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ESSAY ON THE COALIFICATION AND HYDROCARBON POTENTIAL OF THE NORTHWEST EUROPEAN PALAEOZOIC[1]

In memory of THEODOR SORGENFREI (8.12.1915 – 5.11.1972)

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ABSTRACT

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The palaeogeographic knowledge of the European Palaeozoic (Lower Permian, Carboniferous and Devonian) is closely connected with the search for hydrocarbon deposits, because the biggest deposits of natural gas have been found so far in the Rotliegendes (Lower Permian). An extension of these reservoirs into geologically older formations, especially into Upper Carboniferous and uppermost Devonian is expected and systematic exploration investigations are being proposed.

An important tool for this is the research on coalification, which has already resulted internationally in much success and is now used intensively in the European Palaeozoic. This regional-geologic survey points out the current state of knowledge in the palaeogeographic as well as geochemical and coal-petrographic studies.[3]

INTRODUCTION

Between 1939 and 1969 *Theodor Sorgenfrei* regularly published the latest information about the geology at depth in Denmark. From 1951 (GREGERSEN & SORGENFREI) he also included the results of deep drilling in Denmark and the neighbouring Northwest European area, both onshore and offshore, which were important for the exploration of oil and gas. *Sorgenfrei's* untimely death prevented the planned joint publication with him of a modern regional-geologic study of Northern Europe. Therefore the present publication, in the footsteps of and in memory of *T. Sorgenfrei* is to analyse his European field of work from a different scientific angle, together with problems of coalification in the Palaeozoic.

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[3] According to the intention of a regional geological essay, the figures and diagrams included in this paper cannot be discussed in detail in the light of their coalification problems. These are intended as source data, in which all of the relevant scientific results can be found.

[4] The term 'Europe' in this paper includes the northern portion of Central Europe, between Northern France and Poland, and North Europe, offshore and onshore between Britain and the Baltic Sea.

PALAEOGEOGRAPHIC FEATURES OF THE LOWER PERMIAN, UPPER CARBONIFEROUS AND DEVONIAN

The history of the European[4] natural gas fields in the Upper Palaeozoic is closely connected with the palaeogeographical configuration of its formations.

During the *Early Permian (Rotliegendes)* (Fig. 1) Europe possessed a semi-arid to arid climate. The Variscan (Hercynian) Mountain Chain, which had risen during the Carboniferous forming the tectonic framework of Europe to a large extent was subject to intensive denudation and eventual peneplanation. The eroded red material, sands and clays, accumulated in the basins surrounding the former Variscan Mountains (KATZUNG, 1972; LUTZ *et al.*, 1975; FALKE, 1976; PLEIN, 1978). In the north the Central European Basin with its local depressions became especially important in the present programme for hydrocarbon exploration. Ideal conditions existed for the preservation of natural gas fields (good structural conditions and pay horizons, good seal by rocksalt precipitation) between Britain and the continent, including the southern North Sea. The giant Slochteren gas field (Province of Groningen, Northeast Netherlands) was discovered in 1959 and the present important Rotliegendes gas fields were also found here. An intensification and extension of these

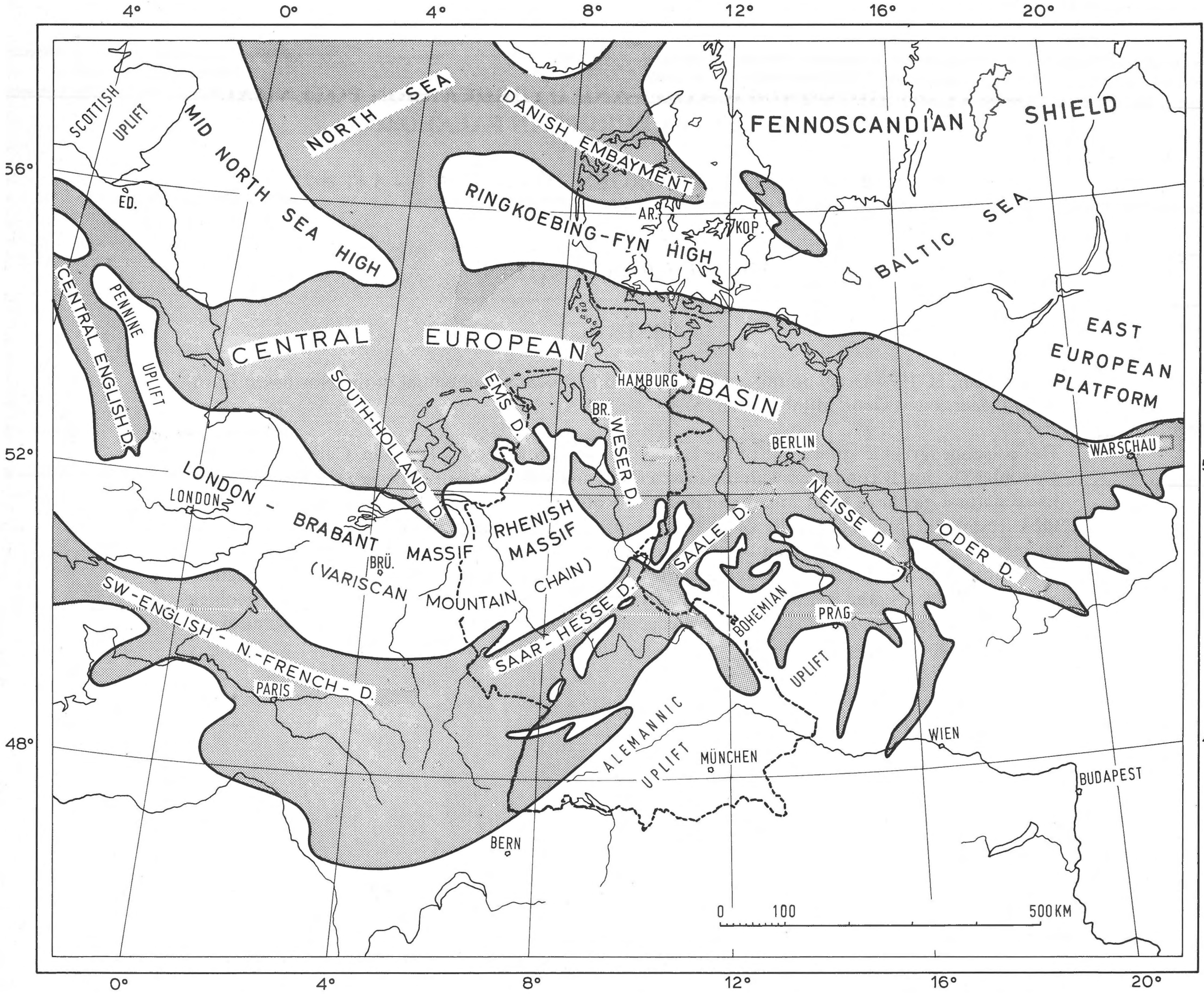

Fig. 1
Distribution of the Lower Permian-Rotliegendes in Europe. Shaded areas = areas of deposition; white areas = areas of denudation; D = depression.
Names of capitals and some other towns are mostly abbreviated and written in German language. ED = Edinburgh, BRÜ = Brussels, AR = Arhus, KOP = Copenhagen, BR = Bremen (Fig. 1); AM = Amsterdam, FR = Frankfort, BRE = Breslau (Fig. 2). Dashed lines: Boundary of the Federal Republic of Germany.

discoveries, especially in an eastern direction to Poland (GURARI *et al.*, 1976; POKORSKI, 1976) and European Russia (ORJOL & SOLOWJOW, 1977), is now being attempted.

The *Upper Carboniferous* (Fig. 2), equivalent to the *Pennsylvanian* in the United States, with its coal seams and shales of marine to freshwater facies, contains the source beds necessary for the Upper Palaeozoic and Lower Triassic gas deposits. The deposition of this rich organic matter took place during a predominantly humid climate in delta-like basins in the foreland of the arising Variscan Mountain Chain (BARTENSTEIN, 1968-a,b, 1979-a,b).

The area of Europe is particularly important as the palaeogeographic configuration of the Upper Carboniferous is similar to that of the Lower Permian-Rotliegendes (Fig. 1 and SCHMIDT & KRULL, 1978).

Intensive investigations of the different coalification ranks of the organic material showed that within the European coal basin with its maximum thickness of up to 5,000 m (16,500 feet) ideal conditions for the generation of natural gas existed. Centres with anthracite rank of coal, especially clear in Germany (Fig. 7) as well as in the British portion of the North Sea, are caused by local structural-geological peculiarities (deep burial, tectonic movements, igneous intrusions, high geothermal gradient: BARTENSTEIN & TEICHMÜLLER, 1974, p. 141-146). They are surrounded by areas of lower coalification, where the discoveries of gaseous hydrocarbons are predominantly concentrated.

The *Devonian* (Fig. 3) is especially known for its areas of

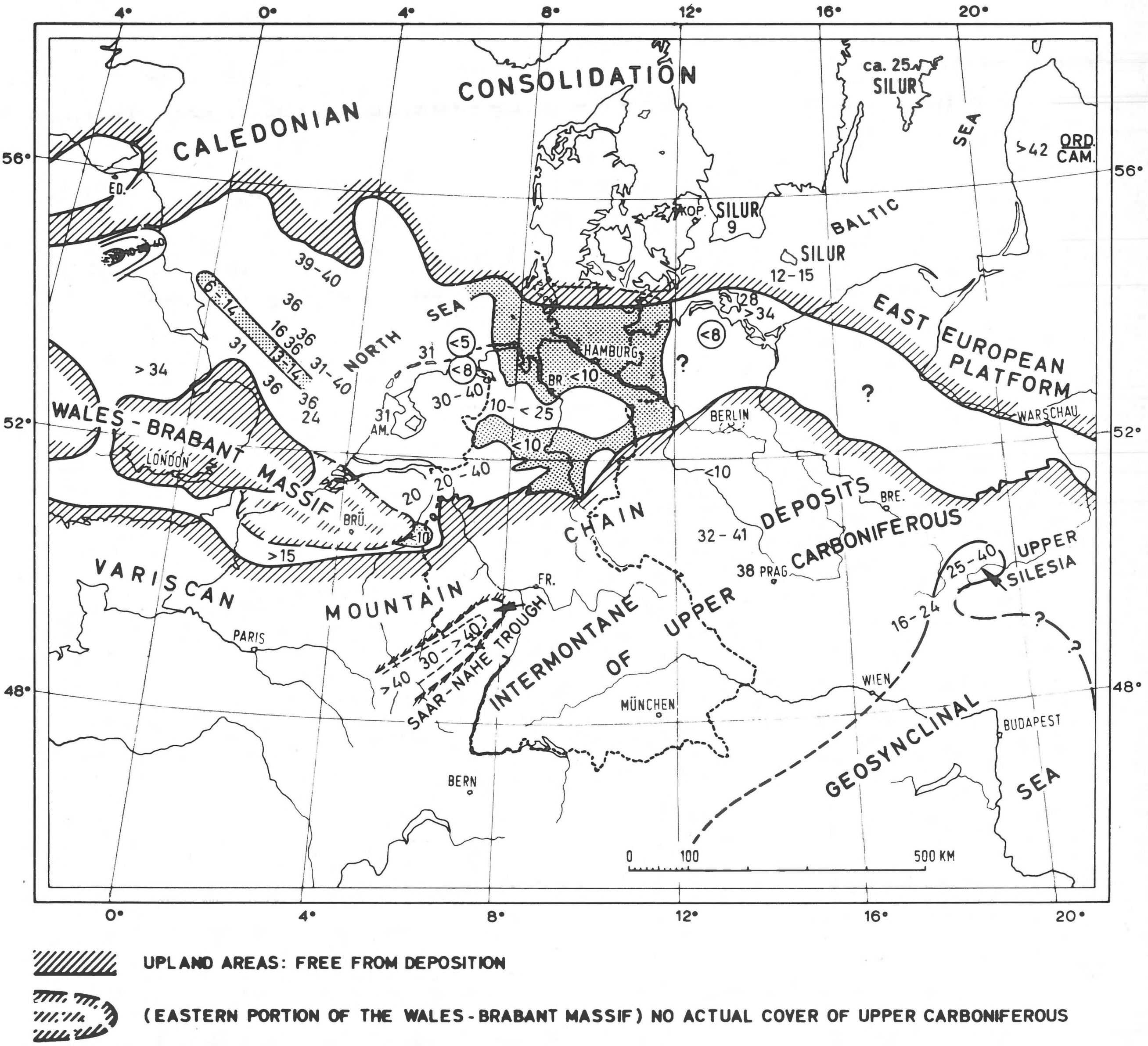

Fig. 2
Distribution of Upper Carboniferous (Pennsylvanian) in Europe, mostly Westphalian time.
Numbers explaining the coalification rank (% volatile matter, dry, ash-free matrix) of the organic material in the Upper Carboniferous. Exceptions: pre-Carboniferous rocks in the north east on the East European Platform.
Dotted fields = anthracite stage in Germany and adjoining parts of the North Sea. Numbers in brackets = locally high coalification rank caused by intrusive rocks of Upper Carboniferous or Lower Permian age. Question mark: Coalification data not available. Letters for towns: see Fig. 1.
Reference level is exposed or drilled Westphalian (below overburden the highest coal or organic shale material).

predominant reef formation. Within the Rhenish Trough, passing through Central Europe and Germany from west to east, potential reservoir rocks may be expected in the higher Middle Devonian and lower Upper Devonian. The exploration of these rocks is in its initial stages as it is to be concentrated on relatively deeply buried Devonian below 6,000 to 7,000 m, where geological data are hardly known as yet. In the German area of investigations relatively high degrees of coalification have to be expected. Important Devonian wells, such as Mühlbach No. 1 (drilled 1954), Münsterland No. 1 (drilled 1962) and Saar No. 1 (drilled 1966), considerably extended our palaeogeographic knowledge about the Devonian, so far gained from exposures of the Rheinisches Schiefergebirge, in the Harz, and from publications about several other deep wells (GOTTHARDT *et al.*, 1978; KREBS, 1975, 1978).

The chances of commercial finds in the Devonian of North-

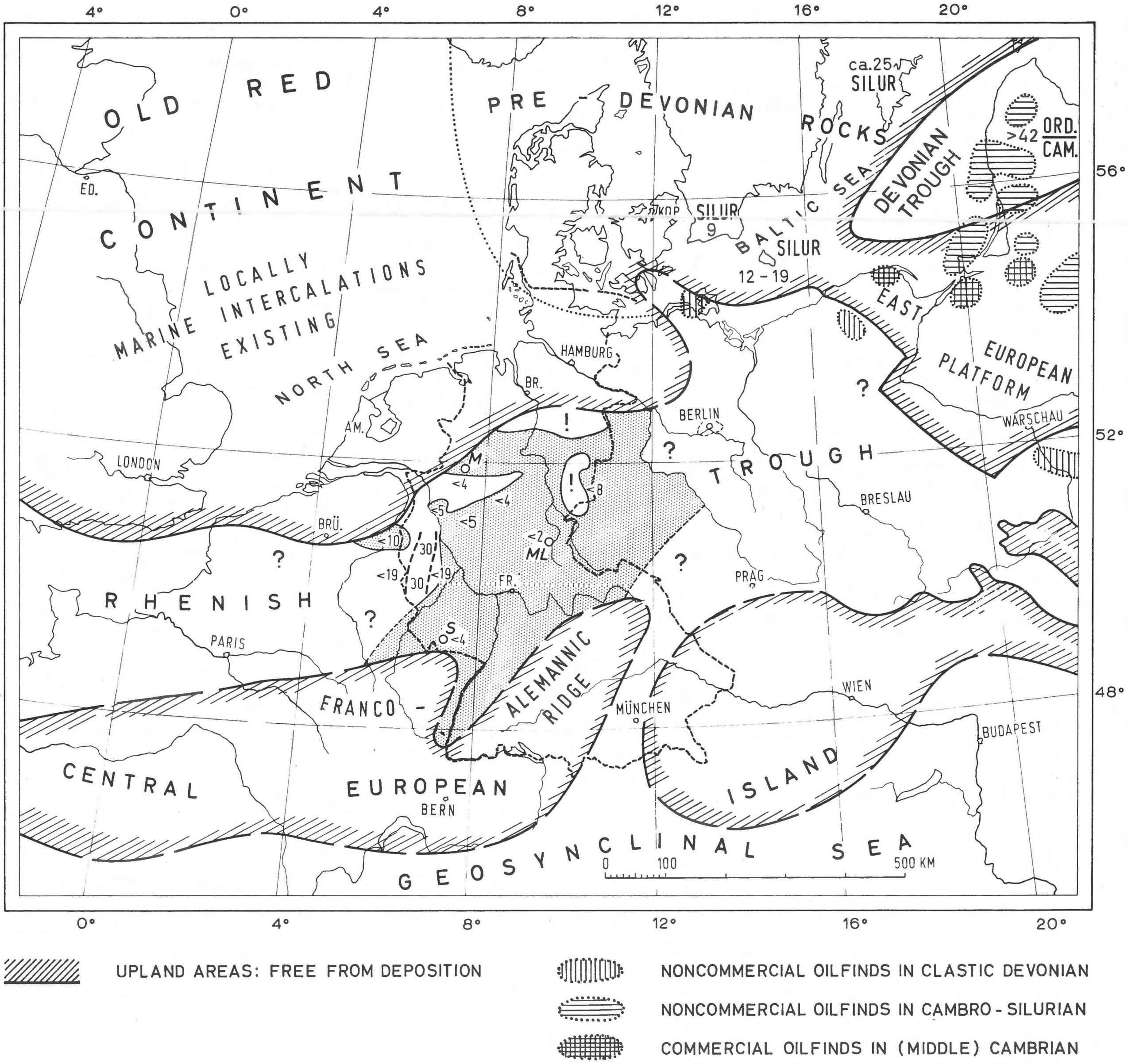

Fig. 3
Distribution of the higher Denovian, the time of the reef formation in Europe.
Numbers explaining the coalification rank (% volatile matter, dry, ash-free matrix) of the organic material in the Devonian or in the pre-Devonian of the East European Platform.
Dotted fields = anthracite stage in Germany and adjoining parts of Belgium and France.
M = well Münsterland 1, ML = well Mühlbach 1, S = well Saar 1.
? = Coalification data not available.
! = Coalification rank in the Devonian of Germany unknown.
Letters for towns: see Fig. 1.

ern Europe, with its Old Red Continent, the East European Platform, and Southern Europe, with its postulated Central European Island, are unlikely or must be regarded as very low. However, between Britain, Northern France (in the west) and Poland (in the east) the hydrocarbon exploration within very deep clastic-sandy and/or reefy Devonian may reach successful results in the coming years, especially in the context of the present energy crisis (BARTENSTEIN & TEICHMÜLLER, 1974, p. 146-153; DADLEZ, 1974; GRIGJALIS ET AL., 1970).

The same applies to an exploration campaign in East Germany (SCHMIDT & FRANKE, 1977). In the deeper part of the North East German Trough, the lithofacies conditions as well as the structural features of the expected Early Carboniferous and/or Devonian limestone reefs under an overburden of more than 7,000 m thickness are highly questionable

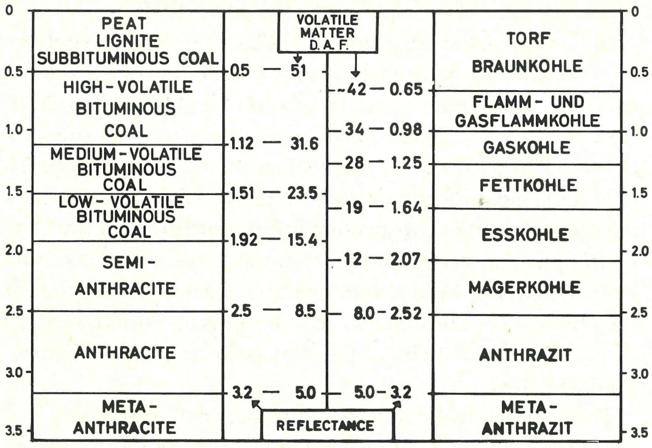

Fig. 4
Sketch chart of a classification of coals according to the degree of coalification by reflectance (% in oil) of the vitrinite component.
Mid: equivalent numbers of volatile matter (% D.A.F. = dry, ash-free matrix) and of reflectance (% in oil).
Left: American nomenclature. Right: German nomenclature.
Upper and lower limit of the German Magerkohle (12 and 8% volatile matter daf) furthermore under discussion: other values = 14 and 10% volatile matter daf resp. 1.92 and 2.23% R_{OIL}.

(FRANKE, 1978)[5].

RELATIONS BETWEEN THE COALIFICATION RANK AND THE DISTRIBUTION OF HYDROCARBON DEPOSITS

Investigations in the field of coalification over many years, especially in the laboratories of the USA, the USSR and in Germany, have enabled a general synthesis to be made of the different scientific opinions (TEICHMÜLLER & TEICHMÜLLER, 1966).

Thus today the *classification of coals* according to the degree of metamorphism is agreed upon to a considerable degree (Fig. 4). The numbers, whether based on volatile matter (% dry, ash-free matrix = D.A.F.) or on mean average reflectance (% in oil), now permit the standardization of coalification maps and charts (HOOFD ET AL., 1975; MCCARTNEY & TEICHMÜLLER, 1972).

All coalification is connected with gas separation. Laboratory investigations over many years have sufficiently clarified the details of this gas separation (JÜNTGEN & KARWEIL, 1966). During the whole process of coal metamorphism changing portions of carbon dioxide, nitrogen, water and

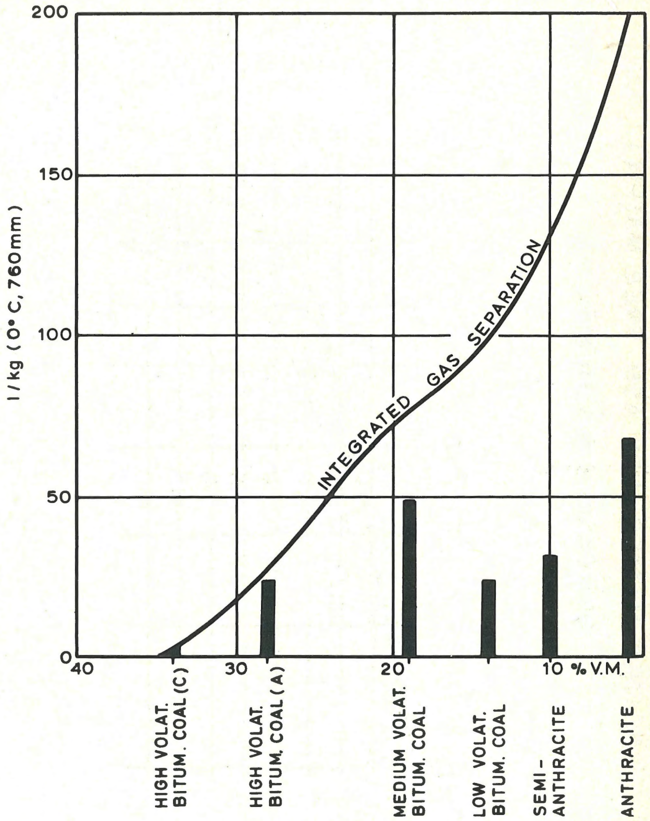

Fig. 5
Formation of methane during coalification in the different rank stages of bituminous coals and anthracites.
Abscissa: length of gas columns indicates amount of methane at specific coalification stage (high volatile bituminous coal through anthracite). Ordinate: shows the generated methane in litres per kg and m^3 (Vn) per ton, respectively, of coal. After Jüntgen & Karweil, 1966.

methane are separated together with small amounts of heavier hydrocarbons.

In younger coals predominantly carbon dioxide is released, which may leave the seams when dissolved in water. Nitrogen in contrast to this is enriched during the early coalification stage, but later, in higher coalification stages (less than 35% of volatile matter, dry, ash-free matrix) nitrogen diminishes again in the same percentage as methane increases (Fig. 5). About 33% of the entire methane generated during the metamorphism of coal (= right column of figure 5) is produced during the anthracite stage, which means that *in the highest coalification stages especially important amounts of pure methane can be expected.*

During the higher coalification stages gaseous hydrocarbons become even more difficult to accumulate, because the net porosity of the reservoirs is related to the metamorphism of the rocks and decreases steadily with depth, as shown in figure 6. This figure is calculated for *sandstones* within the Northwest German sedimentary basin and may not be valid in other basins. In Germany it is locally subjected to certain variations due to special tectonic and structural conditions.

[5] Source rock and hydrocarbon possibilities in the Palaeozoic, especially in Devonian, Upper Carboniferous and/or Lower Permian-Rotliegendes reservoir horizons, have been discussed in various papers of the two North Sea conferences in Bergen, Norway, December 1973 (WHITEMAN ET AL., 1975) and in London, Great Britain, November 1974 (WOODLAND, 1975).

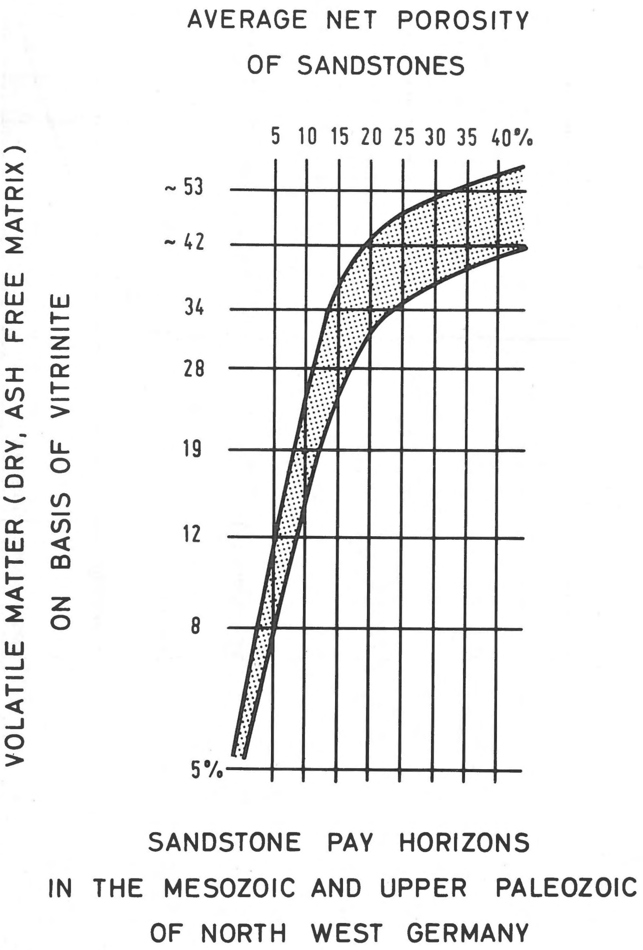

Fig. 6
Estimated decrease of the net porosity of sandstones during the coalification process in Mesozoic and Upper Palaeozoic rocks of North West Germany.

Limestone and dolomite reservoirs, of course, *will behave differently.* Figure 6, however, is shown in order to point out the presence of low porosities in reservoir rocks present at a time (or depth) when (where) high coalification stage gas accumulates.

Coalification investigations on the Palaeozoic formations of the Rheinisches Schiefergebirge outcropping onshore (PAPROTH & WOLF, 1973), as well as in deep wells in its northern foreland, and also in deep offshore wells in the North Sea have been systematically carried out for several years. They provide the determinations of the degree of coalification, the increase of coalification with depth and the *geothermal gradient* of the rocks (EVANS & COLEMAN, 1974; CORNELIUS, 1975, p. 29-67; GINDORF & PÄTZ, 1977).

The calculated sequence of the *organic maturity zones,* the concept of the *cooking time,* and the *palaeotemperature* analyses (COOPER *et al.,* 1975, p. 487-492) of a distinct area are important, and document modern techniques both in appraising the presence of source rocks and in evaluating the hydrocarbon potential at greater depths (BARTENSTEIN & TEICHMÜLLER, 1974, p. 131-137; LUTZ *et al.,* 1975).

In *Germany* there are already sufficient published geological data available to show the *actual distribution of the anthracite rank in the Palaeozoic* in relation to the distribution of gas fields (Fig. 7). In the north, where the Carboniferous lies below 6,000 to 7,000 m, the coal substance may already be degassed and the pore-volume already reduced to such a degree that further prospecting for hydrocarbons in the Carboniferous and pre-Carboniferous pay horizons seems to be risky. Of course, local exceptions from a general temperature distribution (or carbonates) may be present (GOTTHARDT ET AL., 1978; KREBS, 1978; TEICHMÜLLER ET AL., 1979; BARTENSTEIN, 1979-a).

The same is valid for the area between Hannover and Emsland, where the Palaeozoic in the core of the *Bramsche Massif* has already been heated to such a degree by an igneous body that its *sandstone* reservoirs can be assumed to have become tight and impermeable (Fig. 6). It also appears that in this extremely high anthracite stage a sufficient shaly seal is missing. Here again exploration for hydrocarbons in the Carboniferous and pre-Carboniferous appears to be risky, even if relatively favourable palaeogeographic conditions might be present (BARTENSTEIN ET AL., 1971).

CONCLUDING REMARKS

The methods of coalification investigations, which originated and were first checked onshore, were subsequently extended and confirmed offshore. They are now applied generally throughout the Palaeozoic of the Northwest European Basin in an intensification of hydrocarbon research (USPENSKAJA, 1976).

So far neither the experience in regional geology and palaeogeography (Figs. 1-3) nor that in geochemistry and coal petrology (Figs. 4-7) have been able to be fully utilised. The area between the Atlantic and the East European Platform with a west-east distance of more than 2,500 km is too vast and the knowledge of the source-bed parameters and the structural conditions for reservoir rocks in the subsurface is still too scarce.

Regional scientific cooperation beyond national boundaries is now urgent for petroleum exploration in the Palaeozoic in Europe (WHITEMAN ET AL., 1975; WOODLAND, 1975). This means for example taking the Upper Carboniferous (Fig. 8) and being able to map the distribution of its individual formations from Germany to Britain in the west, and to the East European Platform in the east, *using a unified stratigraphical nomenclature.* When extended to the over- and underlying strata (Lower Permian, Lower Carboniferous and Devonian), such an investigation could give an important impetus to petroleum geology. This really would be in the spirit of the late *Theodor Sorgenfrei* whose geological perspectives always reached beyond the Danish Embayment, the Scandinavian sedimentary basins and the North Sea, to comprise the whole of Northern Europe.

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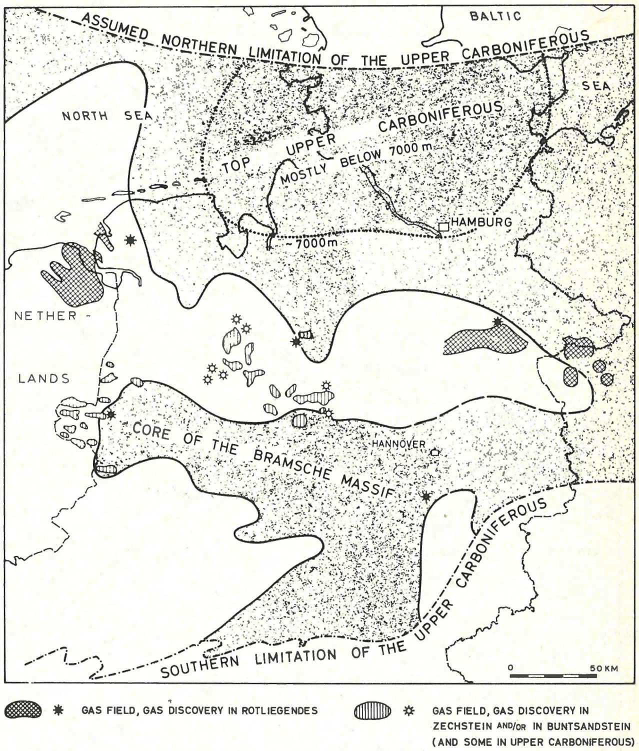

Fig. 7
Actual distribution of the anthracite rank in the German Palaeozoic in relation to the distribution of gas fields. Dotted areas = anthracite stage with less than 10% of volatile matter (daf) including non-prospective and speculative areas for Carboniferous and older hydrocarbon reservoirs.

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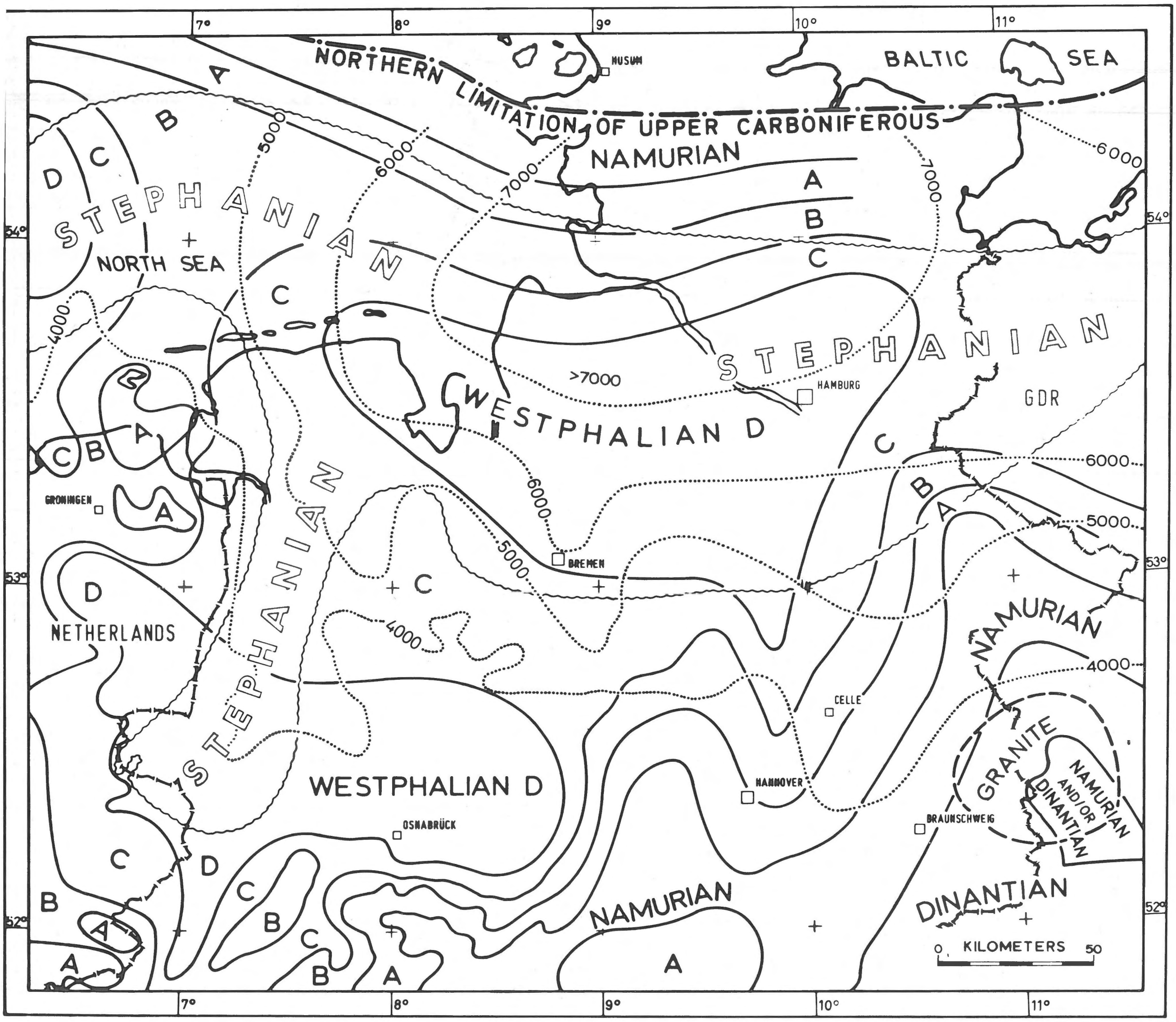

Fig. 8

Distribution and depth of the Upper Carboniferous units onshore on the Continent between Netherlands and Germany. 4000, 5000, 6000, 7000, > 7000 = depth in metres below sea level. D, C, B, A = Westphalian D to A. In the southwestern part of the map (Westphalian, Ruhr region) limits of the Carboniferous units more simplified. Contour lines according to published data of the Dutch and German petroleum industry.

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