



## Petrological character of lignite (brown coal) from Badenian salts in the Bochnia Mine (Southern Poland)

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The salt deposit in Bochnia is located in the marginal zone of the Carpathian Foredeep. The salt succession, composed of rock salt deposits, with claystone, mudstone and zuber interbeds was, in its original location, *ca.* 80 m thick. The carbonized organic material described herein occurs within three salt units: in the southern salts, in the middle salts, and in the northern salts. There are two petrographic forms of coal in the Bochnia rock salt succession: xylite and gelitic coal. Xylites are fragments of fossil wood. Externally, xylite demonstrates a fibrous texture, and can be splintered along the fissility with uneven transverse fractures. The fragments are strongly gelified and show a zonal structure: their internal parts are made of highly cracked textinite, although the external part of the xylite fragments is built of ulminite. The gelitic coal was found in the form of lenticles, formed exclusively of euulminite. Their main mineral components include metasideronatriite ( $\text{Na}_2\text{Fe}[\text{OH}][\text{SO}_4]_2 \cdot \text{H}_2\text{O}$ ) and anhydrite while their subsidiary components are gypsum, pyrite and halite. The degree of carbonization shows that, the plant material from the Bochnia rock salt deposit is an ortholignite with xylitic and gelitic varieties.

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### INTRODUCTION

The occurrence of inclusions or layers containing fossil carbon within rock salt from the Bochnia Salt Mine is commonly known. However, in the geological literature, there have been only brief mentions on the subject. Windakiewicz (1927), who described the lithology of the salt succession uncovered in the Ferro traverse, mentioned finding several pieces of lignite (xylite)<sup>1</sup>, while Poborski (1952) in his monograph on the geological structure of the Bochnia salt deposit, only quoted information on the occurrence of coal chips and larger coal fragments within the southern salts. Recently, the most extensive accumulation of carbonized remains of plants located on level III Wernier has been put under legal protec-

tion. That project was related to the documentation of sites in the Bochnia Salt Mine (Rozporz dzenie Nr 64/05).

In this paper the authors present preliminary results of petrological investigations of a coaly substance occurring in selected exposures in the Bochnia Salt Mine, and follows research and analyses of analogous coal sediments that occur in the Wieliczka Salt Mine (Wagner *et al.*, 2008).

### THE OCCURRENCE OF COALS IN THE BOCHNIA SALT SUCCESSION

The Bochnia salt deposit is located in the marginal zone of the Carpathian Foredeep. In that area, as a result of the uplift of the Carpathians, strong folding and the accumulation of a salt

<sup>1</sup> In the contemporary brown coal nomenclature, the term “lignite” has been replaced with the name of “xylite”. Lignite (from Latin *lignum* = wood) means now a weakly-carbonized coal, regardless of its variety, whereas xylite (from Greek *xylon* = wood) is an international term applied to woody forms of brown coal.

succession took place within a narrow belt, only several hundred metres wide. The salt succession was uplifted and folded, creating a narrow belt of the “allochthonous” Miocene along the edge of the Carpathians (Poborski and Skoczylas-Ciszewska, 1963; Garlicki, 1979). The evaporite deposits which occur there (rock salt, gypsum and anhydrite) have been identified within two large folds (Poborski, 1952): the Bochnia Anticline (directly under the town centre of Bochnia) and the Uzbornia Anticline (located slightly farther to the south). Both those folds are highly uplifted and inclined towards the north (Fig. 1). In the northern part of the Bochnia Anticline, the rock salt deposit has been mined. The salt succession occurring there have been tectonically dislocated, secondarily folded, while some of the layers have been broken and repeatedly thrust one upon another (Fig. 2A).

The rock salt deposits, with claystone, mudstone and zuber interbeds were, in their original location, ca. 80 m-thick (Fig. 2B). Claystones often include anhydrite interbeds (anhydritic claystones). Also, there are marls with sporadically thin layers of pyroclastic material – tufites (De Leeuw *et al.*, 2010), as well as layers containing a carbonized organic substance or pieces of xylite. The carbonized organic material described herein occurs within three salt layer units: in the southern, the middle and the northern salts.

**The southern salts** may be divided into several varieties that occur in layers each 2–4 m thick. The predominant salt is grey, medium- and coarse-grained, which is additionally strewn with coarser crystals of halite, making the rock texture appear porphyritic. Other varieties include dark grey, fine-grained salt, and white salt, streaked with blurred, centimetre-thick layers of grey salt. Following the tectonic dislocations, those salts have formed larger concentrations near the southern border of the deposit (hence their name). Within the coarse-grained variety of the southern salts on level III Wernier, the occurrence of brown-red clay, ca. 10 cm-thick, was identified. The clay contains numerous coal chips, rounded

halite grains (up to several centimetres in diameter), as well as clasts of brown marl. The coal xylite clasts often have elongated fabrics, with longer axes reaching a dozen or so centimetres in length, or occur in the form of tiny, crumbled fragments. Samples for petrological investigation (further referred to as the BW-1) were collected from an old chamber, located ca. 160 metres east of the Sutoris shaft, near the Wernier V transverse (Fig. 3A).

**The middle salts** are mainly medium-grained, grey, with thin, alternating layers of white salt (the “striped salt”). In the bottom part of the middle salts there is a layer of medium-grained salt with interlayers of grey, clayey anhydrite, of a very thinly layered (book-like) structure. The third element in the middle salts is a layer of medium- and coarse-grained salt, which contains individual, large (up to several centimetres) halite crystals. The total thickness of the middle salts amounts to 12 m. Locally, within the bank of coarse-grained salts, and locally within the “striped salts” one can find streaky accumulations of coal matter that form regular layers, with thicknesses ranging from several to a dozen or so centimetres. Sample BW-2 (Fig. 3B) was collected from the underground exposure of that fragment of the middle salts on level IV August (in a small transverse heading with no name, near the entrance to the old part of the mine, called the “Stare Góry”).

**The northern salts** are composed of alternated layers of fine-grained salt and claystone with anhydrite. Rock salt occurs in layers of a maximum thickness of 1 metre, are contaminated evenly with clay and anhydrite, and locally include layers of pure salt. The claystone is most often laminated with nodular anhydrite and enterolitic anhydrite. The salt succession occurs mainly along the northern border of the deposit and, due to a high admixture of barren rock, the rocks have been mined only to a limited extent (the major part of the salts has remained in the deposit). The thickness of the northern salts amounts to 10 metres. Within the northern salts one can find larger fragments of coal (xylite), surrounded by characteristic rims of ferric ox-

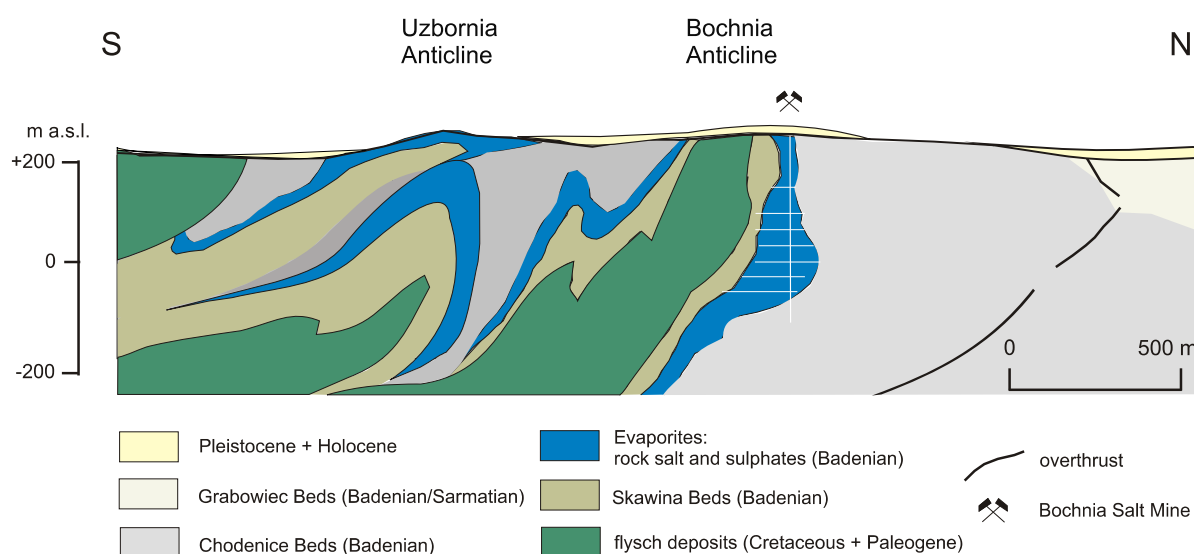
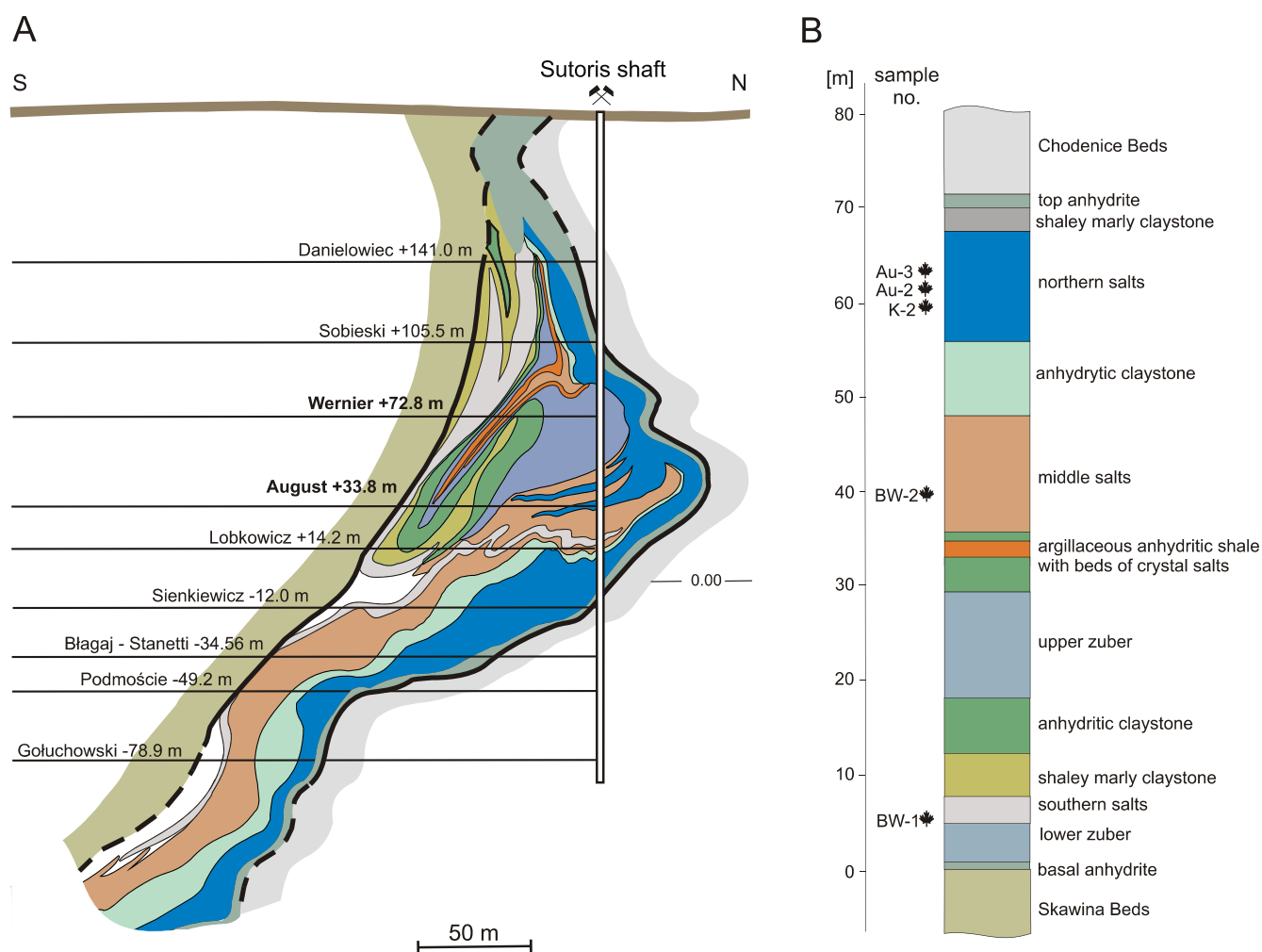


Fig. 1. Schematic geological section of the Bochnia rock salt deposit (after Garlicki 1968, modified)



**Fig. 2. Structure of the Bochnia salt deposit**

**A** – cross-section of the northern limb of the Bochnia Anticline on the Sutoris shaft meridian (according to Poborski, 1952, modified);

**B** – lithostratigraphic profile of the salt succession (according to Poborski, 1952, modified)

ides and yellow minerals. The northern salts provided a sample for further examination (collected from the north side wall of the August drift, ca. 30 metres to the west of the entrance to St. Kinga's Chapel, designated K-2), while other samples (designated Au-2 and Au-3, respectively) were collected from the south side wall of the same drift, ca. 130 metres to the east of the Campi shaft (Fig. 3C).

## METHODS

Five coal samples were collected from four localities of profile salt rocks (Fig. 2) and subjected to petrographic and chemical analysis. For the reflected light microscopy, samples of organic matter were embedded in epoxy resin, polished, and examined under both reflected and blue-fluorescence reflected light. The reflectance (random) measurements were taken under oil immersion on sample blocks, using an *Opton-Zeiss MPM-400* photometer.

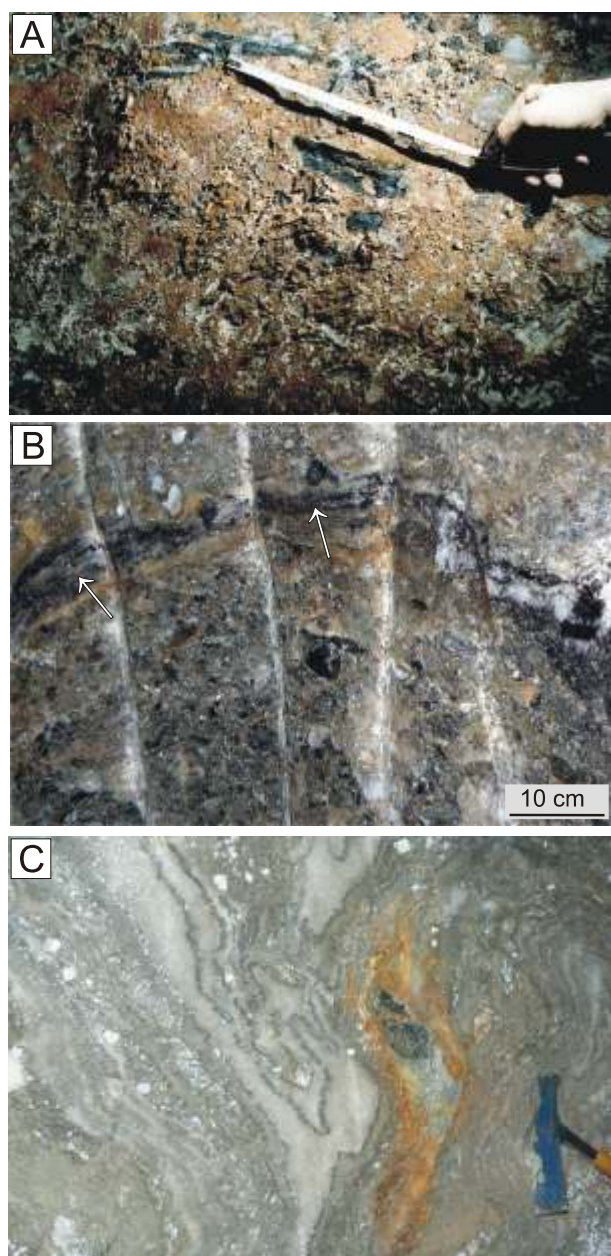
X-ray examination of natural samples were carried out (*Jeol JSEM 5200/EDX Link*).

Chemical analysis of C and S contents, ash and moisture were determined according to procedures recommended by the International Standards for solid fuels.

## COAL OCCURRENCE FORMS AND THEIR PETROGRAPHIC NATURE

As far as the rock salt in the Bochnia deposit is concerned, coal is a rock that occurs seldom, because evaporites are not typical coal-bearing lithologies. Hence the carbonized organic matter contained in salt-bearing rocks is allochthonous, although the carbonization of that matter, in diagenesis, took place already under the condition of the salt deposit.

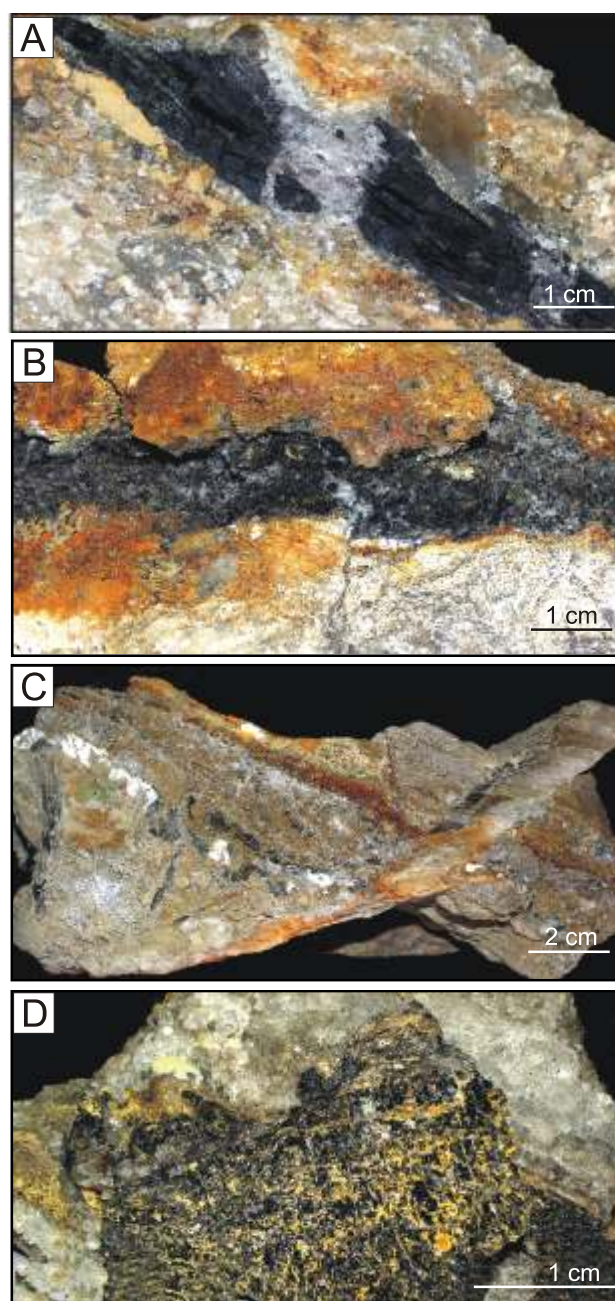
There are two petrographic varieties of coal in the Bochnia rock salt deposit series: xylites and gelitic coal.



**Fig. 3. The lignite from the salt succession of the Bochnia Salt Mine**

**A** – coal within red and brown claystones containing large grains of halite and clasts of marl, level III Wernier, the Bochnia Salt Mine, sample BW-1; **B** – streaky gelitic coal occurring within the coarse-grained variety of the middle salts, level IV August, the Bochnia Salt Mine, sample BW-2; **C** – xylite within the folded succession of the northern salts, level IV August, the Bochnia Salt Mine, samples: Au-2 and Au-3

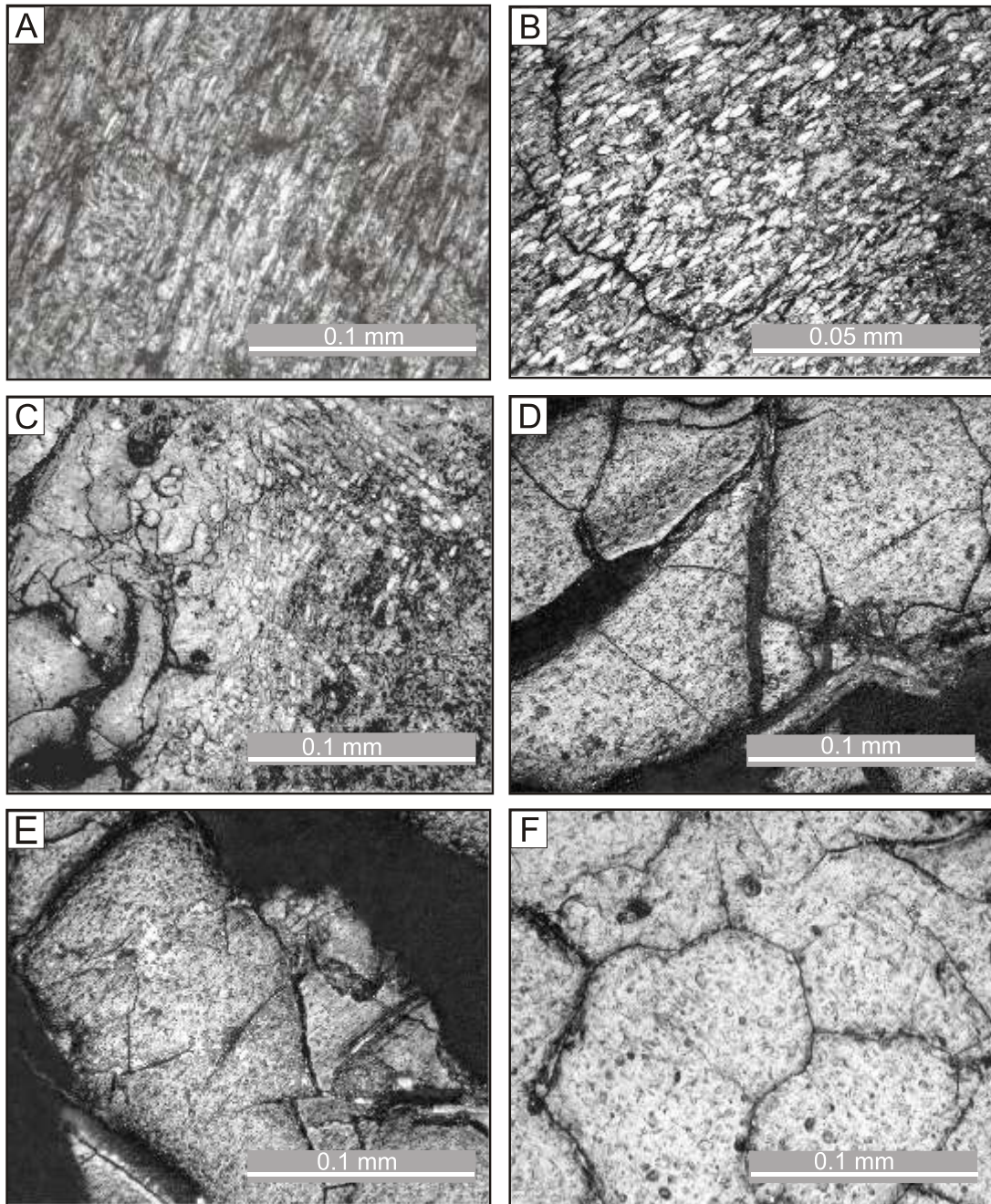
Xylites are fragments of fossil coal, with lithological features specific to the component of the xylite variety of ortholignite (Kwiecińska and Wagner, 1997). Xylites occur in the form of large chips of fossil wood, up to 10 cm long and up to 2.5 cm thick (Fig. 4A, B), as well as in the form of smaller fragments with sizes ranging from 1 cm sand-sized (Fig. 4C). Both forms of xylite form aligned accumulations within the rock salt, which emphasize the stratification of the surrounding



**Fig. 4. Petrographic varieties of coal rocks from the Bochnia salt deposits**

**A** – xylite (sample BW-1); **B** – xylite impregnated with halite (sample Au-2); **C** – dispersed xylite material (sample Au-3); **D** – gelitic coal (sample K-2); yellow filling is metasideronatrite

salt. Strong gelification of the xylites is a reason for, among other things, their black colour. Externally, xylites demonstrate properties specific to wood (a fibrous texture) and can be splintered along the length of the fissility with uneven transverse fractures. Xylites are often impregnated with salt minerals (halite, anhydrite and gypsum), and, consequently, they are brittle. Locally they occur in a rock salt margin, coloured brown with iron oxide compounds (samples Au-2 and Au-3).



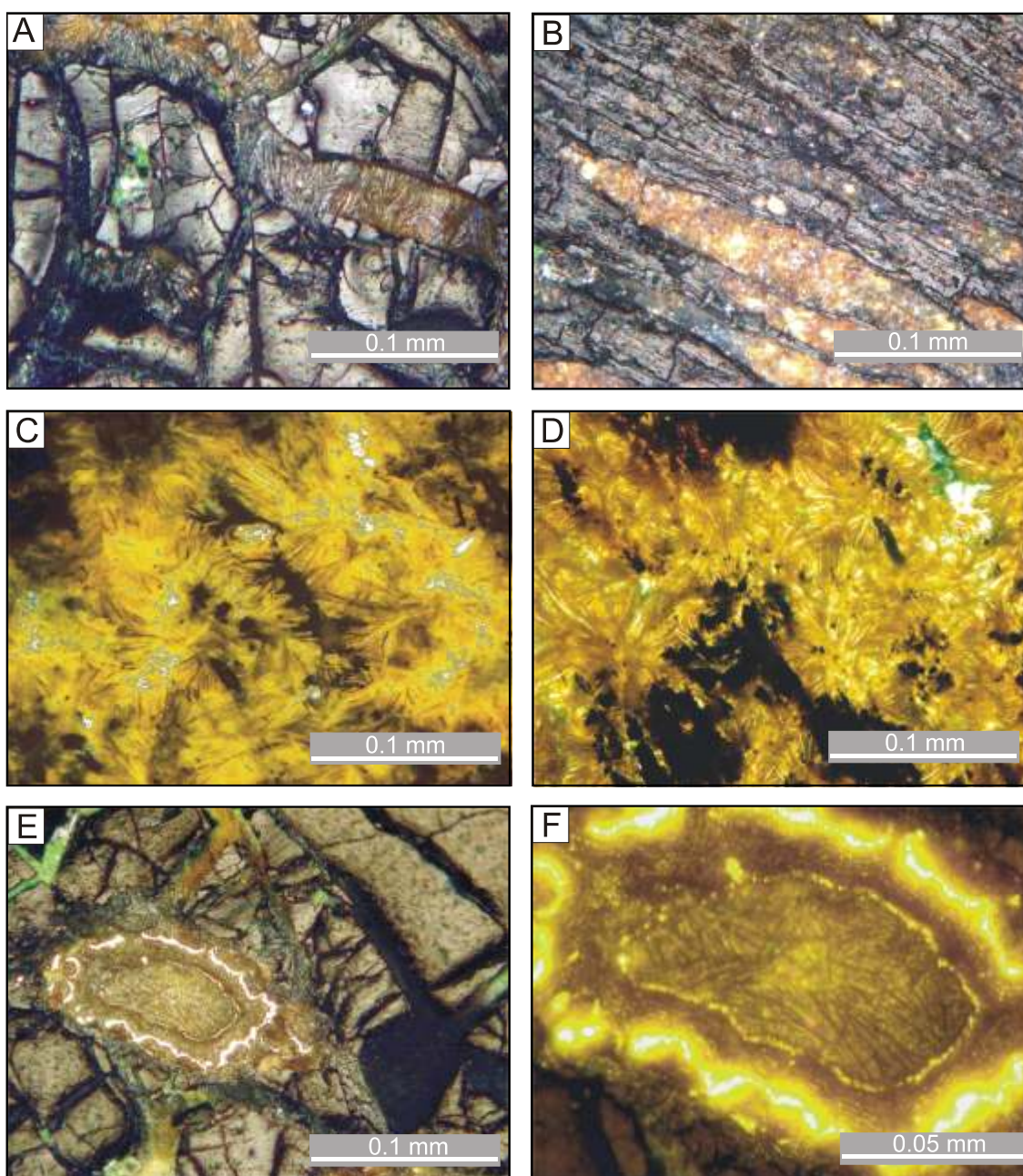
**Fig. 5. Petrographic composition of coal from the Bochnia rock salt deposit**

**A** – textouminite (sample Au-3); **B** – textouminite with corpogelinite (sample Au-3); **C** – resinite in textouminite and eulminite (sample BW-1); **D–F** – eugelinite with anhydrite inclusions (sample K-2); reflected light

Larger xylites have diverse petrographic compositions. They show a zonal structure: their internal parts are made of highly cracked textouminite (Fig. 5A), which is most often filled with corpogelinite (Fig. 5B). The latter comprises wood components, that include, among other things, deciduous tree tannins which, in the course of diagenesis, become hydrolyzed and transformed into phlobaphinite. Another form of textinite is distinguished by its oval, slightly oblate cellules, partially filled with weathered resinite, which comprises forms of fossil resins and waxes (Fig. 5C). Both forms of textinite comprise botanically varied wood remains, originating both from conif-

erous trees (those with resinite), and from deciduous trees (those with phlobaphinite). The coaly material of the internal zone in the xylites is weakly carbonized. This is shown by the remains of cellulose in textinite, taking the form of anisotropic inclusions in gelified wood fibres.

The external part of the xylites is built of ulminite, i.e. a maceral, which developed as a result of strong gelification of plant tissue (Fig. 5C). This is mainly a variety of ulminite, distinguished as eulminite, which in turn is a product of complete gelification of wood tissues. The contact zone of both macerals is clear, which indicates rapid gelification as a result of the pen-



**Fig. 6. Minerals that occur jointly with coal in the Bochnia salt deposits**

**A** – endogenous cracks filled with anhydrite and metasideronatriite (reflected light, immersion technique, sample K-2); **B** – anhydrite lenticles in xylites (reflected light, immersion technique, sample Au-3); **C, D** – metasideronatriite in gelitic coal (reflected light, dry objective, sample K-2); **E, F** – mineral concretions in gelitic coal, composed of metasideronatriite and pyrite (reflected light, immersion technique, sample K-2)

etration of brine to the inside of the wood fragments during their sedimentation and diagenesis.

Both textinite and ulminite contain, in their contraction cracks, halite and anhydrite inclusions, and rarely in few places also those of a rare mineral, namely metasideronatriite, and pyrite. Those minerals also develop lenticular forms within the xylites (Fig. 6B). Xylites smaller than 1 cm are made exclusively of euulminite.

The gelitic coal was found in the form of a single lenticle up to 10 cm-thick in the northern salts of the August drift close to St. Kinga's Chapel (Fig. 4D).

That coal is black, with a dull lustre, and shows a marked tendency to break into isometric fragments of 2–3 mm diameter as a result of intensive cracking. The cracks are endogenous, and the nature of the cracks is shown by the development of three systems of crevices, which are perpendicular to

each other, and seldom in a spherical pattern. Those cracks are easily visible, being filled up with a mineral mixture that is brown-yellow in colour (Fig. 6A). Their main mineral components include metasideronatrite ( $\text{Na}_2\text{Fe}[\text{OH}][\text{SO}_4]_2 \cdot \text{H}_2\text{O}$ ) and anhydrite ( $\text{CaSO}_4$ ), while their subsidiary components are gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), pyrite ( $\text{FeS}_2$ ) and halite ( $\text{NaCl}$ ). The cracks are often secondarily enlarged as a result of recrystallization of these minerals – the gelitic coal in those places is subjected to a stronger fragmentation to chips of 0.05 to 0.1 mm diameter.

The gelitic coal is formed exclusively of euulminite. It is variably gelified through the coagulation of the organic colloid. That gelification took place during the sedimentation of the evaporites in concentrated brine is shown by numerous, microscopic inclusions of anhydrite and pyrite in the gelinite (Fig. 6D–F).

The gelitic coal is quite a rare variety of ortholignite that takes the form of an allochthonous component, and which can be found in deposits that are genetically unrelated to typical coal deposits (Wagner, 2009).

#### MINERALS THAT OCCUR JOINTLY WITH COAL

Among minerals that fill cavities and cracks in the xylites and the gelitic coal, mainly anhydrite ( $\text{CaSO}_4$ ) and metasideronatrite were recognized. Subsidiary minerals include pyrite, halite and gypsum.

**Anhydrite** is a common component of the rocks examined. In rock salt that contains xylites it occurs in the form of oval, semi-convex concentrations of up to 1 cm in diameter, whereas in xylites and gelitic coal it is present in cracks that locally have been enlarged into lenticular forms (Fig. 6A). Anhydrite is developed in the form of bar-like and fibrous aggregates, while rhombic crystals can be seen less often. Many cracks are filled with anhydrite in the form of secretions.

On the X-ray diffraction image anhydrite is documented by strong lines of the values of 3.50, 2.32, and 2.19 Å, as well as by other lines that are common for the associated minerals (Fig. 7).

**Metasideronatrite** ( $\text{Na}_2\text{Fe}[\text{OH}][\text{SO}_4]_2 \cdot \text{H}_2\text{O}$ ) is the main component that fills cracks in the gelitic coal. It is also present in the xylites, yet in amounts that cannot be identified by means of visual examination, and which can only be detected by means of SEM/EDS probe analysis (Fig. 8B).

Metasideronatrite occurs in the form of orthorhombic crystals, 5–10 µm long, which mainly form larger, compact aggregates that completely fill many cracks in the gelitic coal. These are pseudomorphs after anhydrite, rosette aggregates (Fig. 6C, D) or oval concretions with 2–3 generations of minerals, expressed by means of an alternating arrangement of metasideronatrite and pyrite (Fig. 6E, F). When viewed under macroscopic examination, the mineral is yellow to light brown, with a dull lustre. It is soft (1.5 on the Mohs scale). In a microscopic image, both under transmitted light and under reflected light it is orange-yellow, and birefringent (0.0910 – Garvie, 1999). When subjected to X-ray diffraction it reveals a number of diagnostic lines, such as 8.05, 6.68, 3.99, 3.13, 2.75 Å, that are common for other minerals (Fig. 7). The occurrence of metasideronatrite has also been confirmed by SEM/EDS analysis (Fig. 8B, D). Its joint occurrence with pyrite relates to the genesis of that mineral, from weathering of pyrite in the presence of saline water, as described by Garve (1999; from pyrite shales on the present-day coasts of the North Sea), by van Breemen (1976; from saline soils of Thailand), and by Zodrow *et al.* (1979; from coastal strata in coal mines in Nova Scotia, Canada), respectively.

**Halite** ( $\text{NaCl}$ ) impregnates the xylites, and which is also present in cracks in the gelitic coal. Together with that mineral, there were isotropic crystals of slightly positive relief identified, which were weakly fluorescent under blue light. On an SEM image, halite is seen as a light bloom on the xylites and as an impregnation (Fig. 8A, C). That bloom is a reason for a high reduction of random reflectivity rate of ulminite. The occur-

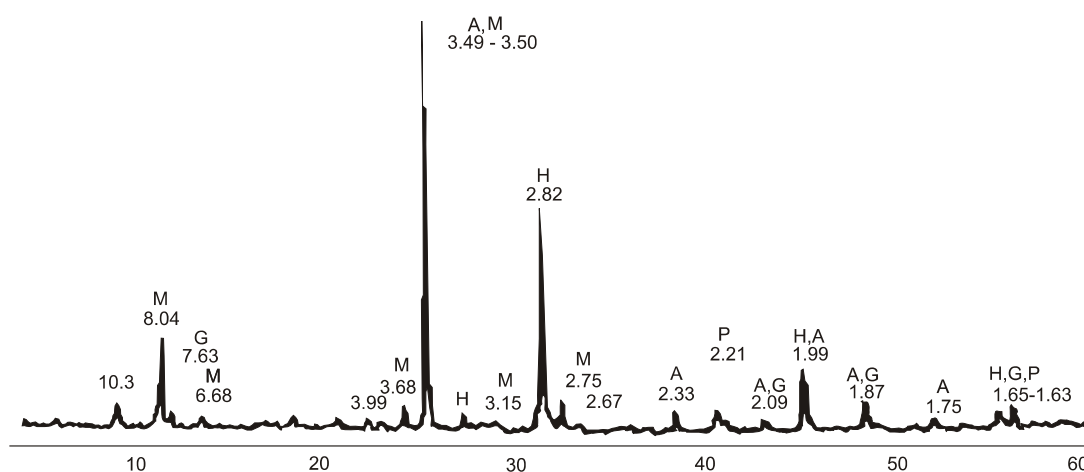


Fig. 7. X-ray diffraction pattern showing mineral filling of gelitic coal

M – metasideronatrite, H – halite, A – anhydrite, P – pyrite, G – gypsum

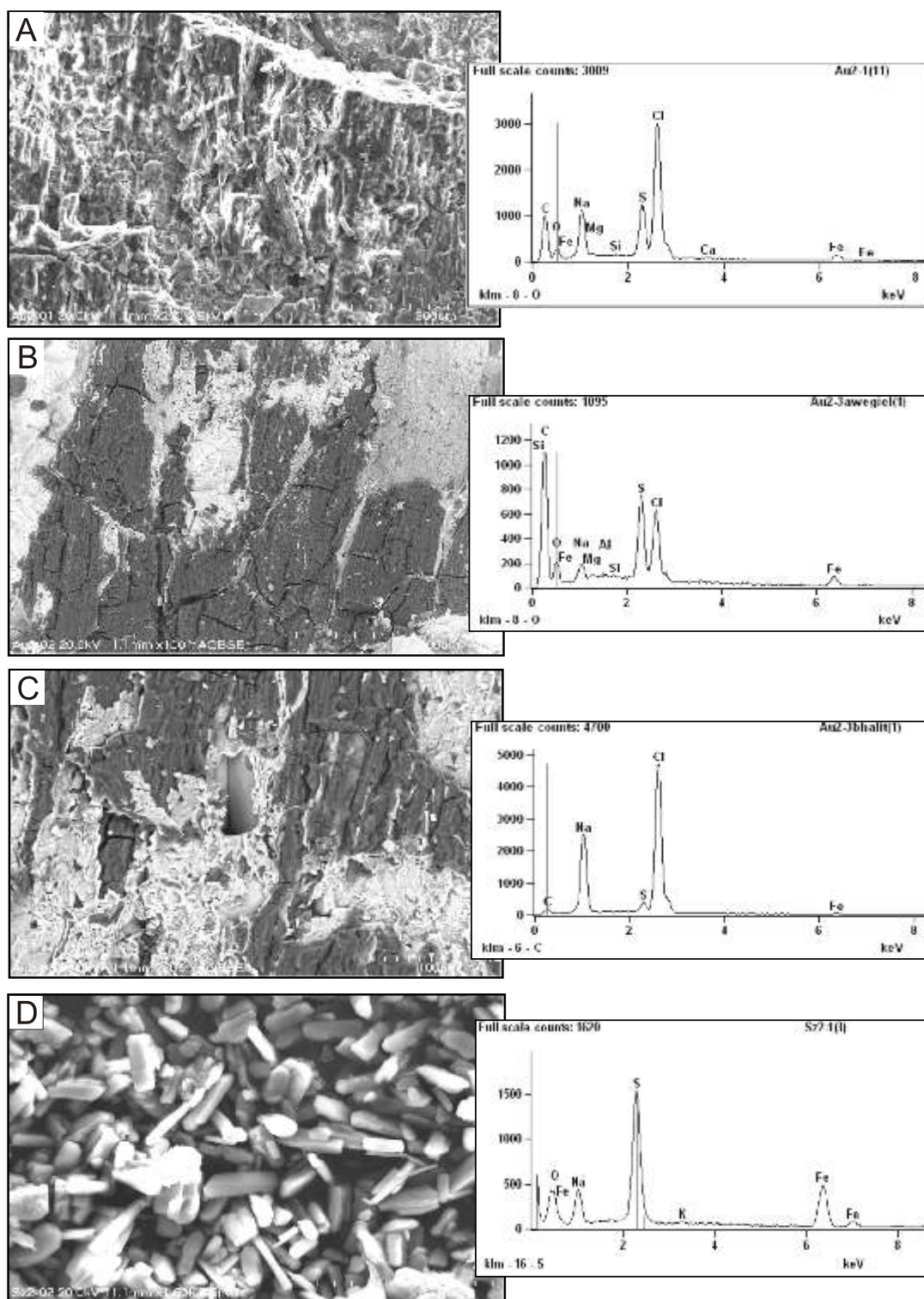


Fig. 8. SEM images and spectral analysis charts of coal and jointly-occurring minerals

A – xylite impregnated with mineral contents; B – micro-impregnation of xylite (dark areas, sample Au-2); C – halite bloom and impregnation (light areas, sample Au-2); D – metasideronatrie in gelitic coal (sample K-2)

rence of that mineral is documented by the presence of lines at 2.82, 3.26 in the diffraction spectrum, as well as by other lines also common to other minerals (Table 1).

In the gelitic coal, small amounts of gypsum ( $\text{CaSO}_4 \times 2\text{H}_2\text{O}$ ) were also identified. Gypsum was detected based only

on X-ray diffraction examination, since the mineral is difficult to recognize optically in mineral mixtures. The presence of gypsum was indicated by moderately intense diffraction lines with values of 7.64, 4.29, 1.87, as well as by other lines (Fig. 7).



Table 1

**Technological, chemical analyses and huminite reflectance data of coal ulminite from the Bochnia salt deposits**

Sample	$W^a$ [wt.%]	$A^d$ [wt.%]	$C^{daf}$ [wt.%]	$S_t^d$ [wt.%]	$R_r^o$ [%]
K-2 sur	8.1	18.0	66.8	7.76	0.28
K-2/1 wzb	9.8	7.8	66.5	2.17	0.28
Au-2/1 sur	9.8	27.6	65.1	11.10	0.15
Au-2/1 wzb	6.3	5.2	65.7	6.21	0.16
BW1	8.2	25.7	63.5	2.70	0.26

$W^a$  – analytical moisture,  $A^d$  – ash content recalculated to dry basis,  $C^{daf}$  – carbon content recalculated to dry and ash-free basis,  $S_t^d$  – total sulphur content recalculated to dry basis,  $R_r^o$  – random reflectivity rate of euulminite B, sur – run-of-mine sample, wzb – washed sample

### THE RATE OF ORGANIC MATTER CARBONIZATION

The carbonization of the plant material, which is represented in the Bochnia deposit profile by xylites and small concentrations of gelitic coal is low, specific to ortholignite.

The carbon content of that material ranges from 63.5 to 66.8% by weight, with the gelitic coal showing a slightly higher content (Table 1, sample K-2). This translates also to a value of the B mean random reflectivity of euulminite, of ca. 0.28%, as opposed to 0.26% in xylites. Under natural conditions, coal aggregates contain medium-ash coal (18.0 to 27.6% by weight) and a high, though variable total sulphur content (2.17–11.10% by weight). Manual, mechanical washing demonstrates that the ash content of that material and its total sulphur content are much lower once mineral contents in cracks have been reduced. This shows that the sulphur is mainly related to sulphate minerals (metasideronatriite, anhydrite and gypsum).

Those xylites which are strongly impregnated with halite, and which are megascopically distinguished by a higher hardness rate, demonstrate a very low average reflectivance (0.15–0.16%), that is almost 50% lower than that of other xylites and of the gelitic coal (cf. Table 1). This is related to their impregnation with that weakly reflective material (the  $R_r^o$  of halite is about 0.05%) in areas of diameter of a few to ca. 300  $\mu\text{m}$ .

Using standard means of determining the rate of carbonization (ISO 11760:2004, PN-ISO 11760:2007), the plant material from the Bochnia rock salt deposit is a soft brown coal (C ortholignite) of xylite and gelitic varieties. The same results were obtained for carbonized plant material from the Wieliczka salt deposit (Wagner *et al.*, 2008).

The rate of carbonization of the xylites and of the gelitic coal found in the rock salt deposits of Bochnia and of Wieliczka is identical to that of presently mined Lower Miocene deposits of the brown coal at Bełchatów, Szczerców and Turów (Poland).

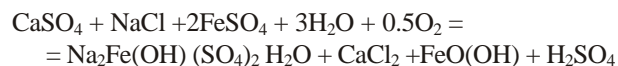
### COMMENTS ON THE SEDIMENTATION OF THE COALY MATERIAL

The coaly material, represented in the Bochnia salt deposits by xylites and by gelitic coal, is allochthonous in origin. The sources of that material were forests and peat bogs which surrounded the dessicating marine embayment with the resultant rock salt precipitation. The forests were mesophytic, presumably subtropical. They provided the marine basin with fragments of wood of various sizes, but mainly with small fragments of branches, roots, and perhaps stumps. The petrified structure of the wood suggests that it did not suffer from putridity. One can therefore suppose that periodically swollen rivers transported the wood. The xylites might have come from washed out riverside salt water marshes, which in their distal parts maybe developed as raised bogs. This is shown by the presence of gelitic coal in the salt deposits, since gelitic coal is mainly sedimented from gravitational flows of humic acid solutions that have been washed out from raised bogs of low pH (Wagner, 2009). Strong humidification of lignin and cellulose materials takes place under warm (subtropical) climate conditions, in distal areas of mangrove coasts, intensified by saline water and alkaline reactions in frequent backwaters (tides). Humic acids are washed out and deposited in depressions in shallow salt bays in the form of humus gel. That gel, transformed during diagenesis into gelitic brown coal, appears in the salt deposits usually in the form of lenticular concentrations. The organic deposit must have been periodically emergent, which resulted in its drying and in contraction cracks of half-solidified gel and crystallization of metasideronatriite in contraction cracks of the accumulating coal. According to Garvie (1999), the source of that mineral was pyrite weathering under moderately dry and warm climate conditions from rocks washed with saline water, as seen in pyrite-bearing Eocene mudstones on sea shores near Hampshire, England. This has been also reported from seaside caves at Rising Sun near Backworth in Northumberland (Randall and Jones, 1966) and from coastal coal-bearing rocks of the Sydney Coal Basin in Australia (Zodrov *et al.*, 1979). Metasideronatriite ( $\text{Na}_2\text{Fe}[\text{OH}][\text{SO}_4]_2 \cdot \text{H}_2\text{O}$ ) is a mineral that can be derived from anhydrite ( $\text{CaSO}_4$ ), pyrite ( $\text{FeS}_2$ ) and halite ( $\text{NaCl}$ ), under oxidizing conditions in an aqueous environment.

Under such conditions, pyrite is transformed, as follows:



and, further:



The calcium chloride ( $\text{CaCl}_2$ ), as a highly hygroscopic and soluble material (the hydrophylic mineral), is washed out from the sediment, which is why it is missing from the gelitic coal. The solid by-product of those reactions is goethite, which becomes solidified adjacent to the gelitic coal, i.e. within rock salt by alkaline reaction (brown rims, Fig. 3C). The transport of or-

ganic gel from peat bogs, considered to be gel flows, was described by Wagner (2009).

During burial diagenesis the organic material became carbonized. The carbonization is now at the stage of an orthophase, or the ortholignite (soft brown coal) stage. The level of  $R^o$  random reflectivity coefficient, ranging from 0.26 to 0.28%, suggests that the over burden thickness might have reached a minimum of same 500 metres, enabling the organic

sediment to reach a palaeotemperature of *ca.* 50–60°C (average geothermal gradient about 5°C/100 metres, Stach *et al.*, 1975, wierczewska *et al.*, 2007) during a period of about 10–20 million years (Burnham and Sweeney, 1989).

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