ein Beitrag zur Fazies und Genese gebänderter Braunkohlen. Ph.D. Thesis, RWTH Aachen.

Diessel, C.F.K., 1992. Coal-Bearing Depositional Systems. Springer, Berlin, 721 pp.

Ferrús, B. and Santanach, P.F., 1994. Análisis de la fracturación en la cuenca Cenozoica de As Pontes (La Coruña). Geogaceta, 15: 147–150.

González Vila, F.J., Martín, F. and Cubero, F., 1987. Composición química de la fracción cérea del lignito de Puentes de García Rodríguez. An. Quím. Ser. C, 83(3): 295–299.

Hagemann, H.W., 1981. Die petrologische Charakterisierung von Braunkohlen als Grundlage der Bewertung ihrer rohstofflichen Eigenschaften. Habil. Fak. Bergbau Hüttenwesen RWTH Aachen, 129 S.

Hagemann, H.W. and Hollerbach, A., 1981. Spectral fluorometric analysis of extracts, a new method for the determination of the degree of maturation of organic matter in sedimentary rocks. Bull. Cent. Rech. Explor. Prod. Elf-Aquitaine, 5: 635–650.

Hagemann, H.W. and Hollerbach, A., 1986. The fluorescence behaviour of crude oils with respect to their thermal maturation and degradation. In: J. Rullköter (Editor), Advances in Organic Geochemistry, 1985. Leythaeuser, pp. 473–480.

Hagemann, H.W. and Wolf, M., 1987. New interpretations of the facies of the Rhenish brown coal of West Germany. Int. J. Coal Geol., 7: 337–348.

Hollerbach, A., 1980. Organische Substanzen biologischen Ursprungs in Erdölen und Kohlen. Erdöl Kohle, 33(6): 362–367.

Hollerbach, A., 1985. Grundlagen der Organischen Geochemie. Springer, Berlin.

IGME, 1979–1984. Proyecto para la investigación de lignito en la región de Galicia. Fases I–III. Inst. Geol. Min. Esp., Madrid.

ISO, 1975. ISO 1015: Brown coals and lignites — determination of moisture content, direct volumetric method. International Standards Organisation.

ISO, 1976. ISO 1928: Solid mineral fuels — determination of gross calorific value by the calorimeter bomb method and calculation of net calorific value. International Standards Organisation.

ISO, 1981. ISO 1171: Solid mineral fuels — determination of ash. International Standards Organisation.

ISO, 1984. Methods for the petrographic analysis of bituminous coal and anthracite. Part 5, Method of determining microscopically the reflectance of vitrinite. International Standards Organisation.

Jacob, H., 1964. Neue Ekenntnisse auf dem Gebiet der Luminiszenzmikroskopie fossiler Brennstoffe. Fortschr. Geol. Rheinl. Westfalen, 12: 569–588.

Kantorowic, J.D., 1985. The petrology and diagenesis of Middle Jurassic clastic sediments, Ravenscar Group, Yorkshire. Sedimentology, 32: 833–853.

Khorasani, G.K. and Murchison, D.G., 1988. Order of generation of petroleum hydrocarbons from liptinic macerals with increasing thermal maturity. Fuel, 67: 1160–1162.
López, M.N., Fernández Marrón, M., Peláez, P. and De la Peña, A., 1993. Estudio paleontológico de las cuencas terciarias de Galicia. Rev. Soc. Geol. Esp., 6: 19–28.
Manera Bassa, A., Barrera Morate, J.L., Cabal García, J.M. and Bacelar, J., 1979. Aspectos geológicos de la cuenca terciaria de Puentes de García Rodríguez (provincia de La Coruña). Bol. Geol. Min., 95: 452–461.
Martín, F., González Vila, F.J., Cubero, F. and Verdejo, T., 1986. Organic geochemical significance of the humic acid fraction isolated from a Spanish lignite. In: R. Rodríguez and Y. Tardy (Editors), Proc. Int. Meet. Geochemistry of the Earth Surface and Processes of Mineral Formation (Granada), C.S.I.C.–C.N.R.S., Madrid and Paris, pp. 441–447.
Martín Serrano, A., 1979. El conocimiento del lignito y del Terciario de Galicia: Exposición crítica. Tecniterrae, S-203: 46–54.
Martín Serrano, A., 1982. El Terciario gallego. Significado y posición cronoestratigráfica de sus yacimientos de lignito. Tecniterrae, S-255: 19–41.
Mauffret, A., Boillot, G., Auxietre, J. and Dunand, J., 1978. Évolution structurale de la marge continentale au Nord-Ouest de la peninsule Ibérique. Bull. Soc. Géol. Fr. 7, 20(4): 375–388.
Medus, J., 1965a. Contribution palynologique à la connaissance de la flore et de la vegétation néogene de l'ouest de l'Espagne: Étude des sediments récents de Galice. These 3ème Cycle, Univ. Montpellier.
Medus, J., 1965b. L'evolution biostratigraphique d'une lagune Néogene de Galice (Espagne). Pollen Spores, 7: 381–391.
Moinelo, S.R., Menendez, R. and Bermejo, J., 1987. Utilization of flash chromatography for the fractionation of coal derived liquids. Chromatographia, 23(3): 179–183.
Nonn, H. and Medus, J., 1963. Primeros resultados geomorfológicos y palinológicos referentes a la cuenca de Puentes de Garcia Rodríguez (Galicia). Notas Comun. Inst. Geol. Min. Esp., 71: 87–94.
Philp, R.P., 1985. Fossil fuel biomarkers (applications and spectra). Methods Geochem. Geophys., 23: 1–294.
Pickel, W., 1991. Kohlenpetrographische und organisch-geochemische Untersuchungen im Zusammenhang mit der Reifung verschiedener Liptinitmacerale. Ph.D. Thesis, RWTH Aachen.
Pickel, W. and Wolf, M., 1989. Kohlenpetrologische und geochemische Charakterisierung von Braunkohlen aus dem Geiseltal (DDR). Erdöl Kohle, 42: 481–484.
Postma, D., 1977. The occurrence and chemical composition of recent Fe-rich mixed carbonates in a river bog. J. Sediment. Petrol., 47: 1089–1098.
Pye, K., 1981. Marshrock formed by iron sulphide and siderite cementation in saltmarsh sediments. Nature, 294: 650–652.
Qi Ming, Rong Xilin, Tang Dazhong, Xia Jian and Wolf, M., 1994. Petrographic and geochemical characterization of pale and dark brown coal from Yunnan Province, China. Int. J. Coal Geol., 25: 65–92.
Sáez, A. and Cabrera, L., 1994. Sedimentación lacustre en la cuenca cenozoica de As Pontes (A Coruña). Geogaceta, 15: 59–62.
Santanach, P., Baltuille, J.M., Cabrera, L., Monge, C., Sáez, A. and Vidal-Romaní, J.R., 1988. Cuencas terciarias gallegas relacionadas con corredores de fallas direccionales. 2nd Congr. Geol. Esp. (Granada), Simposios, pp. 123–133.
Sitte, P., Ziegler, H., Ehrendorfer, F. and Bresinsky, A., 1991. Strasburger Lehrbuch der Botanik. Fischer, Stuttgart, 535 pp.
Stach, E., Mackowsky, M.-Th., Teichmüller, M., Taylor, G.H., Chandra, D. and Teichmüller, R., 1983. Stach's Textbook of Coal Petrology. Borntväger, Berlin, 535 pp.
Teichmüller, M., 1974. Entstehung und Veränderung bituminöser Substanzen in Kohlen in Beriehung zur Entstehung und Umwandlung des Erdöls. Fortschr. Geol. Rheindl. Westfalen, 24: 65–112.
Virgili, C. and Brell, J.M., 1975. Algunas características de la sedimentación durante el terciario en Galicia. R. Soc. Esp. Hist. Nat., Madrid, 1st Cent. Vol., pp. 515–523.