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Permian Coals from Western Dronning Maud Land - Composition, Environment, and the Influence of Jurassic Magmatism on their Maturity

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Abstract - Coal seams and coaly shales are intercalated in the lower Permian Amelang Plateau Formation of Fossilryggen and Schivestolen (western Dronning Maud Land, Antarctica). The sedimentary sequence records ice withdrawal subsequent to Gondwana glaciation, starting with diamictites and passing from periglacial deltaic-lacustrine sedimentation to fluviatile (Schivestolen) and marginally marine (Fossilryggen) environments with the formation of peat.
The rank of the coals and the coaly material in shales lies between subbituminous C at Schivestolen and meta-anthracite at Fossilryggen. The thermal maturity mainly depends on the distance from Jurassic dolerite dykes and sills.
Microscopic analyses of coal samples with lower rank revealed a maceral composition with high inertinite contents, which is typical of Permian Gondwana coals. Three kaolin-coal tonsteins identified in the study are the first encountered and described from Permian coal measures of Antarctica.

Keywords: *Dronning Maud Land, Beacon Supergroup, coal, kaolin-coal tonstein*

INTRODUCTION

Permian coal measures in western Dronning Maud Land (Fig. 1) are known from two localities: Fossilryggen, the easternmost nunatak of Vestfjella (Fig. 2a) and Schivestolen massif in the northern Heimefrontfjella (Fig. 2b).

First geological investigations during the 1960's (Hjelle & Winsnes, 1972; Juckes, 1972) led to a general outline of the geology of Vestfjella and northern Heimefrontfjella. While petrography and sedimentology of the sedimentary cover were studied, the coals remained unconsidered. Since 1982 both regions were visited for detailed geological work by several expeditions with

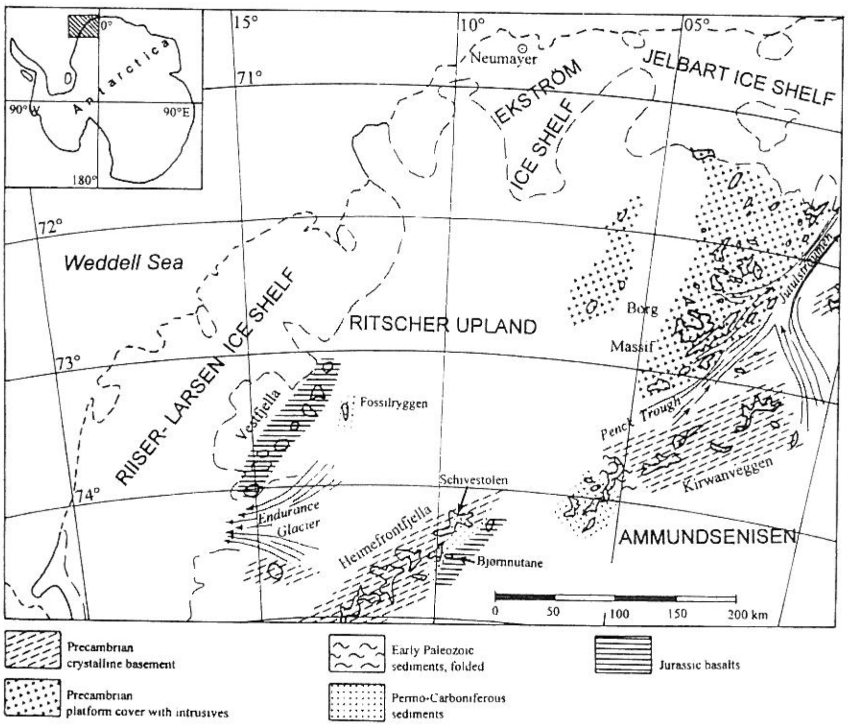

Fig. 1 - Simplified geological sketch map of western Dronning Maud Land. Permian coal measures are exposed at Fossilryggen and Schivestolen.

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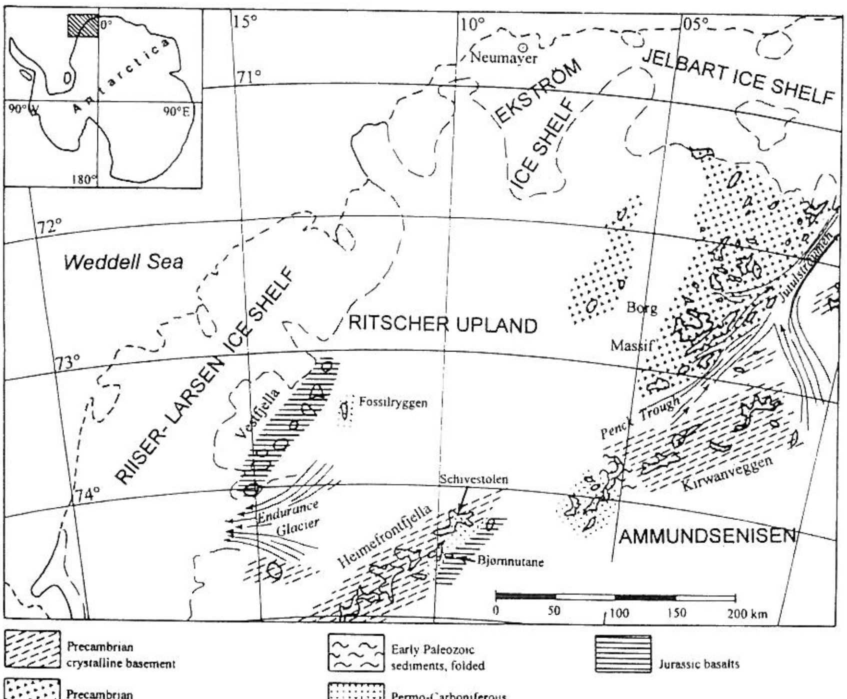

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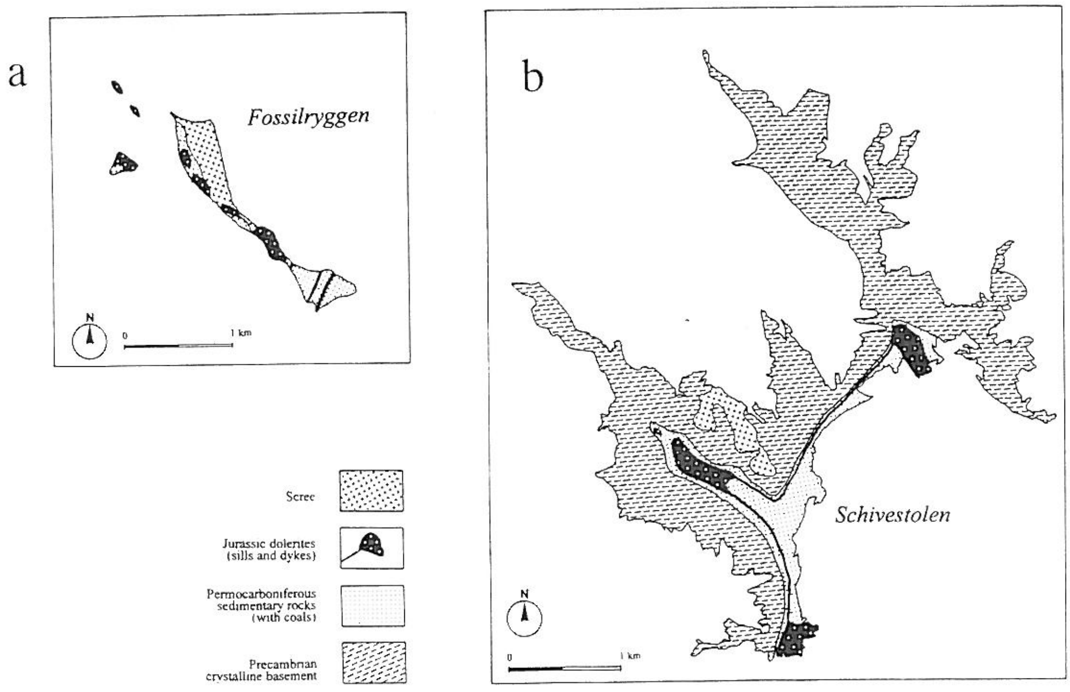


Fig. 2 - a) Geological sketch map of Fossilryggen/Vestfjella (modified after Hjelle & Winsnes, 1972); b) Geological sketch map of Schivestolen massif/Heimefrontfjella.

participation of German and Austrian scientists (e. g. Behr et al., 1983; Arndt et al., 1987; Poscher, 1988; Weber et al., 1995).

The Permian coal measures are within the Amelang Plateau Formation (Wolmarans & Kent, 1982), a sedimentary sequence of basal diamictites, cross-bedded sandstones with intercalations of shales, carbonaceous shales, and thin coal seams, overlying a Precambrian metamorphosed and folded basement. The Amelang Plateau Formation is a part of the Beacon Supergroup. Plant fossils suggest an early Permian age of the coal measures (Plumstead, 1975; Larsson et al., 1990). On the basis of palynologic analyses the minimum age of basal diamictites from Schivestolen can be narrowed down to the period between the uppermost Carboniferous and the early Permian (Larsson et al., 1990).

The sedimentary sequence is intruded by dolerite dykes and sills of Jurassic age (Rex, 1972) and covered by a now largely denuded thick pile of Jurassic lava flows which form the Kirwanveggen Formation (Wolmarans & Kent, 1982). The present relict distribution of the sedimentary strata is a result of mainly pre-Jurassic erosion. The maximum thickness of the Amelang Plateau Formation is preserved at the Schivestolen massif (160 m) but 30 km southward at Bjørnnutane only two meters of sandstone remain between the crystalline basement and the overlying Jurassic basalt flows. An original thickness of the basalt flows of 2000 m was estimated by Jacobs et al. (1992).

SEDIMENTARY ENVIRONMENTS AND FACIES

HEIMEFRONTFJELLA

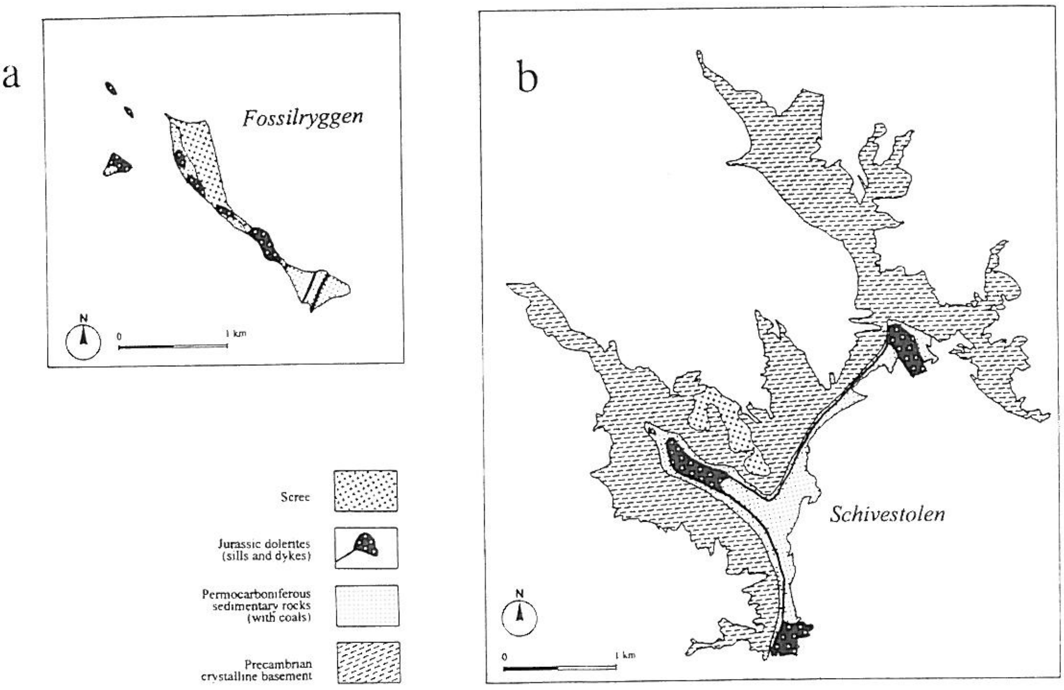
The sequence of upper Palaeozic clastic rocks (Amelang Plateau Formation) can be divided in three units: the basal diamictite facies (Poscher, 1992), the dropstone-bearing siltstone facies, and the coal-bearing sandstone facies.

At Heimefrontfjella, terrestrial glaciation can be confirmed. The facies interpretation of the diamictites as glacial is based on a provable contact with the glacially abraded and striated basement as well as striated and faceted clasts in the diamictites. The palaeo-ice flow direction of 335° ±10° was determined from the striated basement.

The assumption of glacial to periglacial conditions in the overlying strata is substantiated by oxygen isotopic composition (Poscher, 1994) and by a wide range of sedimentary structures such as dropstones and ice-dump tills, which, for the most part, can solely be explained by periglacial conditions. Plant fossils indicate a cool and arid climate (Plumstead, 1975), as do palynologic analyses (Poscher, 1994).

The coal-bearing sandstone facies forms the uppermost part of the Amelang Plateau Formation. It comprises light-brown to white, feldspar-rich sandstones. The maximum thickness of this facies is preserved at Schivestolen (140 m), but at other outcrops of the Amelang Plateau Formation in Heimefrontfjella it has commonly been removed by erosion.

The first carbonaceous shale occurs 35 m above the base of the measured section, directly below a Jurassic dolerite sill. From the top of the sill to 105 m a section of laminated siltstones, coaly siltstones, and sandstones with mainly planar bedding is exposed. The overlying beds (105 to 115 m) are fluvial fining-upward sequences, consisting of graded sandstones with trough cross-bedding passing into laminated siltstones showing very flat cross-bedding or ripples. Some of the fining-upward sequences terminate with a thin coal seam (up to 40 cm). The



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FOSSILRYGGEN

The sedimentary rocks of Fossilryggen were described by Hjelle & Winsnes (1972) and Olaussen (1985). In the southern part of this nunatak, 43 m of Permian beds crop out. The lower 25 m are relatively pure, cross-bedded quartz-sandstones. The upper 18 m consist of cross-bedded sandstones and laminated, dark clay-shales. At the northern tip of the nunatak an outcrop shows 10 m of dark shale, thin sandstone layers and coaly shales. These rocks are rich in plant remains. According to Olaussen (1985) the sedimentary rocks of Fossilryggen were deposited in an estuarine to marginal marine environment.

ORGANIC PETROGRAPHY AND MATURITY OF COAL SAMPLES FROM WESTERN DRONNING MAUD LAND

ORGANIC PETROGRAPHY

Quantitative microscopic analyses of five coal samples from an 18 cm thick seam in the Schivestolen profile revealed high inertinite and vitrinite contents (Tab. 1). The lower 5 cm of the seam is mineral matter-rich. The high inertinite content is typical of Permian Gondwana coals (e. g. Hobday, 1987). In comparison with other Gondwana coals the liptinite content is relatively high (e. g. Stach et al., 1982). Within the liptinite group, mainly sporinite but also minor amounts of cutinite (Fig. 3a) and fluorinite occur. The inertinite group is predominantly composed of inertodetrinite and degradofusinite. Macrinite and semifusinite are less frequent, as is well preserved secretion sclerotinite. The vitrinite group comprises thin telinite, telocollinite and desmocollinite (Fig. 3b). Oxidation rims and cracks around vitrinite grains are sometimes visible (Fig. 3c). These rims are probably a result of weathering and show lower reflectivity than the central part of the grain which must be considered for reflectance measurements. Common allochthonous components of the coals are anisotropic longish particles with coke texture, showing a fine mosaic, fiber or domain like shape type (Fig. 3d) of a spore.

Three samples (KK 3, KS 48, and KS 49) were identified as kaolin-coal tonsteins, comprising kaolinite pseudomorphs, probably after feldspar and mica (Fig. 3a). Single kaolinite blebs are up to 200 mm in diameter (Fig. 3e). Other minerals are missing in the kaolinite-rich layers. Kaolin-coal tonsteins are often interpreted as fossil ash falls (Stach et al., 1982). A possible source of volcanogenic material may have been the Permian volcanic arc of Marie Byrd Land (Mukasa, 1995).

Tab. 1 - Average composition of five coal samples, ash free, (Z 490/3, 500/1-4) from the Schivestolen profile.

Macerals		Microlithotypes	
Vitrinite	45%	Vitrite	16%
Inertinite	46%	Inertite	19%
Liptinite	9%	Liptite	0%
		Clarite	7%
		Vitrinertite	20%
		Durite	2%
		Trimacerite	36%

VITRINITE REFLECTANCE

Vitrinite reflectance values between 0.41 and 0.59% Rr were measured at vertical distances greater than 65 m from the 15 m thick Jurassic dolerite sill of Schivestolen (Tab. 2). These coals have the lowest rank (subbituminous C) of any known Permian coals of Antarctica (e.g. Rose & McElroy 1987). Closer towards the dolerite sill the vitrinite reflectance increases to a maximum value of 3.29 % Rr at the contact (sample U 30, Tab. 2). Vitrinite reflectance versus the distance of the samples from the sill is shown in figure 4.

Maximum palaeotemperatures have been estimated using Bostick's (1973) diagram. The estimated palaeotemperatures follow the curve of Bostick (1973) which shows the calculated maximum temperatures in the sedimentary rocks in distance of an intrusion with 1200°C (Fig. 4). The thermal aureole is two or three times the sill thickness. Raymond & Murchison (1988) suggested that the width of an aureole depends on the volume of porewater present at the time of emplacement and increases with the degree of compaction. The wide thermal aureole, therefore, indicates that the Permian sedimentary rocks

Tab. 2 - Vitrinite reflectance data from samples of Schivestolen and Fossilryggen. Oil immersion, 546 nm wavelength. Abbreviations: c. = coal, c.s. = coaly shale, k.c.t. = kaolin-coal tonstein. Rr = average mean reflectance, Rmax = average maximum reflectance, ρ = standard deviation, m: distance from Jurassic dolerite sill (Schivestolen) in meter.

Sample		Rr	σ	R_{max}	σ	m
Schivestolen						
KK 1	c.	0.41	0.03			66
KK 2	c.	0.43	0.04			66
KK 3	k.c.t.	0.48	0.03			66
KS 48	k.c.t.	0.46	0.04			>70
KS 49	k.c.t.	0.44	0.03			>70
KS 50	c.	0.47	0.04			>70
KS 51	c.	0.41	0.02			>70
KS 52	c.	0.44	0.03			>70
KS 53	c.	0.45	0.04			>70
S 70	c.s.	0.53	0.06			34
S 435	c.s.	0.54	0.07			30
S 960	c.s.	0.76	0.10			25
S 980	c.s.	0.59	0.12			26
U 30	c.s.	3.29	0.18	4.14	0.52	0
U 105	c.	2.64	0.40	2.75	0.47	1.5
U 115	c.	2.82	0.25	3.03	0.30	1
U 170	c.	2.54	0.10	2.80	0.24	2
Z 490	c.	0.54	0.04			65
Z 500	c.	0.55	0.03			65
Fossilryggen						
A 31	c.s.			7.18	0.69	
A 32	c.s.			6.63	0.68	
A 34	c.s.			6.69	0.85	
A 50	c.			5.95	0.62	
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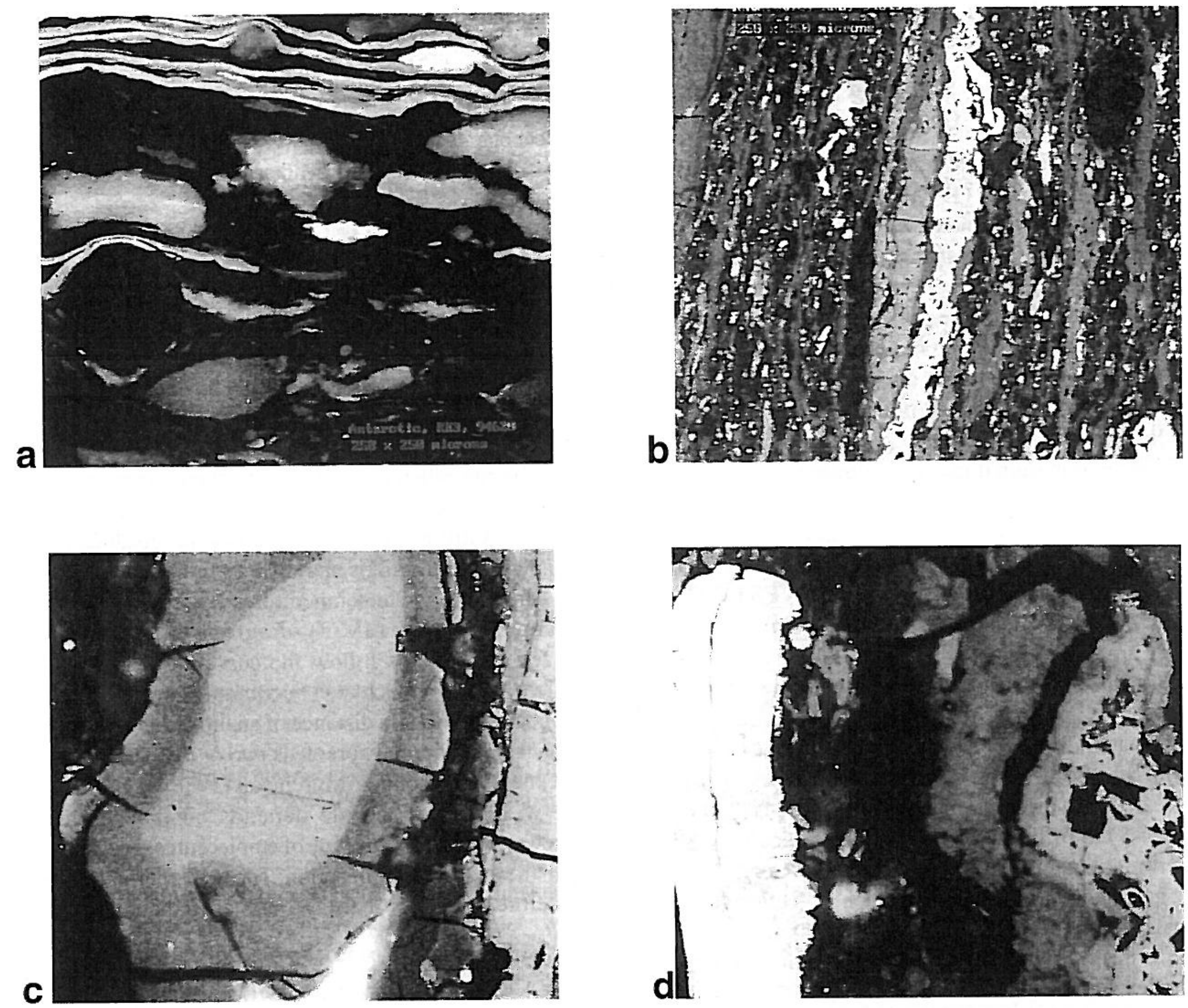


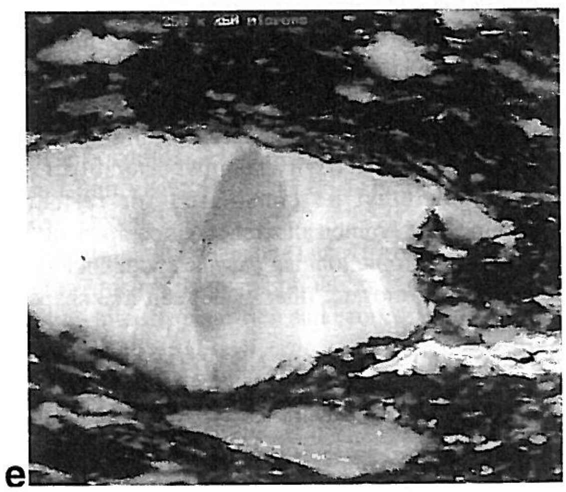
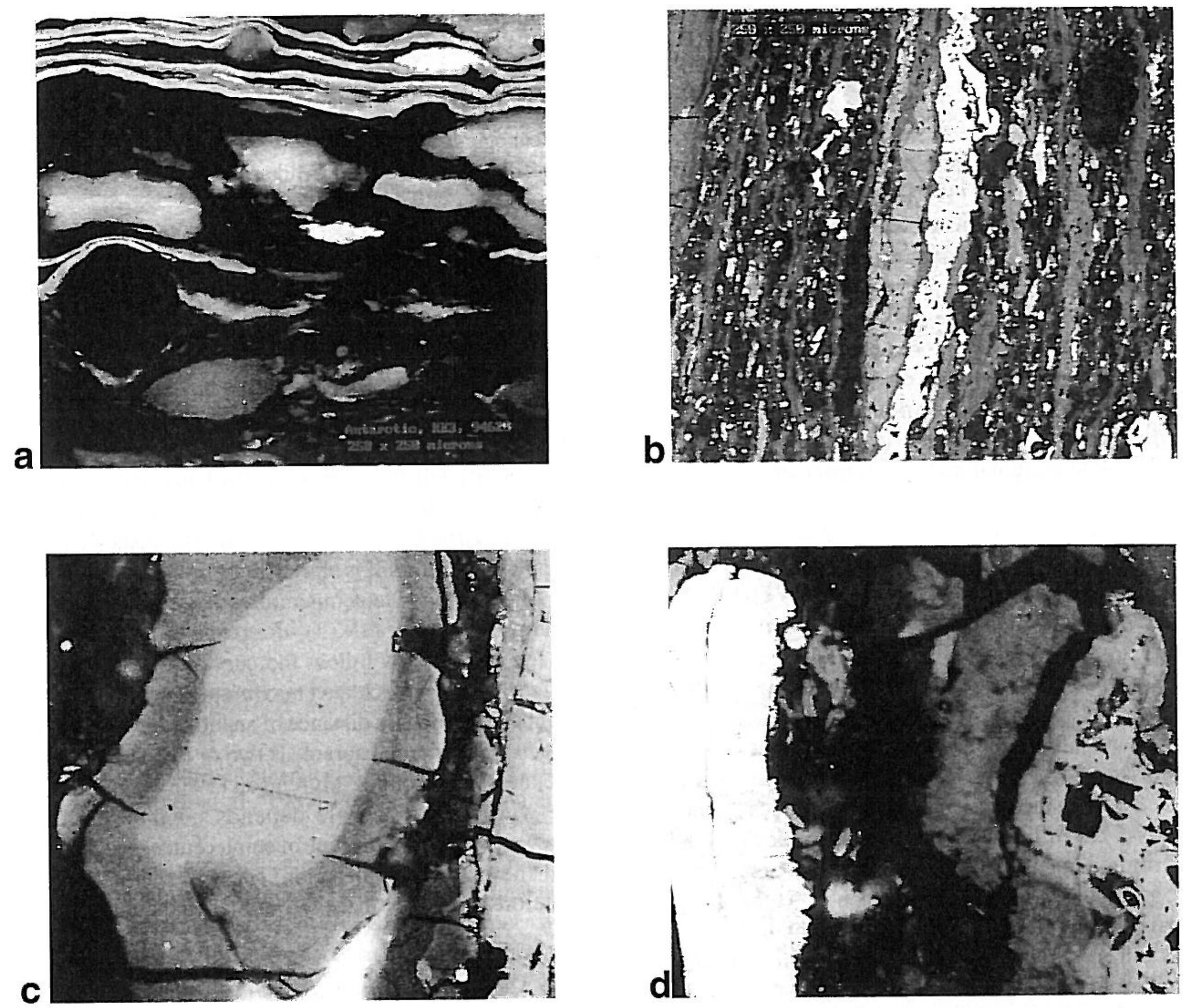


Fig. 3 - a) The upper part of the photo shows a layer which is relatively rich in liptinite (cutinite), the yellow-greenish particles are kaolinite crystals; sample KK 3, polished surface, oil immersion, blue light irradiation, vertical length 250μm; b) Fine-grained, mineral rich coal (sample KK 2) composed of telocollinite, desmocollinite, semifusinite, and inertodetrinite; polished surface, oil immersion, vertical length 250μm; c) Oxidation rim around a vitrinite grain; sample KS 48, polished surface, oil immersion, vertical length 250 μm; d) Coke particle (left), showing a domain-like shape type, in the kaolin-coal tonstein KS 48; polished surface, oil immersion, vertical length 250 μm; e) Kaolin-coal tonstein, sample KK 3. Thick kaolinite crystal with greenish-yellow colour; polished surface; oil immersion, blue light irradiation, vertical length 250μm.

were already consolidated and lithified at the time of intrusion. This is in accordance with the assumption of major pre-Jurassic erosion.

The coal-bearing strata of Fossilryggen have been injected by numerous Jurassic dolerite dykes and sills. Contact metamorphism led to a very high rank, up to meta-anthracite, of the phytoclasts in the coaly shales (Tab. 2). At Fossilryggen, in contrast to Schivestolen, no correlation is determinable between vitrinite reflectance and lateral distance to dykes or intrusions. The nunatak is not only intruded by a large number of mafic dykes (only the thickest are drafted in Fig. 2a) and intrusions but the smooth surface is also covered by basalt scree. The scree is probably a relict of now denuded lava flows. The maturity of the organic material was obviously affected by this cover of lava flows rather than by the minor intrusives.



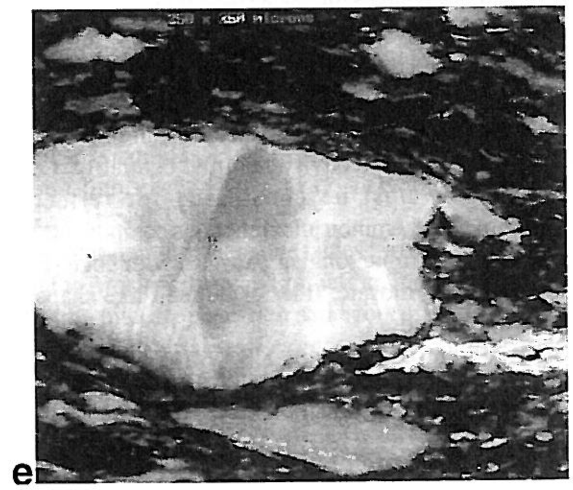


Fig. 3 - a) The upper part of the photo shows a layer which is relatively rich in liptinite (cutinite), the yellow-greenish particles are kaolinite crystals; sample KK 3, polished surface, oil immersion, blue light irradiation, vertical length 250µm; b) Fine-grained, mineral rich coal (sample KK 2) composed of telocollinite, desmocollinite, semifusinite, and inertodetrinite; polished surface, oil immersion, vertical length 250µm; c) Oxidation rim around a vitrinite grain; sample KS 48, polished surface, oil immersion, vertical length 250 µm; d) Coke particle (left), showing a domain-like shape type, in the kaolin-coal tonstein KS 48; polished surface, oil immersion, vertical length 250 µm; e) Kaolin-coal tonstein, sample KK 3. Thick kaolinite crystal with greenish-yellow colour; polished surface; oil immersion, blue light irradiation, vertical length 250µm.

were already consolidated and lithified at the time of intrusion. This is in accordance with the assumption of major pre-Jurassic erosion.

The coal-bearing strata of Fossilryggen have been injected by numerous Jurassic dolerite dykes and sills. Contact metamorphism led to a very high rank, up to meta-anthracite, of the phytoclasts in the coaly shales (Tab. 2). At Fossilryggen, in contrast to Schivestolen, no correlation is determinable between vitrinite reflectance and lateral distance to dykes or intrusions. The nunatak is not only intruded by a large number of mafic dykes (only the thickest are drafted in Fig. 2a) and intrusions but the smooth surface is also covered by basalt scree. The scree is probably a relict of now denuded lava flows. The maturity of the organic material was obviously affected by this cover of lava flows rather than by the minor intrusives.

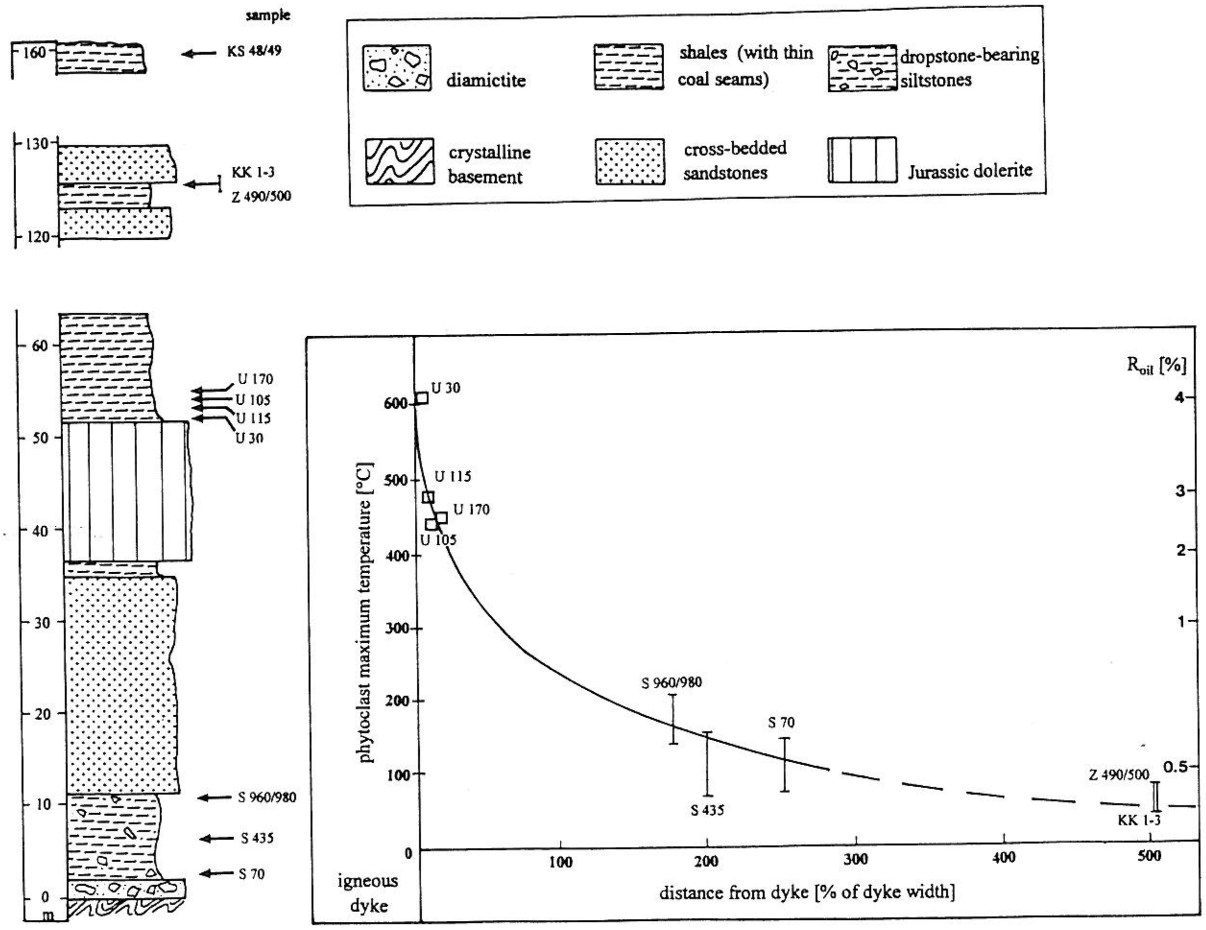


Fig. 4 - Left side: Simplified stratigraphic column of the Permo-Carboniferous at Schivestolen (modified after Poscher, 1988) with sample locations; Right side: Vitrinite reflectance (Rmax for values > 1.0% and Rr with standard deviation for values < 1.0%) and palaeotemperatures vs. distance from the adjacent sill. Palaeotemperatures were derived from vitrinite reflectance values using Bostick's (1973) diagram.

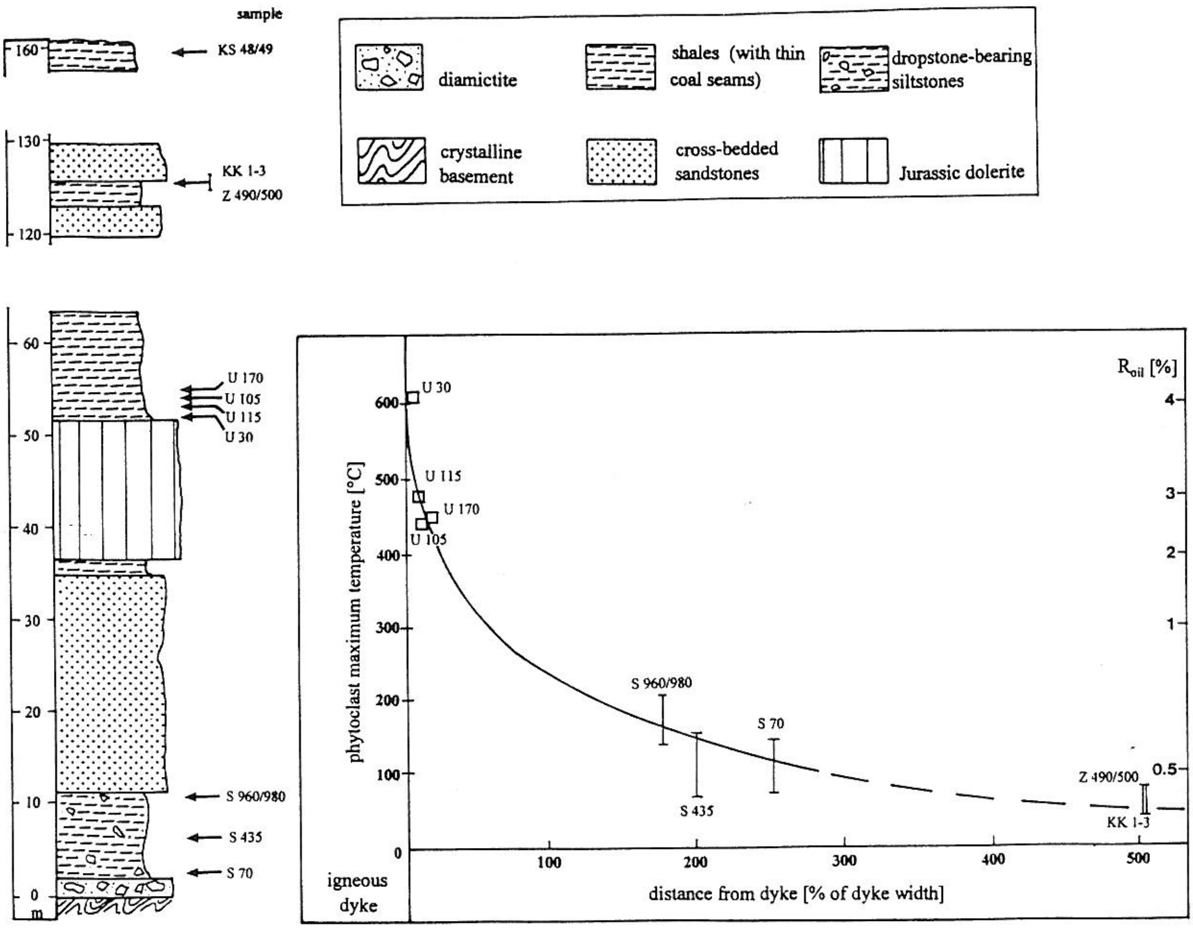
ILLITE CRYSTALLINITY

Illite crystallinity (IC) measurements (e.g. Kisch, 1990) have been carried out on pelitic samples from three sites of Fossilryggen in the vicinity of some dolerite dykes and one site in Schivestolen near the top of the Permo-Carboniferous strata. The grain size fraction <2mm of six pelitic samples was analysed. Sample preparation and separation of illite follows the method described by Nierhoff (1994). All measurements have been made using a SIEMENS D500 diffractometer at 35 kV and 30 mA CuKa radiation (with Ni filter), aperture diaphragms all 1°, detector diaphragm 0.05°, and a time constant of 1 sec. Each slide was scanned from 3° to 23° 2Θ, at a scan rate of 0.6° 2Θ/min and a step width of 0.019. Illite crystallinity was determined as the average of nine measurements of the half-height width of the 10 Å peak.

Tab. 3 - IC-values (mean °Δ2Θ) for Permian siltstones of Fossilryggen and Schivestolen.

Sample (locality)	°Δ2Θ	±σ
A 31 (Fossilryggen-North)	0.226	0.014
A 33 (Fossilryggen-North)	0.222	0.009
A 34 (Fossilryggen-North)	0.219	0.009
A 38 (Fossilryggen-South)	0.268	0.006
KF 30 (Schivestolen)	0.484	0.134
KF 31 (Schivestolen)	0.392	0.112

The °Δ2Θ-values from Fossilryggen (Tab. 3) indicate a thermal maturity at the boundary between diagenesis and the anchizone of metamorphism. The mean boundary between diagenesis and anchizone is represented by an half-height width of illite at 0.214 ±0.016 °Δ2Θ (U. Glasmacher, pers. comm.). In comparison to the results of vitrinite reflectance, we would expect distinctly lower °Δ2Θ-values. Organic material reacts more sensitively than phyllosilicates in response to local, short-time heating caused by intruding dolerite dykes and sills (Teichmüller et al., 1979). While the mineral matrix of the pelitic rocks indicates only diagenesis to very-low-grade metamorphism conditions (sensu Winkler, 1979), the organic material indicates temperatures of low-grade metamorphism for a short time, subsequent to the intrusion of mafic rocks in the early Jurassic. The newly formed phyllosilicates of pelitic samples from the top of the Schivestolen are still composed of mixed-layer (illite-smectite) minerals. Results of IC measurements suggest a relatively low thermal maturity of the Permo-Carboniferous strata at Schivestolen. The values are within the field of diagenesis for clastic sediments.



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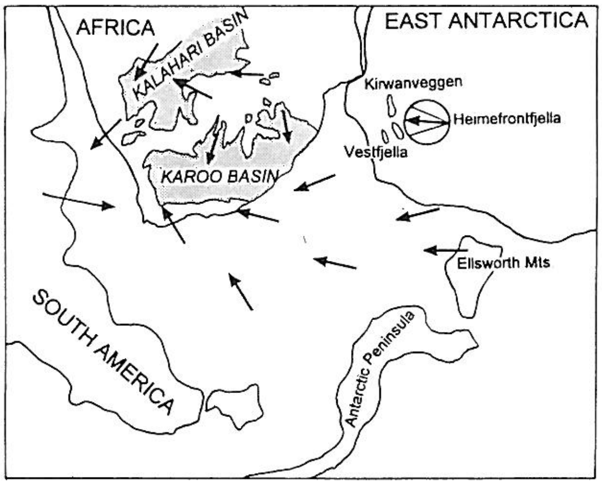

Fig. 5 - Gondwana reconstruction after Lawver & Scotese (1987), generalised and inferred ice-flow directions at late Carboniferous stage following Visser (1989) and supplemented by new results of the Heimefrontfjella area.

These results allow a combination of the upper Palaeozic sedimentary environments in Heimefrontfjella, Kirwanveggen (continental), and Fossilryggen (deltaic/ marginally marine) regions to form a sedimentary basin which shows similarities to facies conditions in southern Africa (Visser, 1989).

INFLUENCE OF JURASSIC MAGMATISM ON THE MATURITY OF ORGANIC MATERIAL

In the Schivestolen profile, the maturation of Permian sedimentary rocks adjacent to a Jurassic sill is strongly affected by contact metamorphism. The temperature close to the sill may have exceeded 500°C. Coals of the upper part of the Schivestolen profile (sample KK1 to KS 53, Tab. 1) are not affected by contact metamorphism. They yielded Rr values below 0.5 %, representing the background reflectance level, which corresponds to coalification temperatures not exceeding 70° to 80°C.

Higher temperatures (>100°C) are indicated by Mesozoic (150-90 Ma) apatite fission track ages of basement rocks and gneissic dropstones within the Permo-Carboniferous cover (Jacobs et al., 1992). According to Jacobs et al. (1992) these temperatures are a result of deep burial by a now denuded, thick pile of Jurassic lava flows, formed by rifting at the beginning Gondwana breakup. The vitrinite reflectance data show that temperatures above 100°C did not occur in the upper part of the Schivestolen profile. This difference can be attributed to: (1) extremely elevated geothermal gradients, which caused significant higher temperatures in the basement and the lowermost part of the Permo-Carboniferous cover than in its upper part; or (2) the apatite data were collected within the aureole of the Mesozoic sill.

A pre-Jurassic erosion surface indicates that the Amelang Plateau Formation was exposed during the early Mesozoic. The original thickness of the Permo-Carboniferous strata in western Dronning Maud Land remains uncertain, with a maximum preserved thickness of 160 m at Schivestolen. Large parts of the Permo-Carboniferous were denuded prior to the magmatic activity in the Jurassic. The assumption of a large original thickness agrees with a broad thermal aureole indicating that the sediments were already consolidated at the time of sill emplacement. With our data it cannot be decided whether the background reflectance level (< 0.5 %Rr) was pre- or syn-emplacement of the Jurassic intrusives and volcanics.

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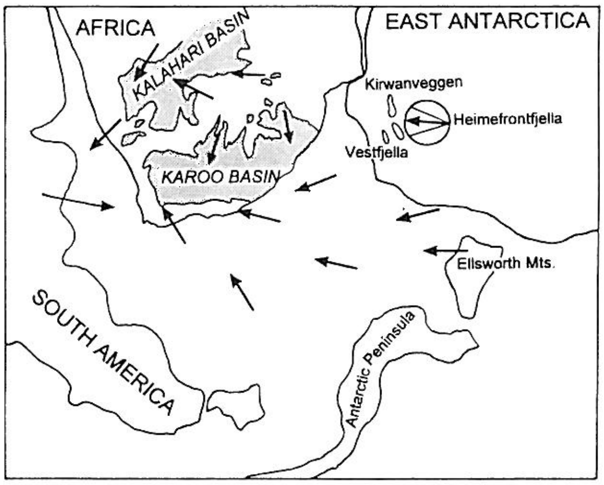

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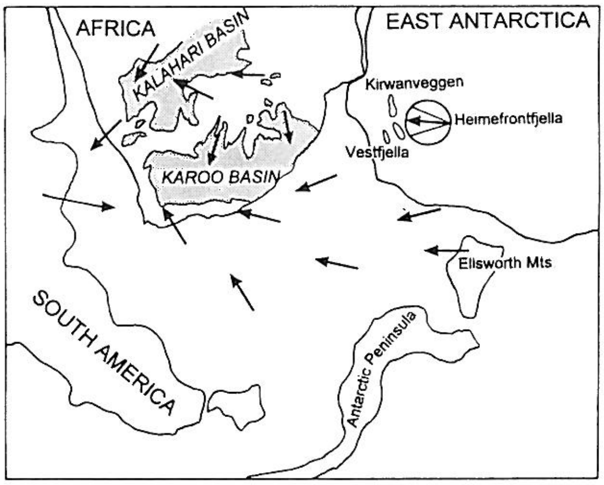

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