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## Late Proterozoic anthracite coals from the Hornsund area, south Spitsbergen

**ABSTRACT:** Anthracite coal matter fills irregular voids in dolostones of the Upper Proterozoic Höferpynten Formation in the Hornsund area, south Spitsbergen. The coals are of organic origin, as indicated by a variety of coal-petrographic studies, and by association with algal structures. They probably derived from bitumina accumulated in voids of dolostone at an early diagenetic stage. The degree of coalification (graphitization) is high but diversified, suggesting several coalification stages, probably related to successive metamorphic events. The oldest changes may correspond to initial stage of the greenschist-amphibolite phase of regional metamorphism, with temperatures of over 500°C and pressure of over 20, 000 MPa. Multiphase graphite crystallites which occur in the coal are mainly fibrous. There are also crystallites which precipitated from gaseous phase, and pyrolitic graphite; they may have originated due to action of mesothermal solutions which had produced ore-bearing veins.

**K e y w o r d s:** Arctic, Spitsbergen, Late Proterozoic, anthracite coal.

## Introduction

Anthracite-grade coal matter filling small irregular voids in Upper Proterozoic dolostones of the Höferpynten Formation (Sofiebogen Group, Hecla Hoek Succession) has been collected in 1990 in the Hornsund area, south Spitsbergen, by K. Birkenmajer during field work sponsored by the Norwegian Polar Research Institute (Oslo). Dr Y. Ohta and his field-assistants, J. Czerny and M. Manecki, completed the geological party whose aim was to correlate different sections of the Hecla Hoek Succession in south Spitsbergen. Their assistance in here acknowledged with pleasure.

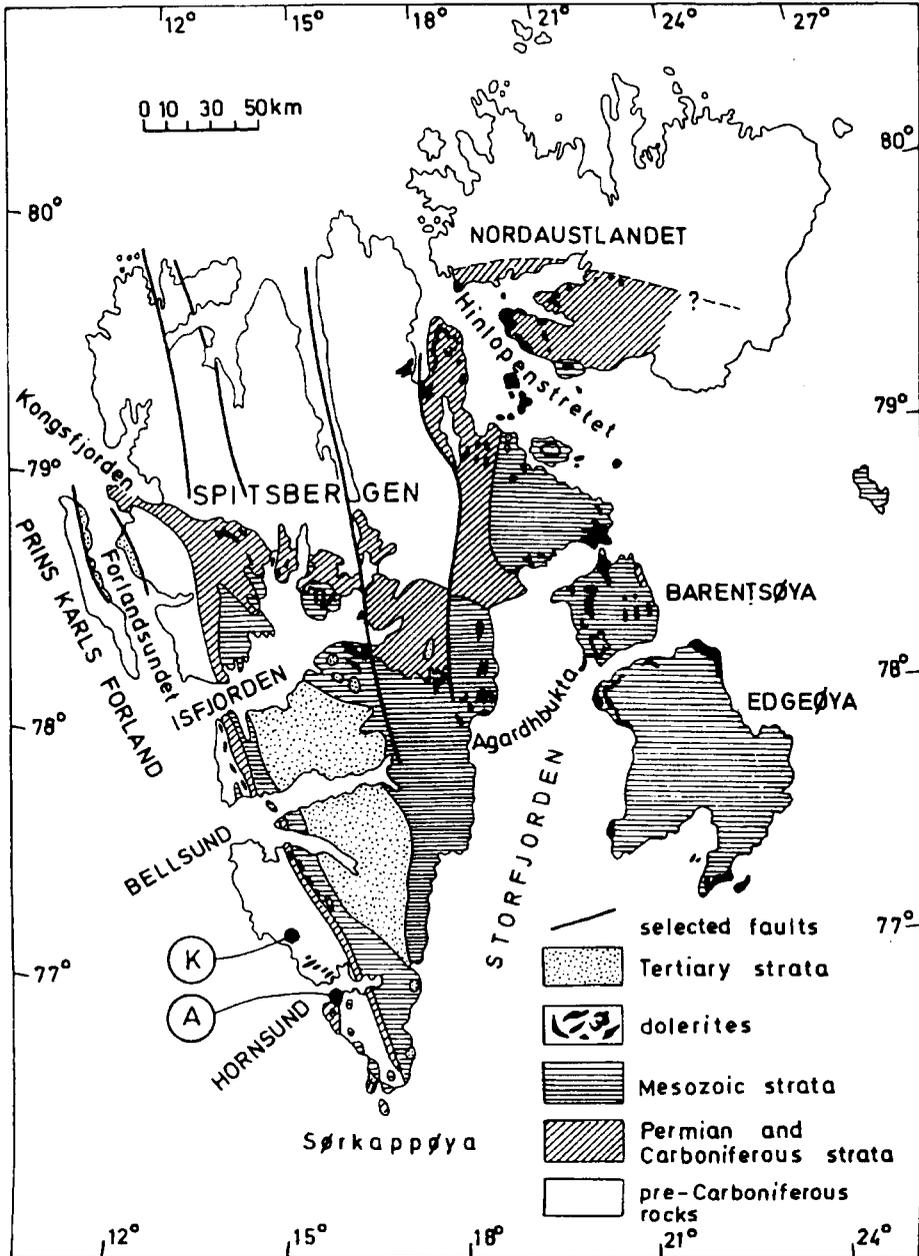


Fig. 1. Location of sites with anthracite coal from Upper Proterozoic strata (Höferpynten Formation), against simplified geological structure of Svalbard: A — Höferpynten-Andvika; K — Krakken

Coal—petrographic and other laboratory studies were performed by J. K. Frankiewicz and M. Wagner at the S. Staszic Technical University of Mining and Metallurgy in Cracow. Our gratitude is expressed to the Institute of Fossil Fuels of this University for covering laboratory expenses of our work.

## Geological setting

The anthracite-grade coal described here was collected at two localities in the Horsund area, south Spitsbegen (Fig. 1): (1) at Krakken, to the north-west of the Raudfjellet massif, north of Horsund; and (2) at Höferpynten-Andvika, southern coast of Horsund. Thick carbonate sequences of the Höferpynten Formation, the middle unit of the Sofiebogen Group, Hecla Hoek Succession, are exposed there. The formal lithostratigraphic standard used is that introduced by Birkenmajer (1972, 1975, 1981, 1992).

(1) **Krakken.** The section investigated in the company of Y. Ohta, J. Czerny and M. Manecki in 1990 in the westernmost part of the Raudfjellet massif, exposes several formations of the Upper Proterozoic succession. The sequence is tectonically reversed, with the oldest units at the south-western end of the mountain (Fig. 2). The oldest is the *Bergskardet Formation* (uppermost unit of the Deilegga Group) developed as greenish-grey to yellowish phyllites with medium-grained, laminated quartzitic sandstone intercalations usually 10-50 cm thick. The sandstones are graded, fining-up in the direction to the contact with the Slyngfjellet Formation.

There follows, with sharp but parallel contact, the *Slyngfjellet Formation* (some 10-15 m thick), consisting of green schistose metaconglomerate with strongly tectonically deformed (lenticular) quartzite- and, less commonly,

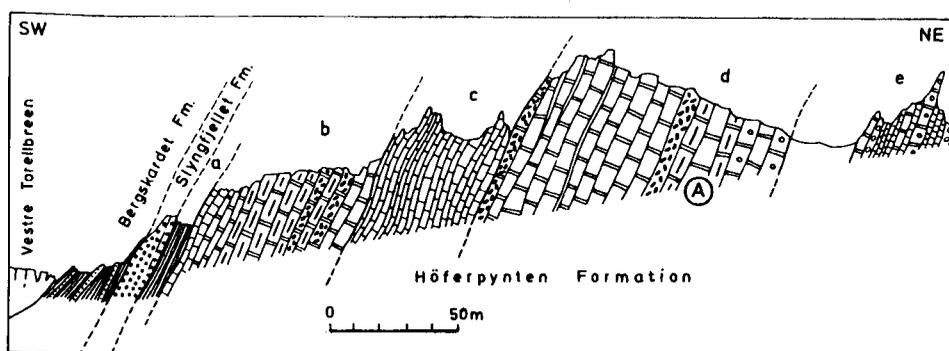


Fig. 2. Position of anthracite coal (A) sampled from the Höferpynten Formation at Krakken (schematic geological cross-section surveyed in 1990 by K. Birkenmajer). For explanations of lithological symbols — see Figs 3, 4. Scale approximate

marble clasts. The quartzite clasts are 2-10 cm in diameter at the stratigraphic base of the unit, but may increase in size to slabs 50 cm long and 10-15 cm thick in stratigraphically higher part. At the contact with the next unit, the quartzite clasts are up to 30-50 cm in diameter.

**Höferpynten Formation.** This formation consists of several lithostratigraphic units of member rank, correlatable to some extent with formal members of the formation as established earlier (Birkenmajer, 1972). Due to preliminary state of investigations at Krakken, we will use informal lithostratigraphic units (*a-e*) instead.

(a) At the base of the Höferpynten Formation there appear black to blue-grey shales and phyllites with pyrite, some 10 m thick. They lie conformably upon the Slyngfjellet conglomerate.

(b) The shale-phyllite unit (*a*) passes to black platy limestone (some 5 m thick), followed by black, often arenaceous limestone and dolostone (about 60 m thick). The rocks show the presence

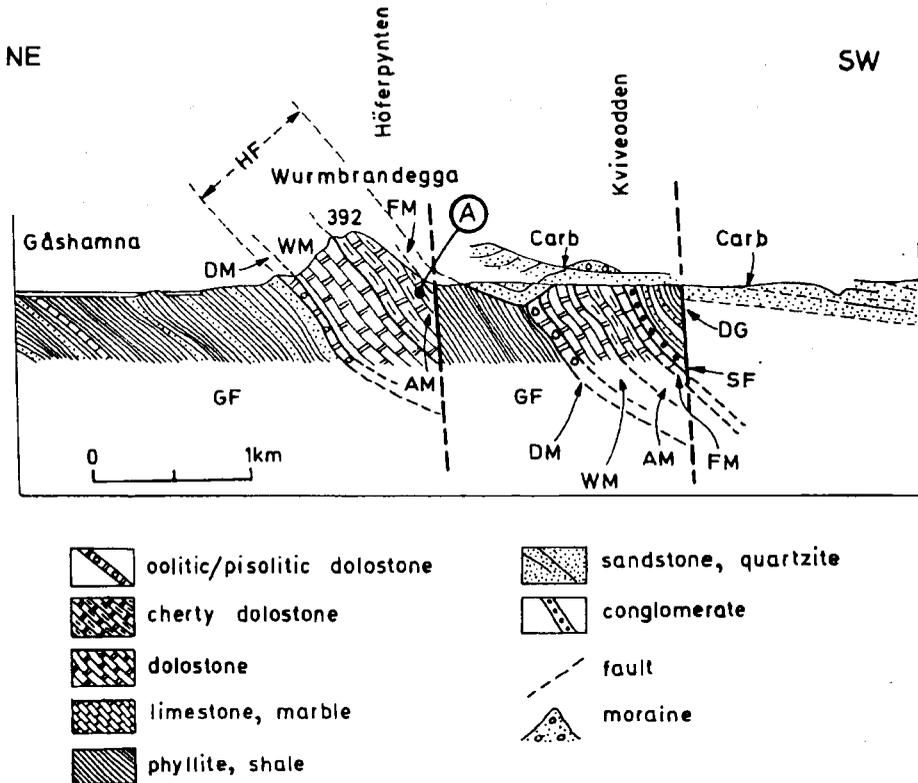


Fig. 3. Position of anthracite coal (A) sampled from the Höferpynten Formation at Höferpynten-Andvika (geology from Radwański and Birkenmajer 1977). Proterozoic: DG — Deilegga Group. Sofiebogen Group: SF — Slyngfjellet Formation; HF — Höferpynten Formation (FM — Fannytoppen Mbr; AM — Andvika Mbr; WM — Wurmbrandegga Mbr; DM — Dunøyane Mbr.); GF — Gåshamna Formation. Post-Caledonian cover: Carb — Carboniferous

of lamination, and contain dolostone microbreccias and pseudo-cherts (probably recrystallized quartz-sand lenses — compare Birkenmajer, 1972).

(c) Concordantly, come grey to whitish (yellow-weathered) phyllitic limestones (about 40 m thick), in plates 1-10 cm thick. They resemble lithotype of the Fannytoppen Member at Fannytoppen and Höferpynten (Birkenmajer, 1972).

(d) At the base of this unit, appears a massive carbonate pellet-breccia 2-4 m thick. It consists of flat fragments 0.5-5 cm long and 0.2-0.5 cm thick of grey limestone and dolomitic limestone. There follow massive bands of grey, yellow-weathered dolostones which, in the upper part, contain intercalations of pseudo-cherts, dolostone pellet-breccias, and oolitic rocks. The unit is some 80-100 m thick. In its lower part there occur also clastic dykes (up to 50 cm thick) filled with dolostone detritus, and black shale intercalations. Small irregular nests (2-5 cm in diameter) filled with black coalshale or hard anthracite-grade coal occur in the upper part of the unit (Fig. 2: A): sample S-1.

(e) The highest unit shown in Figure 2 consists of yellow and orange-weathered dolostones and grey oolitic dolostones, alternating with shaly limestones.

It seems probable that the units *a-c* of the discussed section correspond to the Fannytoppen Member, the *d*-unit to the Andvika Member, and the *e*-unit to the Dunøyane Member. There seems to be an intraformational disconformity between the *c/d* units, marked at the base of the sedimentary breccia (*d*) which contains limestone fragments reworked from the lower unit (*c*). Appearance of clastic dykes in the *d*-unit points to tectonic instability which affected sedimentary basin of the Höferpynten Formation.

(2) **Höferpynten-Andvika.** The section at Höferpynten, southern coast of Hornsund, has been described in papers by Birkenmajer (1972) and Radwański and Birkenmajer (1977). The Höferpynten Formation is there subdivided into four members (Figs 3, 4): the Fannytoppen, the Andvika, the Wurmbrandegga, and the Dunøyane members. Streaks and nests 1-5 cm thick and up to 20 cm long of black anthracite coal (samples S-2 to 6) occur there in massive dolostones with pseudo-cherts (recrystallized quartz-sand lenses) which belong to the Andvika Member (Birkenmajer 1972). The dolostones are crossed with quartz-and quartz-ore veins.

## Sedimentary environment

Carbonate deposits of the Höferpynten Formation were laid down in a shallow-marine, tidal to subtidal and supratidal (lagoonal) environment under warm climatic conditions. This is well evidenced by algal stromatolitic, oolitic-pisolitic, and other biogenic and abiogenic sedimentary structures described in particular from the Dunøyane and Wurmbrandegga members. The Fannytoppen Member might have formed in lagoonal conditions, the Andvika Member represents a transition from lagoonal to shallow-marine (tidal) environment (Birkenmajer 1972; Radwański and Birkenmajer 1977).

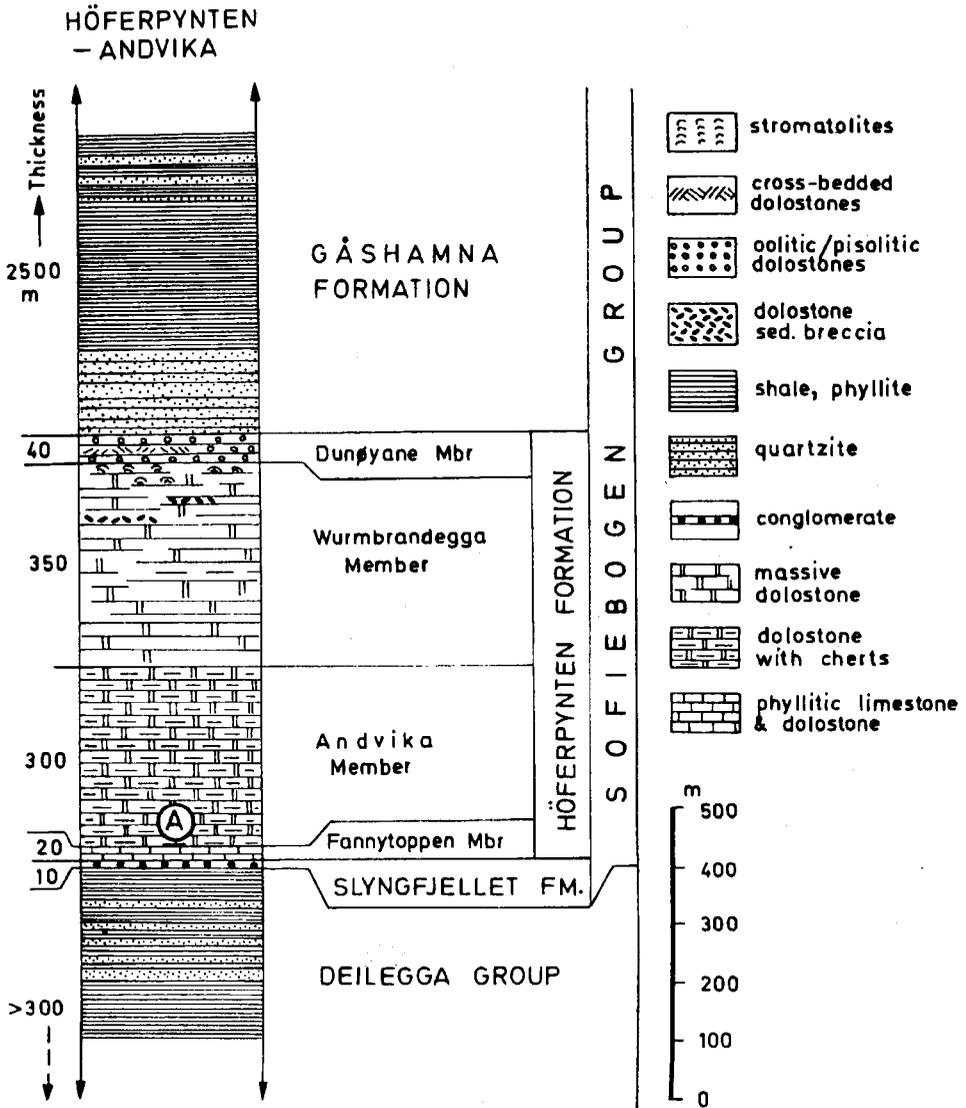


Fig. 4. Lithostratigraphic column to show position of the anthracite coal in the Höferpynten Formation at Höferpynten-Andvika (modified from Radwański and Birkenmajer 1977)

Occurrence of anthracite-grade coal matter which fills small irregular voids in the dolostones of the Höferpynten Formation, here described for the first time, is compatible with the above evidences of rich marine algal life at the time of its deposition. Coal-petrographic and other laboratory studies performed on our samples (see below) confirm organic origin of the coal matter, and suggest algae as its primary source.

## Age of anthracite-bearing strata

The age of the Höferpynten Formation, the middle unit of the Sofiebogen Group, corresponds to Upper Proterozoic. The formation post-dates conglomerates of the Slyngefjellet Formation, and pre-dates the Gåshamna Formation phyllites, the latter correlatable with tillite-bearing strata of Varangian age elsewhere in Svalbard (Birkenmajer 1972, 1975, 1981, 1990). Orogenic angular unconformity exists between the Gåshamna Formation and the Cambrian strata. The sedimentary hiatus covers the highest part of the Proterozoic and the lowermost part of the Cambrian (Birkenmajer and Orłowski 1977; Birkenmajer 1978; 1992).

## Coal petrography

**Methods.** Six samples numbered S-1 (Krakken), and S-2 to S-6 (Höferpynten-Andvika) were investigated, using the following techniques:

- petrographic study in polarized reflected light, with the use of Axioplan Opton and Jena Pol U (C. Zeiss, Germany) microscopes; qualitative and quantitative characteristics of coal; observations in blue fluorescent light; measurements of reflectance coefficient, mean ( $R^0_e$  – random reflectance), maximum ( $R^0_{max}$ ) and minimum ( $R^0_{min}$ ), according to the standards of the International Commission on Coal Petrology (ICCP).

- chemical and technological analysis, based on Polish Normatives: moisture, ash content, volatiles, burning energy, density; content of C, S (after LECO method), H and N; O was calculated from differences;

- roentgenographic analysis using diffractometer HZG/4, stepwise method ( $0.1^\circ$  ( $2\theta$ )/min), with  $CuK\alpha$  radiation; phase identification was performed with the use of IBM X-rayan programme;

- roentgenographic RDF (radial density distribution function) analysis with the use of Siemens diffractometer (Germany),  $MoK\alpha$  and Si[Li] counter; stepwise method  $0.1^\circ$ /min was applied.

- isotopic analysis of coal ( $\delta^{13}C\%$  (PDB)), with the use of mass-spectrometer (USSR).

**Lithology.** Two groups of samples are lithologically distinguishable: S-1 sample (Krakken) represents anthracite coal; S-2 to S-6 samples (Höferpynten-Andvika) represent anthracite coal-quartz breccias or anthracite coal-quartz-dolomite breccias.

The anthracite coal sample (S-1) is homogenous, steel-black in hue, with dull to slightly silky lustre. Its powder colour is black. The coal is massive, compact and hard, uneven to rather smooth at broken surface.

The coal-breccia samples (S-2 to S-6) consist of 2-3 constituents: coal fragments are dispersed in quartz- or quartz-dolomite basal matrix. Isometric

or elongated coal grains are from a fraction to 1.2 mm in diameter. Generally, they display metallic lustre and black hue, however there are numerous grains with silky lustre indicating the presence of crystallites. Quartz and dolomite are milky-white to yellowish in larger aggregates. Thin quartz veinlets and strongly cataclastic coal grains are visible on polished surfaces. Dolomite is the main mineral element in sample S-5, but represents a subordinate element in sample S-4.

**Coal minerals.** The mineralogical character of coal is similar in all samples; the coal phases differ only with respect to the degree of graphitization. Coal phases are the main element of sample S-1, some 3 cm in size, while in the remaining samples they occur as much smaller coal fragments dispersed in quartz (S-2, 3, 4, 6) or dolomite (S-5). Three coal phases have been distinguished:

- well defined graphite-like crystallites (phase 1);
- microgranular matrix of crystallites (phase 2); both phases, together with a small admixture of quartz, occur as structural elements of the majority of coal grains;
- anthracite fragments in breccias, differing from the above phases in low porosity and distinct microcrystalline structure (phase 3).

The graphite-like crystallites are a characteristic element of the samples investigated. They display high reflectance, optic anisotropy ( $AR^0$ ), and occur either as single fibres and globules or, more frequently, as aggregates. The latter may be either massive and irregular, or spherulitic with concentric structure, or band-like. The crystallites are the main element of strongly porous fragments (samples S-2 to 6) and of coal sample (S-1). They occur both at surfaces of empty micropores and between them, and tend to concentrate at margins of anthracite fragments in form of ribbon-like aggregates.

Irregular, massive aggregates with mosaic texture are the most frequent type of occurrence of the crystallites. The latter form fibres, globules, or are irregular in shape, being separated from one another by darker bands. The mosaic texture becomes more regular, concentric-radial close to pores which are up to 30  $\mu\text{m}$  across. There, globular crystallites become more frequent and display wavy light extinction or interference cross. Such crystallites are considered to represent graphite of pyrolitic origin or that precipitated from gaseous phase (Stach 1952; Kwiecińska 1967; Gabzdyl 1978; Probiez 1989).

The diametres of particular graphite crystallites are from 1 to 6  $\mu\text{m}$ , usually 3-4  $\mu\text{m}$ . Their mutual arrangement, together with micropores, often resembles a phytogenic texture related to algal colonies (*cf.* Kwiecińska 1980).

The matrix of crystallites is anisotropic, submicrogranular, consisting of still smaller crystallites, a fraction of  $\mu\text{m}$  in diameter; granular or banded type of optic anisotropy reflects their shapes, undistinguishable under microscope due to small sizes (*cf.* Abramsky and Mackowsky 1952). Usually, both phases (graphite crystallites and their matrix) distinctly differ in crystallite sizes. An

exemption to this rule is represented by sample S-4, in which crystallites of granular matrix are much larger than in the remaining samples, being however smaller than the graphite crystallites of phase 1; this sample may represent a transition stage to full graphitization of coal.

Analogous agglomerations of anisotropic crystallites are known from natural and industrial coke, the latter obtained from low-C stone coals (Jasieńko 1965; Kwiecińska 1967; Gray and Lowenhaupt 1989).

Besides coal grains consisting of phases 1 and 2, there occur in the breccias anthracite fragments resembling coke. The fragments are angular, up to 1 cm in size, showing no sorting. They consist of submicroscopic graphite substance, identical to that of crystallite matrix of phase 1, and display granular or fibrous-granular optical anisotropy. Infrequent pores are regular in shape, spheroidal or ovoidal, filled with quartz. They are sometimes rimmed, or filled, with aggregates of fibrous graphite crystallites. The share of particular coal phases in samples S-1 to 6 is shown in Table 1.

Table 1

Approximate share of carbonaceous and mineral material (matrix) in graphitized Late Proterozoic coals from Spitsbergen (vol. %)

SAMPLE	Graphite crystallites (phase 1)	Matrix of crystallites (phase 2)	Anthracite fragments, matrix (phase 3)	Mineral material
S-1	67.1	32.5	—	0.4
S-2	16.0	4.3	11.6	68.1
S-3	16.9	11.8	20.3	51.0
S-4	26.3	2.6	2.5	68.6
S-6	18.7	—	1.5	79.8

**Variation of reflectance coefficient.** Measurements of reflectance coefficient ( $R^0$ ), performed under standard conditions (ICCP Norms), show a considerable variation within all three coal phases distinguished (Table 2). This suggests differences in the degree of coalification.

Graphite crystallites larger than 5  $\mu\text{m}$  (minimum surface needed for measurements) show maximum reflectance ( $\bar{R}_{\text{max}}^0$ ) from 6.00 to 11.52%, random reflectance ( $\bar{R}_r^0$ ) from 4.60 to 7.66%, and bireflectance over 3.5%. Based on coalification classification standard proposed by Kwiecińska (1980), the analysed samples fall into the following categories:

- Sample S-1:  $\bar{R}_{\text{max}}^0 = 6.00\%$  — metaanthracite crystallites;  
 Sample S-6:  $\bar{R}_{\text{max}}^0 = 7.60\%$  — semigraphite crystallites;

Samples S-2-5:  $\bar{R}_{\max}^0 = 10.0-11.52\%$  – graphite crystallites.

Random reflectance ( $\bar{R}_e^0$ ) of submicroscopic matrix rich in crystallites (phase 2) is similar to that poor in crystallites (phase 3): 5.13 – 5.78 (Table 2). Generally, it is lower than the reflectance of crystallites, save for sample S-1. Taking into account the great variability of such reflectance during particular measurements (6.60 – 4.43%), and the relations established by Ting (1982) indicating that theoretical mean maximum reflectance equals 6.0 – 7.5%, we may conclude that submicroscopic material of phases 2 and 3 is represented by: metaanthracite in sample S-1; semigraphite in sample S-6; and semigraphite with graphite phase in samples S-2 to 5.

Table 2

Variation of reflectance coefficient in Late Proterozoic coals from Spitsbergen. Measurements performed in oil immersion ( $n = 1.54$ ) in green polarized light ( $\lambda = 546$  nm).  $\bar{R}_{\max}^0$  – maximum mean reflectance (%);  $\bar{R}_e^0$  – random reflectance (%); MA – metaanthracite; SG – semigraphite; G – graphite

SAMPLE	Crystallites (1)			Submicrogranular matrix (2)		Fragments (3)	
	$\bar{R}_{\max}^0$	$\bar{R}_e^0$	phase	$\bar{R}_e^0$	phase	$\bar{R}_e^0$	phase
S-1	6.00	4.60	MA	4.30	MA	— lack	—
S-2	10.00	6.88	G	— indistinct	—	5.59	SG
S-3	10.80	7.31	G	— indistinct	—	5.78	SG
S-4	11.52	7.66	G	5.43	SG	5.13	MA SG?
S-5	11.10	7.46	G	5.30	SG	5.32	SG
S-6	7.60	5.70	SG	— lack	—	— lack	—

## Coal roentgenography

**Standard diffractometer investigation.** The most intense diffraction band corresponds to a packet of condensed aromatic rings comparable with the 002 face of graphite crystals. Depending on the degree of graphitization, this corresponds to 3.45 – 3.35 Å (0.345 – 0.335 nm). In analysed samples, this band is intense, becoming slightly fainter at both ends, that indicates poor coordination of graphite packets.

The best result was obtained from sample S-1 which contained only a negligible amount of ash (about 1%) that did not overshadow the main coal

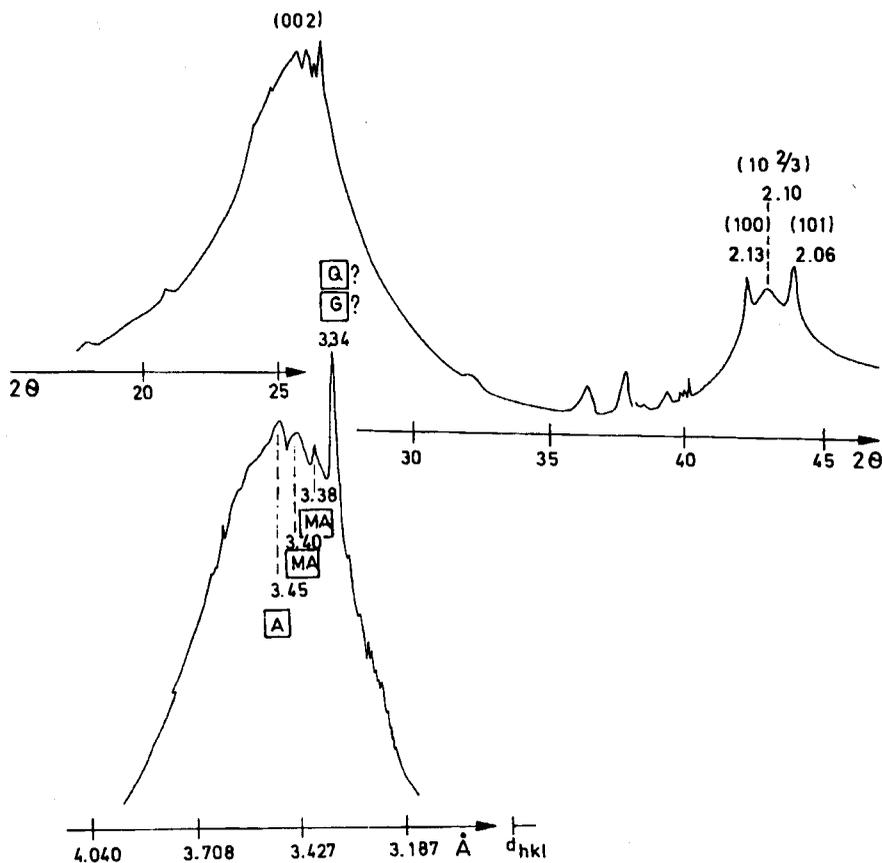


Fig. 5. Diffractogrammes of sample S-1, 20–45 ( $2\theta$ ) band, and position of the 002 band. Symbols — as in Table 2

maximum. Three maxima are visible against wide diffraction band of 002, with  $d = 3.45$ ;  $3.40$ ; and  $3.38$  Å (Fig. 5). The double intense maximum,  $3.40 - 3.38$  Å, indicates the presence of metaanthracite phase (see Kwiecińska 1980), while the fainter one, about  $3.42$  Å, of anthracite phase. These results confirm microscopic observations (based on R) that both crystallites and, to a great extent their matrix, consist of metaanthracite; small admixture of anthracite phase may occur in microgranular matrix.

In the remaining samples (S-2, 3, 5) which are rich in quartz, the 002 band is almost invisible due to overshadowing by the 001 quartz band (ca  $3.34$  Å). All three diffractogrammes show the presence of the following maxima (Fig. 6): ca  $3.45$  Å (anthracite phase);  $3.42$  Å (sample S-3: anthracite phase);  $3.40 - 3.39$  Å (metaanthracite phase);  $3.37$  Å (semigraphite phase, visible in bending of the main quartz peak — Fig. 6, as deduced from measurements of R; the graphite peak coincides here with that of quartz).

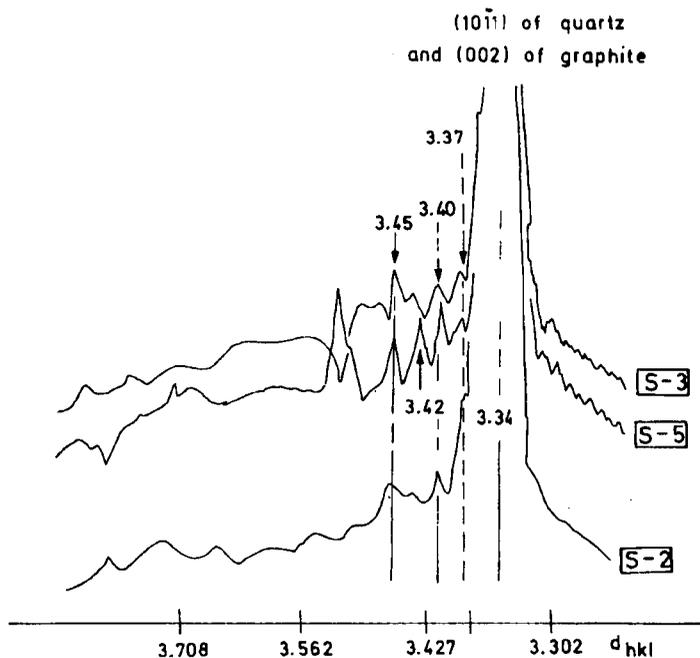


Fig. 6. Diffractogrammes of samples S-2, 3, 5

The graphitization stage, calculated after Oleś *et al.* (1975 — *vide* Kwiecińska 1980), is from 0 (anthracite) to 0.60 (semigraphite), with probability of occurrence of a „turbostatic” structure from 1 (100%) to 0.4 (40%).

Roentgenographic investigations with the use of the DSH method, indicate a complex composition of the matrix of graphite crystallites; it consists of several anthracite phases, a metaanthracite phase and, maybe, also semigraphite phase. All these phases form gradual passages from one another, as indicated by faintly marked second-order maxima at 3.44–3.37 Å.

Additional diffraction bands appear also in the samples investigated: in the 40–45° ( $2\theta$ ), there occur reflexes of graphite phase from hexagonal faces (100) and (101), and from rhombohedral (102/3) one (Fig. 6). This confirms the presence of graphite on our samples.

**RDF method.** This method was applied in order to recognize atomic structure of coal through analysis of radial distribution of atomic density coded in diffuse X-radiation. Such investigations were performed for samples S-1 and S-2.

Quartz, which occurs in sample S-2, deforms X-ray diffraction from coal. It was found that we deal here with  $\alpha$ -quartz, conformable with the JCPDS 33–1161 (150) Chart, enriched in oxygen, and with small translations of atoms inside elementary cell.

Coal material of sample S-1 indicates that interference effects of X-radiation are caused by packets of condensed aromatic rings, *i.e.* by fragments of structure relatively well ordered according to hk0 and 001. Reflexes with mixed indices (hkl) are missing. The diffraction picture thus indicates changing structural patterns in different parts of the sample, that is typical of the anthracite-semigraphite chain. In spite of the fact that the positions of peaks of the RDF curves correspond to interatomic distances of graphite, no order was observed between particular packets (irregular distances between atoms of neighbouring aromatic packets). It was calculated that the mean diameter of aromatic packets was larger than 12 Å (1.2 nm), that corresponds to peri-condensed aromatic ring system with no less than 20 elements (rings). Such structure is typical of the graphite group in the coalification chain.

## Coal chemistry

The results of chemical and physico-chemical investigations of the coals indicate a high degree of coalification (Table 3). The water content, expressed as stable moisture, varies from 0.10 to 0.36 wt %. The ash content varies considerably: sample S-1 contains 1.70 wt % of ash (at 800°C), while the remaining ones which are strongly enriched in quartz, or quartz and dolomite (e.g., S-1: Table 1), contain between 41.76 and 78.71 wt % of ash.

The burning energy ( $Q_s^{daf}$ ) is from 8260 to 8658 kcal/kg (34,582–35,411 kJ/kg). The value of about 8650 kcal/kg (sample S-1) seems to be

Table 3

Chemical parameters of Late Proterozoic coals from Spitsbergen. W — moisture (weight %); A — ash content (weight %); V — volatiles (weight %); F. C. — stable carbon (weight %);  $Q_s$  — burning heat (kcal/kg);  $d_{He}$  — helium density (g/cm<sup>3</sup>); C, H, N, O, S amount in wt %; X<sup>a</sup> — analytical state; X<sup>d</sup> — dry state; X<sup>daf</sup> — dry and non-ash state

SAMPLE	W <sup>a</sup>	A <sup>d</sup>	V <sup>daf</sup>	F.C.	$Q_s^{daf}$	$d_{He}$	C <sup>daf</sup>	H <sup>daf</sup>	N <sup>daf</sup>	O <sup>daf</sup>	S <sup>daf org</sup>
S-1	0.16	1.70	5.14	94.86	8658	1.60	94.8	1.36	0.42	2.79	0.13
S-2	0.33	65.84	3.76	96.24	8260	1.58	94.4	1.31	0.38	3.43	0.09
S-3	0.36	41.76	3.90	96.10	8500	1.60	94.6	1.08	0.39	3.22	0.11
S-4	0.27	52.75	3.95	96.05	8420	1.59	94.0	1.39	0.41	3.60	0.07
S-5	0.28	50.53	3.94	96.06	—	1.58	94.2	1.31	0.37	3.60	0.08
S-6	0.10	78.71	—	—	—	1.32	91.7	—	—	—	0.23

a characteristic one. Other samples, which contain a considerable mineral (quartz, dolomite) admixture, probably yielded apparent values of burning energy, as a result of overlap of coal burning energy and thermal effects of transformations of non-coal minerals.

The volatiles content is low, from 3.76 to 5.14 wt %, while the value of the so-called fixed carbon (F.C.) varies between 94.86 and 96.24 wt %. The elementary carbon content is high, 91.69–97.60 wt %, the hydrogen content is low, 1.08–1.39 wt %. The sulfur content is low to medium, 0.57–1.42 wt % (Table 3). About 1/10 of sulfur is contained in pyrite.

The sulfur content in ash is generally low, as a mean 0.004–0.039 wt %; an anomaly is shown by sample S-6 where it rises to about 0.5 wt %. The nitrogen content varies from 0.38 to 0.42 wt %.

The density, determined in He atmosphere, calculated for organic matter ( $d_{He}^{20}$ ), varies from 1.32 to 1.60 g/cm<sup>3</sup>.

The above indicators of coalification stage are typical for anthracite (S-1) and metaanthracite (S-2 to 6), according to classifications used in Poland, Germany and USA. In the ICCP classification of 1988, the results of our analyses are typical for metaphase anthracites (high coal rank) and semigraphites.

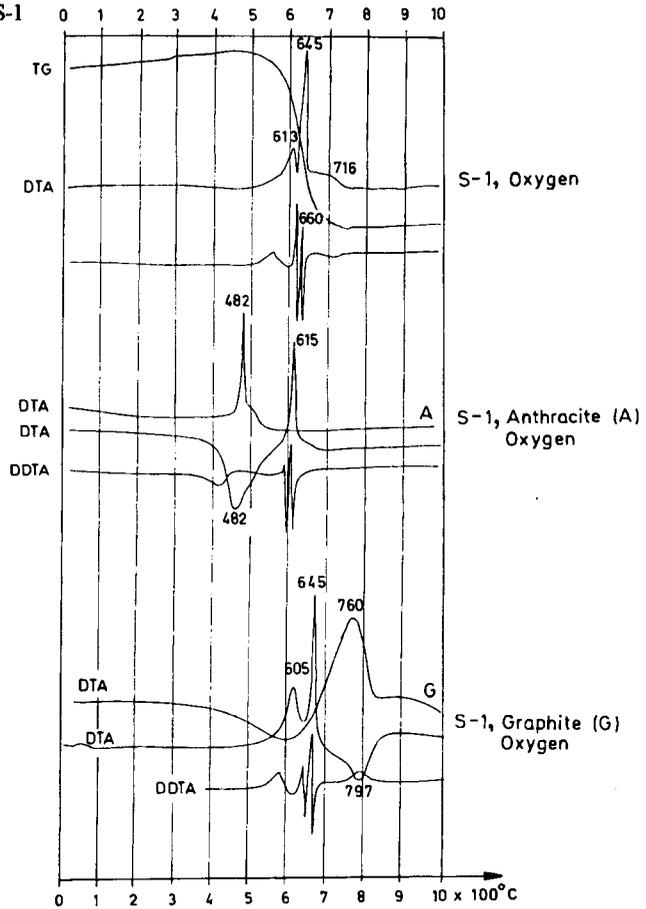
## DTA investigation

Derivatograph investigations performed on our coals gave the best results under dynamic oxygen atmosphere conditions (Figs 7, 8). Besides DTA analyses of particular samples, with the use of  $\gamma\text{-Al}_2\text{O}_3$  as inert substance, anthracite from the Sophie mine (Germany) – a standard for Polish coal laboratories (LR), and rhetort graphite of Bohemian production – a standard for arc-spectrophotometry, were made. These methods allowed to precisely establish the degree of coalification in our samples.

Sample S-1 differs in the character of DTA curves from the remaining ones (as shown by the S-4 example). In the dynamic oxygen atmosphere, S-1 (Fig. 7) shows two sharp exothermal peaks, with a maximum about 613 and 645°C, and a wide exotherm about 700°C. These peaks indicate the presence of three phases differing in the degree of coalification, higher than that of standard anthracite used ( $C^{daf} = \text{ca } 91\%$ ;  $V^{daf} = 5\%$ ), but lower than that of synthetic graphite ( $C^{daf} = 100\%$ ;  $V^{daf} = 0\%$ ). The curves indicate that metaanthracite phases are dominant in the samples.

A similar pattern of thermal changes was observed in the remaining samples; that from sample S-4, treated as a mean one, has been shown in Figure 4. Three phases occur here also, being however characterized by different maxima (620, 660 and 740°C). Comparison with standard anthracite and graphite used, shows that two of these phases (620 and 660°C) have no equivalent in these standards,

Fig. 7. DTA curves for sample S-1



thus corresponding to metaanthracite or semigraphite; the third phase, infrequent in the sample, is similar to graphite.

Temperature ranges of coal burning reactions are indicative of its metamorphic degree (Kwiecińska and Parachoniak 1976, Kwiecińska 1967, Landis 1971). This metamorphism would correspond to greenschist and amphibolite facies of regional metamorphism, as recognized in the Precambrian succession of Horsund (Birkenmajer and Narebski 1960; Smulikowski 1965, 1968). A thermal effect, corresponding to a minimum temperature of  $500^\circ\text{C}$  at 20,000 MPa pressure, as based on Landis's (1971) standard, could be responsible for strong degasification of coals with formation of gaseous-phase- and pyrolytic graphite, and for strongly occluded quartz. There is no field evidence for any intrusive activity of Proterozoic or younger age which would directly affect the Höferpynten Formation, either at Krakken or Höferpynten. However there are numerous evidences of thermal changes in carbonate rocks of this formation,

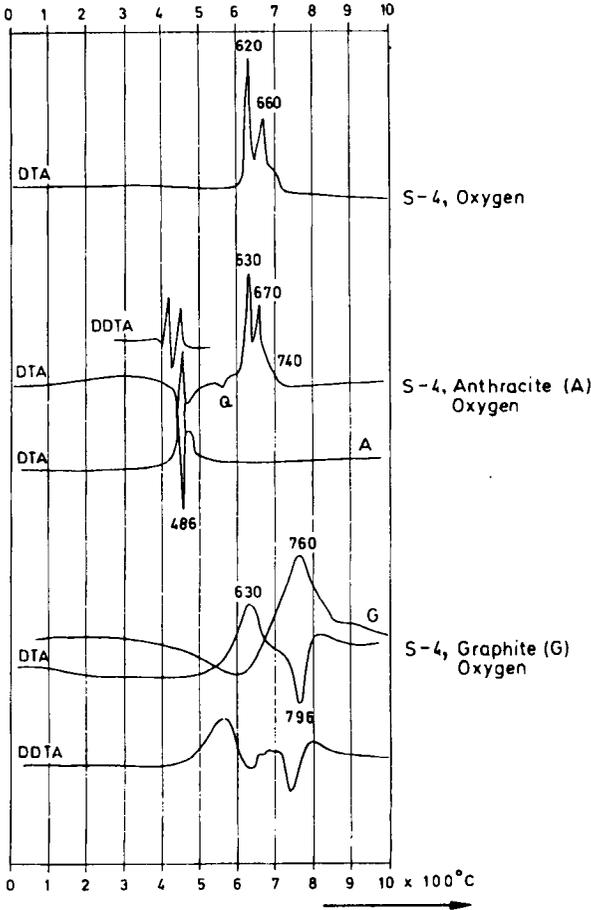


Fig. 8. DTA curves for sample S-4

caused by mesothermal mineralizing solutions of late Caledonian age which had produced ore-bearing (pyrite-copper) quartz-, quartz-ankerite, and ankerite veins (Wojciechowski 1964, Birkenmajer and Wojciechowski 1964, Birkenmajer 1992).

### Isotopic determination of $\delta^{13}\text{C}$

Isotopic determination of carbon, with the PDB (ISO) standard, was performed on three samples (S-1, 2, 3) free of carbonates. They show the value of  $\delta^{13}\text{C}$  within the range of -25 to -29‰ PDB. These values are typical for organic coal formed as a result of biogenic cycle (see Sidorenko and Barshchenskaya 1979 – *vide* Waleńczak 1987). They are different from the  $^{13}\text{C}$  content in carbonates ( $\delta^{13}\text{C}/\text{PDB} \sim 0 \pm 4\%$ ).

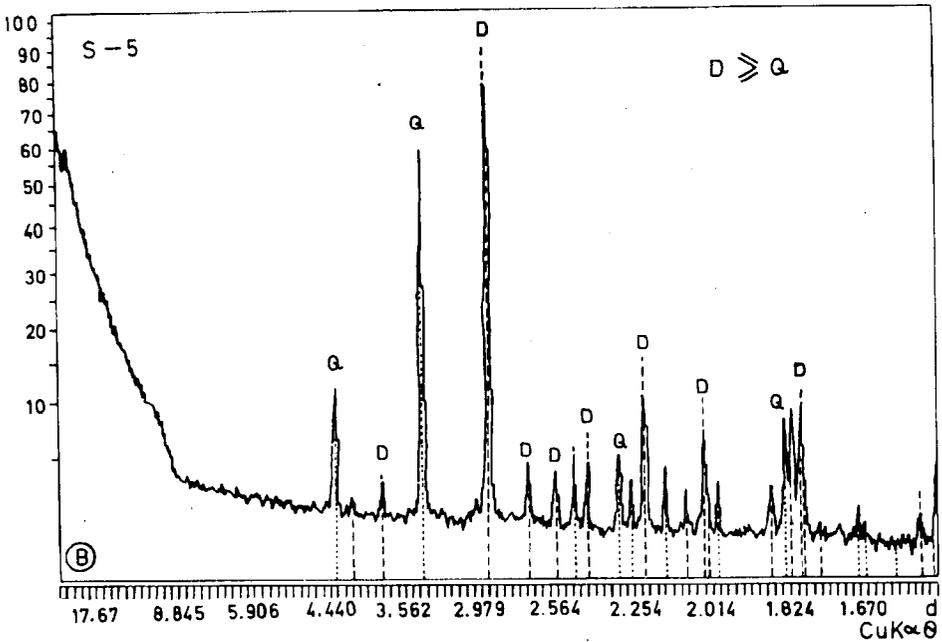
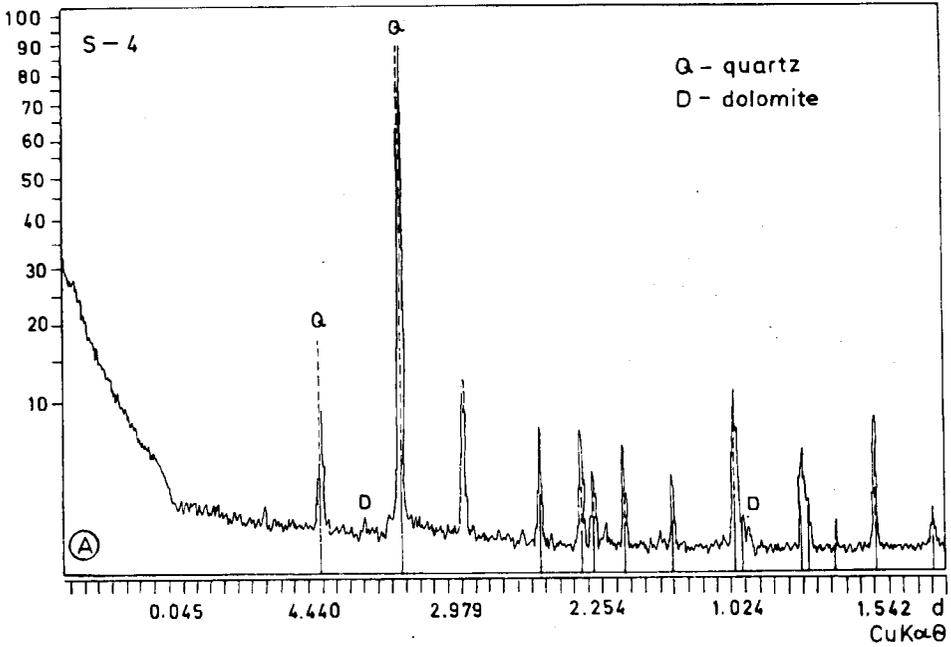


Fig. 9. Diffractogrammes for samples S-4 (A) and S-5 (B).

	FP	ML/SL	SCAL	Phase	Chemical Formula
A:	2.0	11/14	0.91	33-1161	SiO <sub>2</sub> quartz, low, syn
B:	0.5	12/18	0.98	36-426	Ca, Mg (CO <sub>3</sub> ) <sub>2</sub> dolomite (---)
	0.5	10/13	0.61	33-1161	SiO <sub>2</sub> quartz, low, syn (...)

## Mineral material of samples

Sample S-1 contains a minimum amount of barren material (ash content = 1.70 wt %) which cannot be recognized under microscope. A sharp peak at diffractogrammes, with  $d = 3.34 \text{ \AA}$  (Fig. 5), may indicate the presence of quartz. The remaining samples contain a high admixture of non-coal minerals ( $A^d = 41.7 - 78.7 \text{ wt \%}$ ). In samples S-2, 3 and 6, these are represented by quartz with dolomite admixture (Fig. 9B), and in sample S-5 — by dolomite with quartz admixture. These minerals, recognized also on optical examination (Table 1), form basal cement of the breccias.

## Conclusions

(1) The coal matter which fills irregular voids in dolostones of the Höferpynten Formation (Upper Proterozoic) is of organic origin. This is indicated by the  $\delta^{13}\text{C/PDB}$  index of -25 to -29%, and by the presence of relics of algal structures in the samples. Taking into account lagoonal to shallow marine (intertidal) character of the Höferpynten Formation which had formed under warm climatic conditions, and the occurrence of numerous algal structures in it (Birkenmajer 1972, Radwański and Birkenmajer 1977), the presence of coal matter in the dolostones is not surprising. The form of occurrence of this coal, as fills of small voids in the dolostone, suggests migration of bituminous matter, originally more uniformly distributed in the sediment, and its concentration in porous parts of the deposit probably already during early diagenetic stage;

(2) The degree of coalification (graphitization) is high and diversified, that may attest to several coalification stages, probably related to different metamorphic and metasomatic events. Sample S-1 from Krakken which represents a rather homogenous material, shows the lowest degree of coalification corresponding to metaanthracite, as indicated by its reflectance coefficient and roentgenography. Samples S-2 to 6 from Höferpynten-Andvika, show a slightly higher degree of coalification, typical for semigraphites, with subordinate graphite phase;

(3) The oldest metamorphic changes in our coals would correspond to initial stage of the greenschist-amphibolite phase of regional metamorphism, with temperatures of over 500°C and pressure of over 20,000 MPa. This is suggested by thermal characteristics (DTA) of the coal material, its high reflectance and anisotropy;

(4) A characteristic feature of our coals is the presence of multiphase graphite crystallites. The majority are represented by fibrous ones which grew in the coal along with coalification (graphitization) process. Graphite which precipitated from gaseous phase, and pyrolitic graphite, have also been recognized. Together with associated coke-like material, they suggest a rapid degasification of the coal, subsequent to transition from medium-

to stone-coal stage. This is confirmed by the presence of empty micropores coated inside with graphite crystallites, and by mosaic anisotropy of the matrix;

(5) Another component of coal-breccias (from Höferpynten-Andvika) are angular, poorly sorted fragments of metaanthracite and semigraphite composed mainly of crystallite mosaic. Regularly shaped, quartz-filled pores are here infrequent. They probably represent a coal subjected to alteration by hydrothermal (mesothermal) mineralizing solutions, as is also suggested by association with occluded quartz. This metamorphism was probably subsequent to other metamorphic changes in coal grains.

## References

- Abramsky C. and Mackowsky M. - Th. 1952. Methoden und Ergebnisse der angewandten Koxmikroskopie. In: Freud H., Handbuch der Mikroskopie in der Technik. Umschau Verl., Frankfurt/M., Bd. II/1: 311–410.
- Birkenmajer K. 1972. Cross-bedding and stromatolites in the Precambrian Höferpynten Dolomite Formation of Sørkapp Land, Spitsbergen. — Norsk Polarinst. Årb. 1970: 128–145.
- Birkenmajer K. 1975. Caledonides of Svalbard and plate tectonics. — Bull. Geol. Soc. Denmark, 24: 1–19.
- Birkenmajer K. 1978. Cambrian succession in south Spitsbergen. — Stud. Geol. Pol., 59: 7–46.
- Birkenmajer K. 1981. The geology of Svalbard, the western part of the Barents Sea, and the continental margin of Scandinavia. In: Nairn A. E. M., Churkin M. Jr. and Stehli F. G. (eds): The Ocean Basins and Margins, 5: 265–329. Plenum Press, New York.
- Birkenmajer K. 1990. Non-glacial origin of the Slyngefjellet Conglomerate (Upper Precambrian), south Spitsbergen. — Pol. Polar Res., 11 (3–4): 301–315.
- Birkenmajer K. 1992. Precambrian succession at Hornsund, Spitsbergen. A lithostratigraphic guide. — Stud. Geol. Pol., 99: 7–66.
- Birkenmajer K. and Narebski W. 1960. Precambrian amphibolite complex and granitization phenomena in Wedel Jarlsberg Land, Vestspitsbergen. — Stud. Geol. Pol., 4: 37–82.
- Birkenmajer K. and Orłowski S. 1977. Olenellid fauna from the base of Lower Cambrian sequence in south Spitsbergen. — Norsk Polarinst. Årb. 1976: 167–180.
- Birkenmajer K. and Wojciechowski J. 1964. On the age of ore-bearing veins of the Hornsund area, Vestspitsbergen. — Stud. Geol. Pol., 11: 179–184.
- Gabzdyl W. 1978. Wybrane zagadnienia z petrografii węgla. Skrypt nr 803. Politechnika Śląska, Gliwice. 311 pp.
- Gray R. J. and Lowenhaupt D. E. 1989. Aging and weathering. In: Klein R. and Wellek R., Sample selection, aging, and reactivity of coal. J. Wiley & Sons, New York, pp. 255–337.
- Jasieńko S. 1965. Badania fizykochemiczne i strukturalne nad wityrynitami węgla kamiennych i ich stałymi produktami odgazowania. — Chemia Stosow., 9 (1): 263–283. Wrocław.
- Kwiecińska B. 1967. Węgle skoksowane z Zagłębia Wałbrzyskiego (Coked coals from the Wałbrzych Basin). — Prace Mineral. O/PAN Kraków, 9: 1–85.
- Kwiecińska B. 1980. Mineralogy of natural graphites. — Prace Mineral. O/PAN, Kraków, 67: 1–87.
- Kwiecińska B. and Parachoniak W. 1976. Thermal investigations of graphitic substances from metamorphic rocks. — Mineral. Polon., 7: 73–89.
- Landis C. A. 1971. Graphitizations of dispersed carbonaceous material in metamorphic rocks. — Contr. Mineral. Petrol., 30: 34–45.

- Probiez K. 1989. Wpływ metamorfizmu termalnego na stopień uwęglenia i skład petrograficzny pokładów węgla w obszarze Jastrzębia, GZW. — Zesz. Nauk. Politech. Śląskiej (Gliwice), 176: 1–125.
- Radwański A. and Birkenmajer K. 1977. Oolitic/pisolitic dolostones from the Late Precambrian of south Spitsbergen: their sedimentary environment and diagenesis. — Acta Geol. Pol., 27 (1): 1–39.
- Smulikowski W. 1965. Petrology and some structural data of lowest metamorphic formations of the Hecla Hoek Succession in Hornsund, Vestspitsbergen. — Stud. Geol. Pol., 18: 1–107.
- Smulikowski W. 1968. Some petrological and structural observations in the Hecla Hoek Succession between Werenskioldbreen and Torellbreen, Vestspitsbergen. — Stud. Geol. Pol., 21: 97–161.
- Stach E. 1952. Mikroskopie natürlicher Kokse. In: Freud H. (ed.), Handbuch der Mineralogie in der Technik, II/1. Umschau-Verl., Frankfurt/M., pp. 411–422.
- Ting G. 1982. Coal macerals. In: Francis T., Ting G., Structure of coals. — Academic Press, New York, pp. 28–40.
- Waleńczak Z. 1987. Geochemia organiczna. — Wydawnictwa Geologiczne, Warszawa, 160 pp.
- Wojciechowski J. 1964. Ore-bearing veins of the Hornsund area, Vestspitsbergen (Preliminary communication). — Stud. Geol. Pol., 11: 173–177.

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## Streszczenie

W obrębie późnoproterozoicznych dolomitów formacji z Höferpynten w południowym Spitsbergenie (fig. 1–4) występują nieregularne próżnie wypełnione substancją węglową o charakterze antracytu (fig. 5–10, tab. 1–3). Węgiel ten jest pochodzenia organicznego. Powstał on najprawdopodobniej z bituminów pochodzących z rozkładu glonów, co potwierdzają badania petrograficzne i obecność struktur glonowych w dolomitach. Dalsze przeobrażenia metamorficzne w facji zieleńcowo-amfibolitowej doprowadziły do przekształcenia się węgla w odmianę grafitową, wśród której można wyróżnić kilka stadiów odpowiadających kilku stadiom metamorfozy. Występują również krystality, które powstały z fazy gazowej, jak też grafit pyrolityczny; mogły one powstać wskutek działania roztworów mezothermalnych, z którymi związane jest występowanie żył kruszcowych obecnych w dolomitach.