GEOLOGIE EN MIJNBOUW© 1980 VOLUME 59 (1), p. 3-24

THE ROTLIEGEND IN THE NETHERLANDS AND ITS GAS ACCUMULATIONS[1]

D. H. VAN WIJHE[2], M. LUTZ[3] & J. P. H. KAASSCHIETER[3]

ABSTRACT

Van Wijhe, D. H., M. Lutz & J. P. H. Kaasschieter 1980 The Rotliegend in The Netherlands and its gas accumulations – Geol. Mijnbouw 59: 3-24.

The Rotliegend in the Dutch part of the Mid-European Basin contains recoverable gas reserves of at least 2.1 × 10^{12} m^3. A combination of the following favourable conditions is the cause of these prolific accumulations:

(1) up to 2500 m of Late Carboniferous coal-bearing strata form excellent source rocks for gas;
(2) burial of these source rocks to depths of 4000-6000 m has led to generation of methane over a wide area;
(3) excellent reservoirs in aeolian and alluvial Rotliegend sandstone are present, often not adversely affected by diagenesis;
(4) favourable sealing qualities are offered by Zechstein evaporites;
(5) abundant structural traps occur, often formed before the main gas-generation periods.

INTRODUCTION

Only some 15% of the Mid-European Rotliegend Basin is situated within The Netherlands and the Dutch North Sea. Yet, this portion contains some 60% of the total gas reserves, viz. 2.1 × 10^{12} m^3 of the total of 3.6 × 10^{12} m^3. Some 95% of the Dutch portion is contained in Groningen, one of the largest gas fields in the world.

The present paper attempts to summarize and review geologic data which have been acquired over the last 15 years, largely as a result of hydrocarbon exploration. Much of the data presented here has been published earlier. In a former review paper (LUTZ ET AL., 1975) the basic parameters which control the Rotliegend gas accumulations in the basin as a whole were discussed. The present paper concentrates on the Dutch part of the basin, and incorporates some new data.

THE ROTLIEGEND BENEATH THE NETHERLANDS AND THE DUTCH PART OF THE NORTH SEA

General

The Netherlands and the Dutch North Sea cover a slice of the Mid-European Permo-Triassic basin some 200 km wide from its southern to its northern edge, and up to 270 km in an east-west direction, i.e. parallel to the axis of the basin. The Permian basin fill consists of the Rotliegend, a continental sequence of clastics and evaporites over 600 m in thickness, overlain by up to 1000 m of marine evaporites and carbonates of the Zechstein. The Permian strata rest unconformably on Upper Carboniferous and older formations. The Late Carboniferous Coal Measures were the source of the gas trapped in Rotliegend sandstones. Zechstein evaporites form the seal for practically all of the Rotliegend gas accumulations.

The Basin floor

The subcrop map below the Permian reflects the geological configuration at the end of the Carboniferous (Fig. 1). A central area of thick Late Carboniferous (Westphalian to Stephanian) deposits is flanked to the south by the London-

---

[1] Manuscript received: 1979-11-19.
Revised manuscript received and accepted: 1980-01-15.
[2] Nederlandse Aardolie Maatschappij B.V., Postbus 28, 9400 AA ASSEN, The Netherlands.
[3] Shell Internationale Petroleum Maatschappij B.V., Postbus 162, 2502 AN DEN HAAG, The Netherlands.

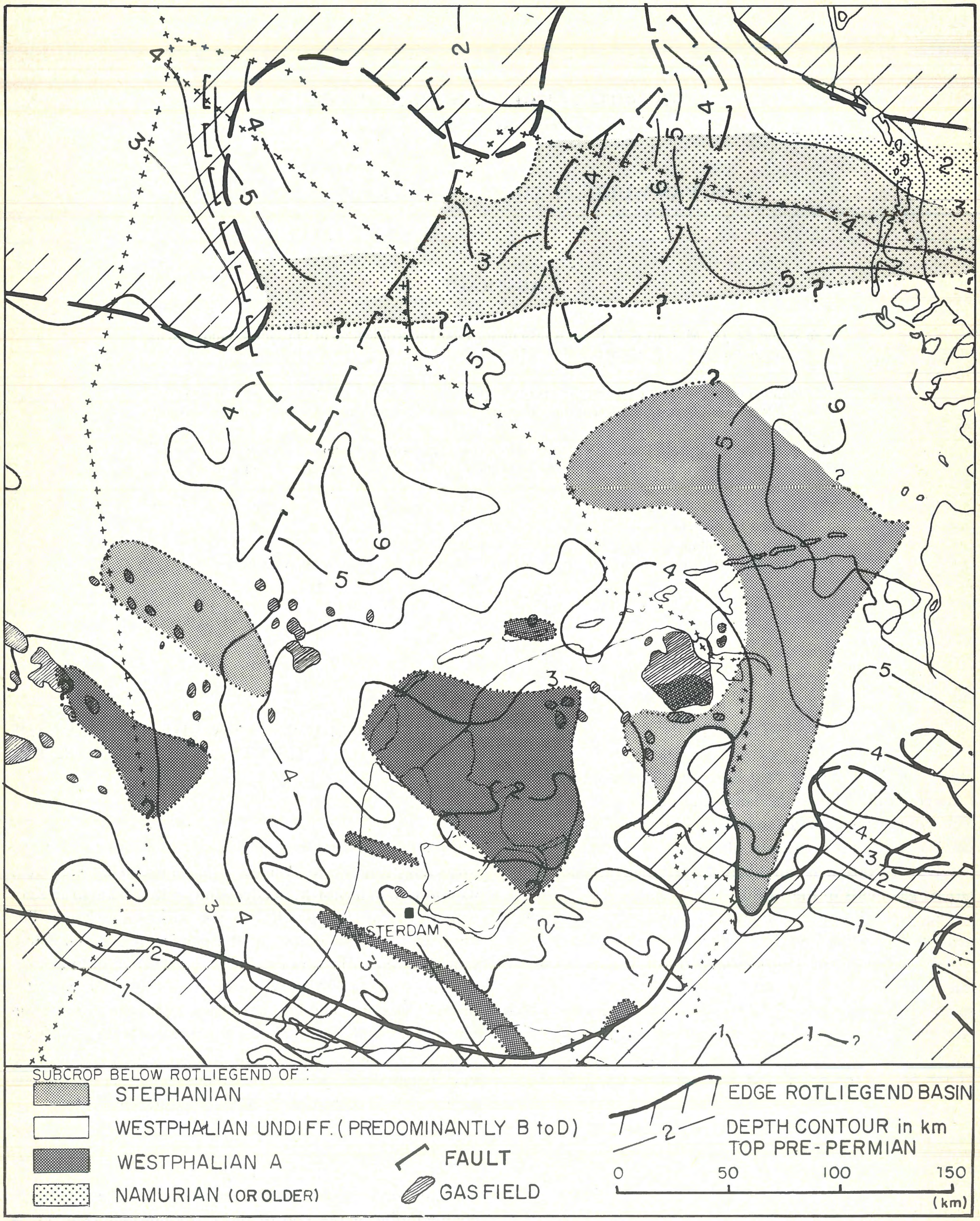


Fig. 1
Floor of the Rotliegend Basin.

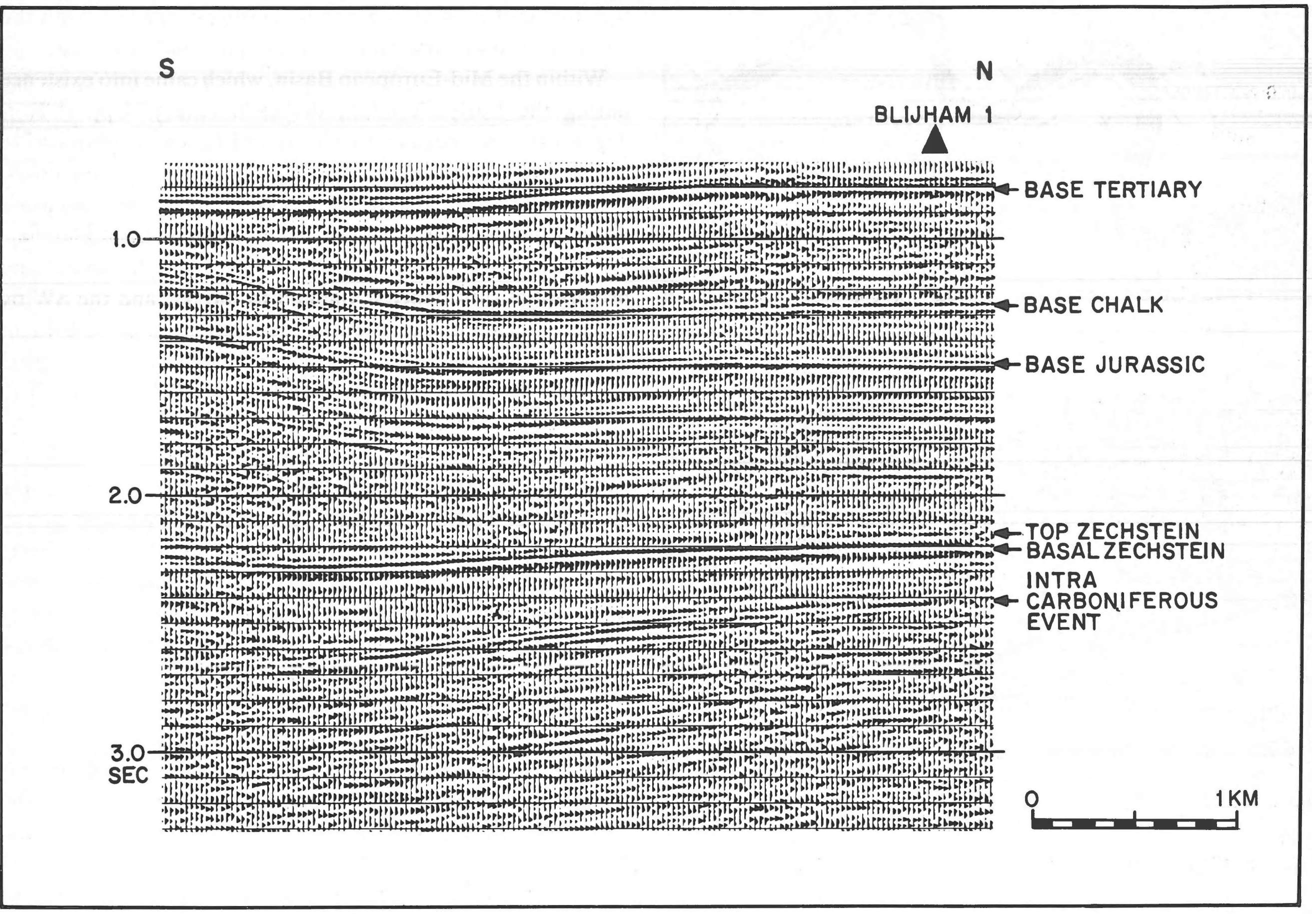


Fig. 2
Seismic section on the eastern flank of the Groningen High showing unconformable relation between Permian and pre-Permian strata.

Brabant Massif and to the north by an east-west striking high of pre-Late Carboniferous rocks.

The total thickness of the coal-bearing Upper Carboniferous (Productive Measures) may be as much as 2500 m (FABIAN, 1971). The Productive Measures may in places be recognized on modern seismic lines as an interval with numerous discontinuous reflections below a seismically transparent unit representing the Westphalian D to Stephanian red shales (Barren Measures). Only in the eastern Netherlands was a subdivision of the Westphalian to Stephanian sequence into correlatable litho-units possible (NAM & RGD, 1979). Regional studies suggest that the Late Carboniferous deposition was interrupted by uplift in most areas towards the end of the Westphalian (HAUBOLD & KATZUNG, 1972). The ensuing Late Variscan tensional movements led to the subsidence of trough- or graben-like elements, which became major depocentres in the Stephanian and early Permian. One of these troughs, the N-S trending Ems Low, played an important role in the subsequent tectonic and depositional development of the area. These movements, and the accompanying deposition in the troughs and erosion on the uplifted areas, resulted in the illustrated distribution of the Carboniferous strata below the Upper Rotliegend (Fig. 1).

The map is based essentially on palynological datings of the highest Late Carboniferous strata encountered in wells. Only in exceptional cases can the pre-Permian unconformity be established by lithological and log correlation of the Late Carboniferous sequence or be recognized on seismic sections (Fig. 2).

Stratigraphy

General – The Rotliegend of The Netherlands is a lithostratigraphic unit of essentially Early Permian age. It consists mainly of clastics; volcanics occur locally in basal layers, and evaporites in the basin centre. The Rotliegend overlies unconformably the Carboniferous, and is conformably overlain by the Zechstein. Zechstein sedimentation started in most cases with the Copper Shale, which is interpreted as an approximately isochronous layer, and said to be situated just above the Early/Late Permian boundary (HAUBOLD & KATZUNG, 1972). Within the limits of the Mid-European Basin, the Rotliegend sedimentation began with the deposition of volcanic and volcanoclastic strata in restricted areas (Fig. 3). In the Federal

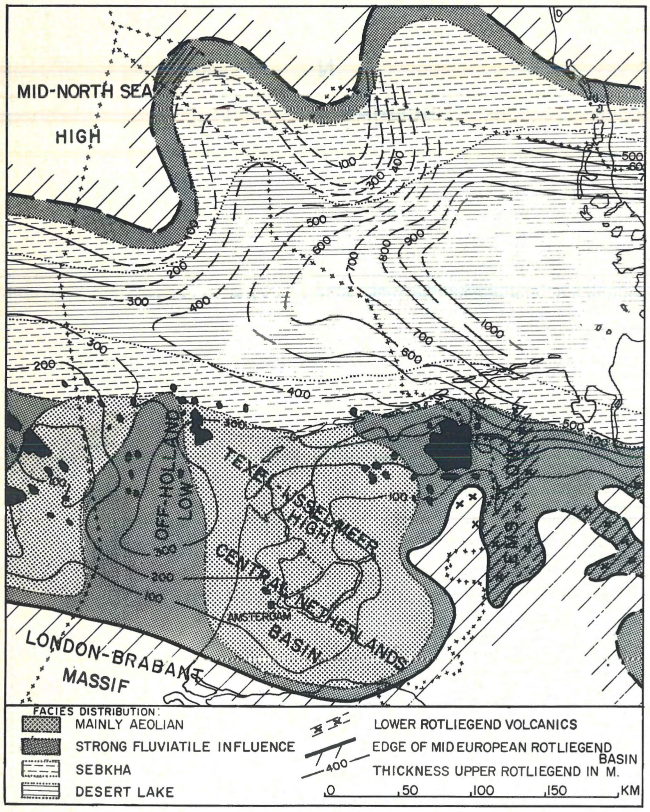


Fig. 3
Upper Rotliegend facies distribution.

Republic of Germany, the volcanic, so-called 'Lower' Rotliegend reaches its greatest thickness in trough-like depocentres (PLEIN, 1978). Rapid thickness variations at the edges of these troughs suggest depositional control by synsedimentary faulting. These faults may have been avenues for the ascent of igneous material which was either intruded into pre-Permian rocks or extruded onto the eroded Carboniferous surface. Such volcanic strata in the basal part of the Rotliegend are also in The Netherlands called 'Lower' Rotliegend. They are only known from wells in the eastern part of the country in an area adjacent to the Ems Low (Fig. 3), and increase in thickness from west to east towards this low (e.g., from 11 m in Exloo-2 to 80 m in Emmercompascuum-1 [4]). Basic dykes and sills have been found in many wells in the Productive Measures of the eastern Netherlands, and are thought to be related to this Early Permian volcanic activity (VAN WIJHE ET AL., 1974).

In general, however, the Rotliegend in The Netherlands does not contain volcanics at its base, and is therefore assigned to the sedimentary 'Upper' Rotliegend. Yet, the Lower Slochteren Sandstone of the Groningen area (see below) contains in its conglomerates numerous basic volcanic pebbles and lithoclasts (DE BOOY, 1968). It can therefore not be excluded that this unit is at least partially contemporaneous with the volcanic strata of the more eastern and southern areas.

Within the Mid-European Basin, which came into existence during the Early Permian, the sedimentary 'Upper' Rotliegend shows a regular thickness and facies distribution. In detail, however, subsidiary structural features are recognized, e.g. the Off-Holland and Ems Lows. Some of these persisted throughout the geological history of the basin. In The Netherlands a NW-SE striking zone of increased thickness and preferential subsidence is flanked to the NE and the SW by similarly trending highs. These elements were again evident during the Late Jurassic-Early Cretaceous as the Central Netherlands Basin, the Texel-IJsselmeer High and the Brabant Massif, respectively (HEYBROEK, 1974).

Environment of deposition and facies distribution of the 'Upper' Rotliegend sediments – Rotliegend deposition occurred under semi-arid to arid climatic conditions (GLENNIE, 1972). In the basin, a sequence of clays and evaporites (essentially rock salt) was deposited in a desert-lake environment. These lake deposits are up to 1500 m thick in the southeastern corner of the North Sea and adjoining land areas (KATZUNG, 1972; TRUSHEIM, 1971) (Fig. 3). The origin of the salt has been a debatable point for the last decade (FALKE, 1976).

Marine influences are restricted to the uppermost few metres of the Rotliegend and are thought to be related to the Zechstein marine ingression (PLUMHOFF, 1966; VAN VEEN, 1974).

These desert-lake sediments are fringed in the south, and to a lesser degree in the north, by sandstones and minor conglomerates which form the major reservoirs for the Rotliegend gas accumulations. Within this coarse clastic belt three main facies realms are distinguished (Fig. 3):

(1) Alluvial sands and conglomerates occur at the basin margin and were introduced into the basin by wadis. In the northeastern Netherlands a transport direction from south to north is deduced from the decrease in both pebble size and thickness of conglomeratic beds (STÄUBLE & MILIUS, 1970). In two north-south trending zones of pronounced Permian subsidence, viz. the Off-Holland and Ems Lows, the percentage of alluvial sandstones is particularly high. Large areas of the hinterland were apparently drained by extensive wadi systems which carried coarse clastics far north into the basin, via these depressions.

(2) Aeolian sands are common along the Dutch and British parts of the southern basin edge due to particularly effective reworking of alluvial sands by wind. This was caused by the interplay of the northward heading drainage system and the west to southwest directed Permian trade winds on this NW-SE trending edge. Extensive dune fields developed, and between the alluvial fans the Rotliegend section mainly consists of aeolian sands.

(3) Sebkha deposits, fine-grained sands and silts, characterize the inner, basinward edge of the sand belt. Sand percentages decrease rapidly towards the basin. Furthermore, the sebkha

---

[4] For the location of wells quoted see figure 5.

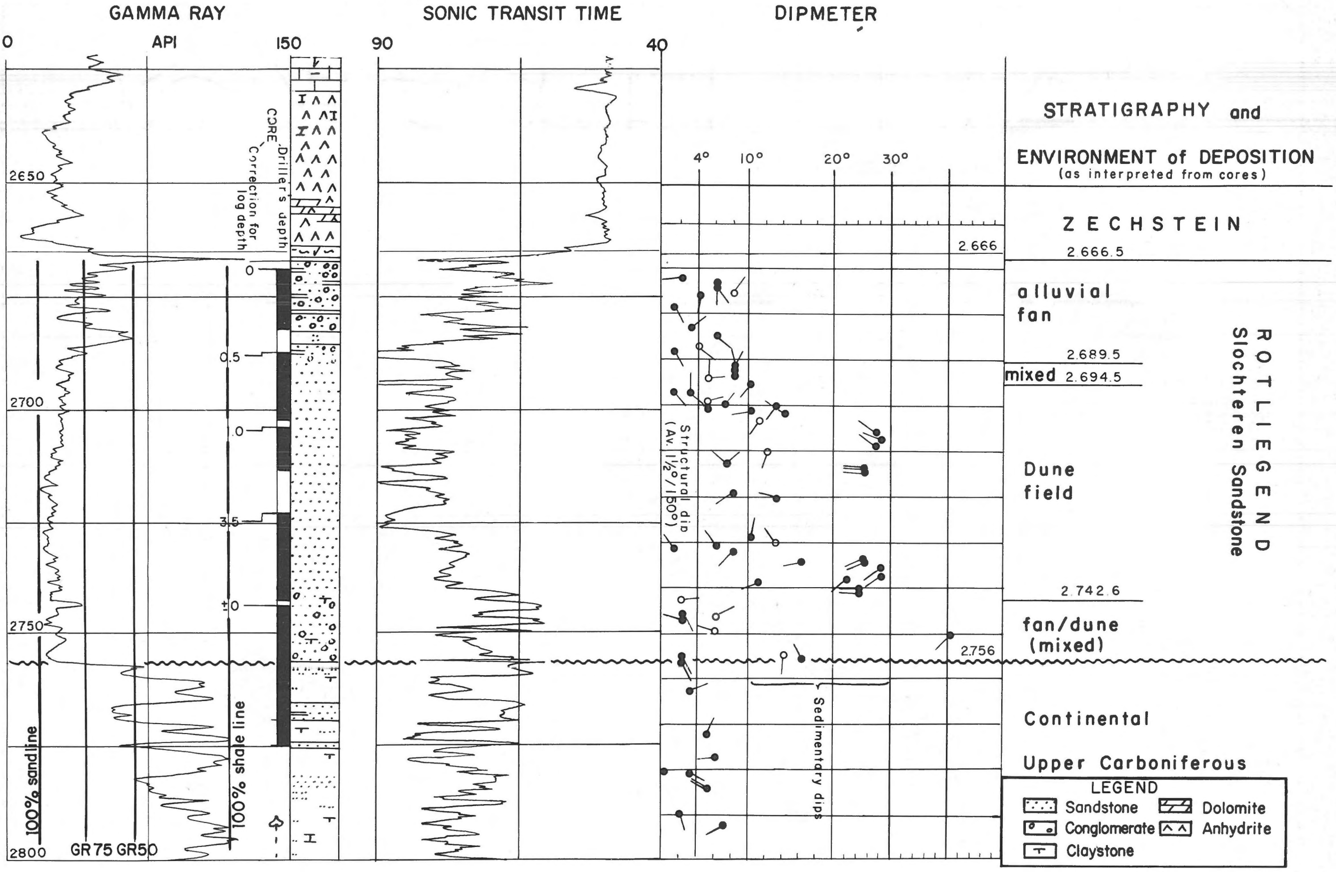


Fig. 4
Lithology, log response and environment of deposition in the Upper Rotliegend of Appelscha-1.

sands are often strongly carbonate-cemented during early diagenesis.

The above subdivision into sediments deposited in different environments was first established on a large number of continuously cored sections, and corroborated by sedimentological studies of Recent arid environments. The general results of these studies have been discussed by GLENNIE (1972), and are in line with a petrographic investigation of a large number of samples from the greater Groningen area (DE BOOY, 1968) which showed a difference in provenance for the fluviatile and the aeolian strata.

The fluviatile intervals s.s. are characterized by a sedimentary and epimetamorphic assemblage of rock fragments and minerals which, on regional grounds, indicate a southern source area. Intervals dominated by aeolian deposits on the other hand, contain more plutonic and higher-grade metamorphic rock fragments and minerals. These components are assumed to be derived from an eastern source.

The continuously cored and sedimentologically interpreted sections have been used to calibrate the petrophysical logs in terms of lithology and environment of deposition; subsequently, thicknesses of the various sand types described could be determined in all wells and their lateral distribution mapped.

The example of the well Appelscha-1, SW of the Groningen gas field, shows how rock type and environment of deposition may be recognized with the help of wireline logs (Fig. 4). Within the Rotliegend, sandstones may be easily differentiated from shales by means of the gamma-ray log. The aeolian sands, which are more porous than the fluviatile sands due to their better sorting, show somewhat higher interval transit times (lower sonic velocities) than the fluviatile intervals. Within the aeolian intervals, the continuous dipmeter log shows the high (10° – 30°) depositional dips of the aeolian sands which had been observed in the cores. Moreover, not only the foresets as such are recognizable on the dipmeter, but also their direction, which cannot be measured on conventional cores. The dip direction of these foresets, which indicates the transport direction of the Rotliegend dune fields, is, within the area discussed here, predominantly towards the west (Fig. 5). Similar foreset directions are reported from the Rotliegend of the British North Sea (VAN VEEN, 1975), from several basins onshore (SMITH, 1972), from the Permian Walkenried Sandstone south of the Harz Mountains (F. R. of Germany, RICHTER-BERNBURG, 1955), and from the Rotliegend of the Magdeburg area (German Democratic Republic, SCHREIBER, 1960).

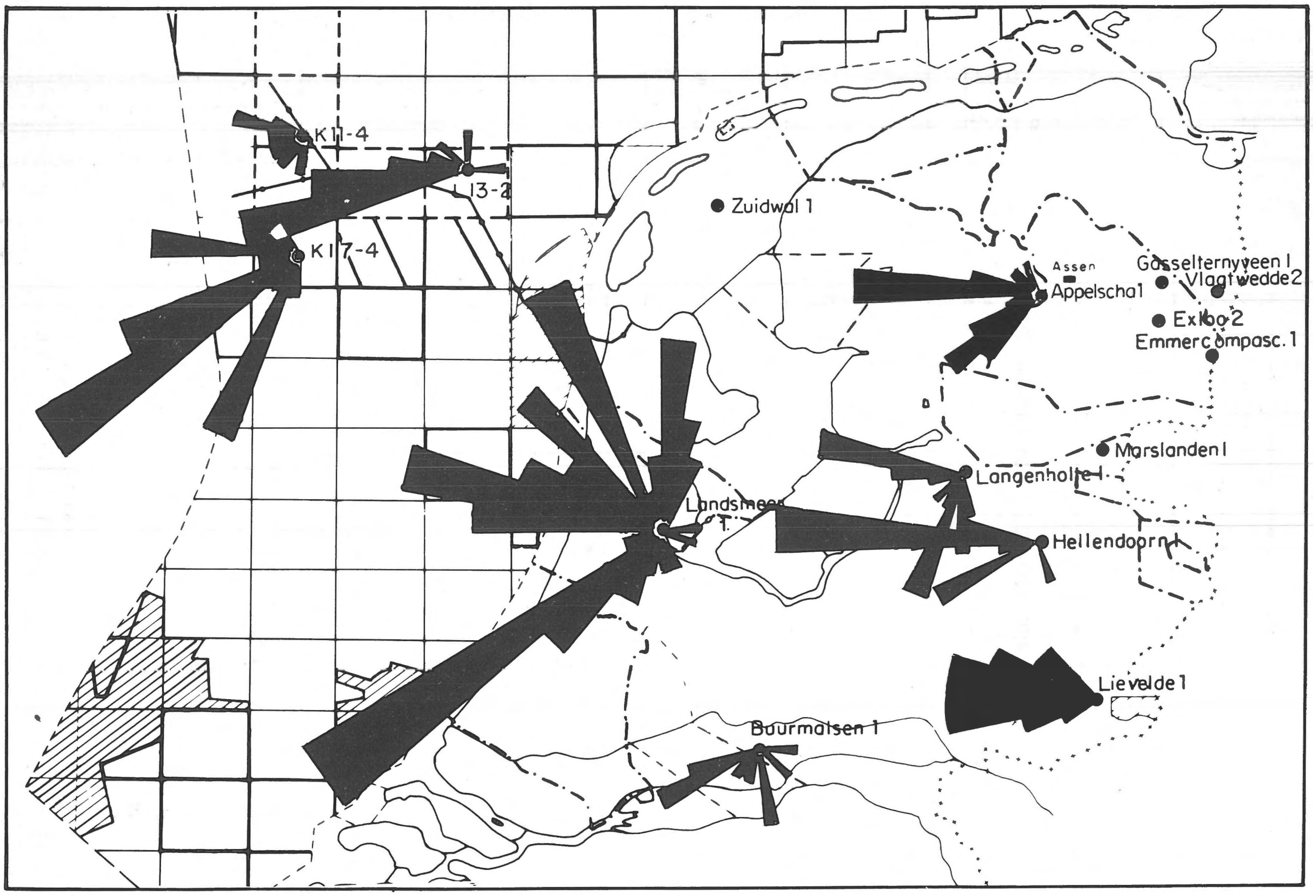


Fig. 5
Aeolian transport directions.

Stratigraphic subdivision of the Rotliegend – Early in the development of the Groningen field, the sedimentary Upper Rotliegend was subdivided into the Ten Boer and Slochteren Members (STÄUBLE & MILIUS, 1970).

In the meantime, this subdivision has been extended and amended to cover the whole Dutch part of the basin and is schematically represented in figure 6. The boundaries between the sandstone and claystone members are defined at the transition from one dominant lithology into an other (e.g., from > 50% sandstone into > 50% claystone). The top and bottom of the Rotliegend evaporites are defined by the highest and deepest occurrences of evaporite layers. As a consequence, the boundaries between members are largely diachronous.

The alternation of sandstone and claystone members in the northern part of the sand-belt reflects changes of transport energy in the hinterland, probably caused by climatic changes or tectonic movements which have been effective on a regional scale. A log correlation from the mainly fluviatile Off-Holland Low to Groningen (Fig. 7) indicates that a similar rock sequence is present in both areas. If the assumption that the lithological alternations are controlled by a regionally effective mechanism is correct, these log correlations –which run more or less parallel to the iso-facies lines– may be regarded as nearly isochronous. Figure 8 indicates that the alternation of high- and low-energy deposits (as reflected by the gamma-ray log) can also be traced in a north-south direction (VAN ADRICHEM BOOGAERT, 1974). Gamma-ray log correlation shows, moreover, that the thicknesses of log units remain rather constant over appreciable distances. The thickness variations of the complete Rotliegend, which are much stronger than those of any one individual unit, are caused by the addition of new units at the base of the sequence in the more basinward sections.

When comparing the 'Lower' volcanic with the 'Upper' sedimentary Rotliegend it has been shown that the younger unit oversteps the older, and is not only much more extensive but also more uniform in thickness. This is also true for the nearly isochronous log units mentioned above within the sedimentary Upper Rotliegend: the younger they are, the more extensive and uniform in thickness they are.

Age – In the Dutch territory, fossil control on the age of the 'Upper' Rotliegend is completely absent and no direct time designation is therefore possible. However, for the general western European region it is assumed in literature that the

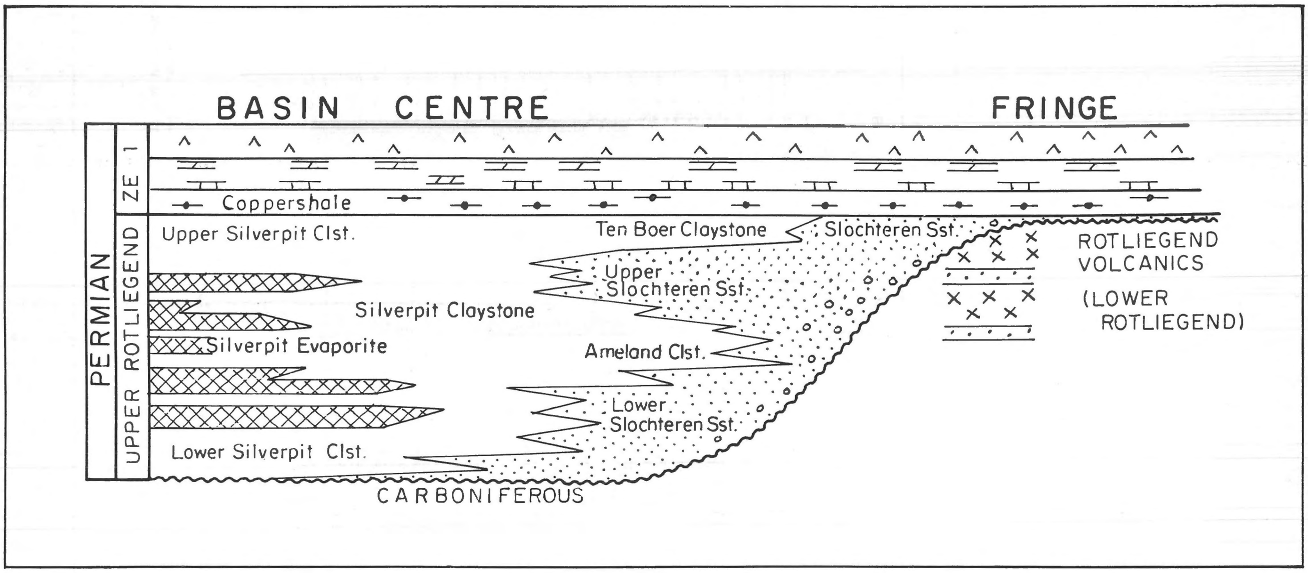


Fig. 6
Rock stratigraphic diagram of the Rotliegend.

Upper Rotliegend is of Saxonian age, i.e. post-Autunian and pre-Thuringian.

The time-stratigraphic position of the Autunian, often equated with the 'Lower Rotliegend', is not well-established. Generally it is considered as the oldest stage of the Permian, but palaeobotanical evidence from the type area in Central France suggests a Carboniferous affinity (JONGMANS & PRUVOST, 1950).

The Saxonian is very poorly defined on palaeontology. Only tetrapod footprints seem to offer diagnostic fossil data (HAUBOLD & KATZUNG, 1972).

The Thuringian refers to the Zechstein as a timerock unit, although fossils of Zechstein-type have also been found in the uppermost beds of the Rotliegend in some localities in NW-Germany (PLUMHOFF, 1966). These fossil occurrences are best interpreted as the first indications of the 'Zechstein'-ingression into the salt lake of the Upper Rotliegend and do not necessarily indicate the Saxonian-Thuringian boundary (viz. the Early/Late Permian boundary) to be located in the top part of the Rotliegend.

Absolute age determinations have been carried out on various igneous rocks of Permian age in NW Europe. These data suggest for the Upper Rotliegend and Zechstein a time-span of some 15.10^6 years (-240 to -225.10^6 years; FALKE, 1972).

The structural development of the Dutch part of the Mid-European Basin

Early Permian structural configuration – In a basin filled with a layered, onlapping sequence as described above, thickness variations broadly reflect the structural configuration at the beginning of deposition, i.e. here at the start of Rotliegend deposition.

The Upper Rotliegend thickness distribution in the southern sand belt is shown in figure 9. Exploration for gas in the Rotliegend of The Netherlands is concentrated on the southern, aeolian-fluviatile and sebkha area. The postulated northern rim is therefore virtually unknown, and will not be treated here. The map shows the general WNW-ESE trend of the southern flank of the basin.

In detail, however, a number of subsidiary highs and lows can be distinguished (Fig. 9), viz.:
(1) the approximately N-S Indefatigable High;
(2) the NNE-SSW Off-Holland Low;
(3) the NW-SE Texel-IJsselmeer High;
(4) the NW-SE Central Netherlands Basin; and
(5) the NNE-SSW Ems Low.

Within this framework thicknesses show rather gradual variations with the exception of a pronounced thickening NE and E of the Groningen High, where fault-controlled subsidence of the Ems Low and its northern continuation into the German offshore must have caused considerable down-warping of the basin floor.

The isopach picture, although sketched across the area where the Upper Rotliegend is partly or completely eroded, is based only on sections where the column is complete, i.e. where it is overlain by the Copper Shale or equivalent basal Zechstein deposits.

The outer rim of the continuous Rotliegend cover is rather ambiguous. In the first place, post-Rotliegend erosion has removed part of the rim deposits, e.g. in eastern England. Secondly, outside the area of continuous cover, thin intervals of coarse clastics occur between the top Carboniferous and

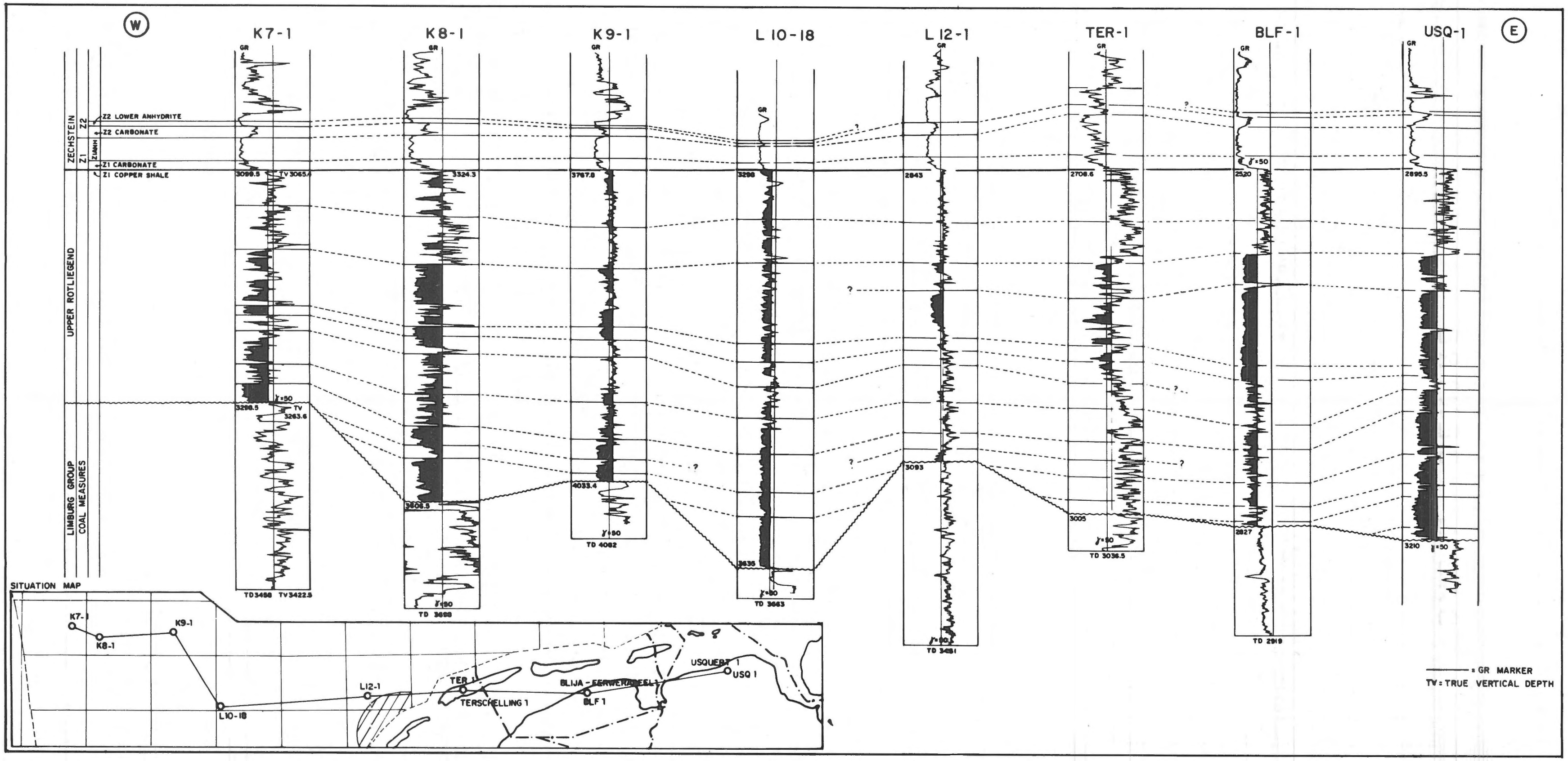


Fig. 7
Rotliegend stratigraphic section K 7-1 – Usquert-1 based on correlation of gamma-ray logs.

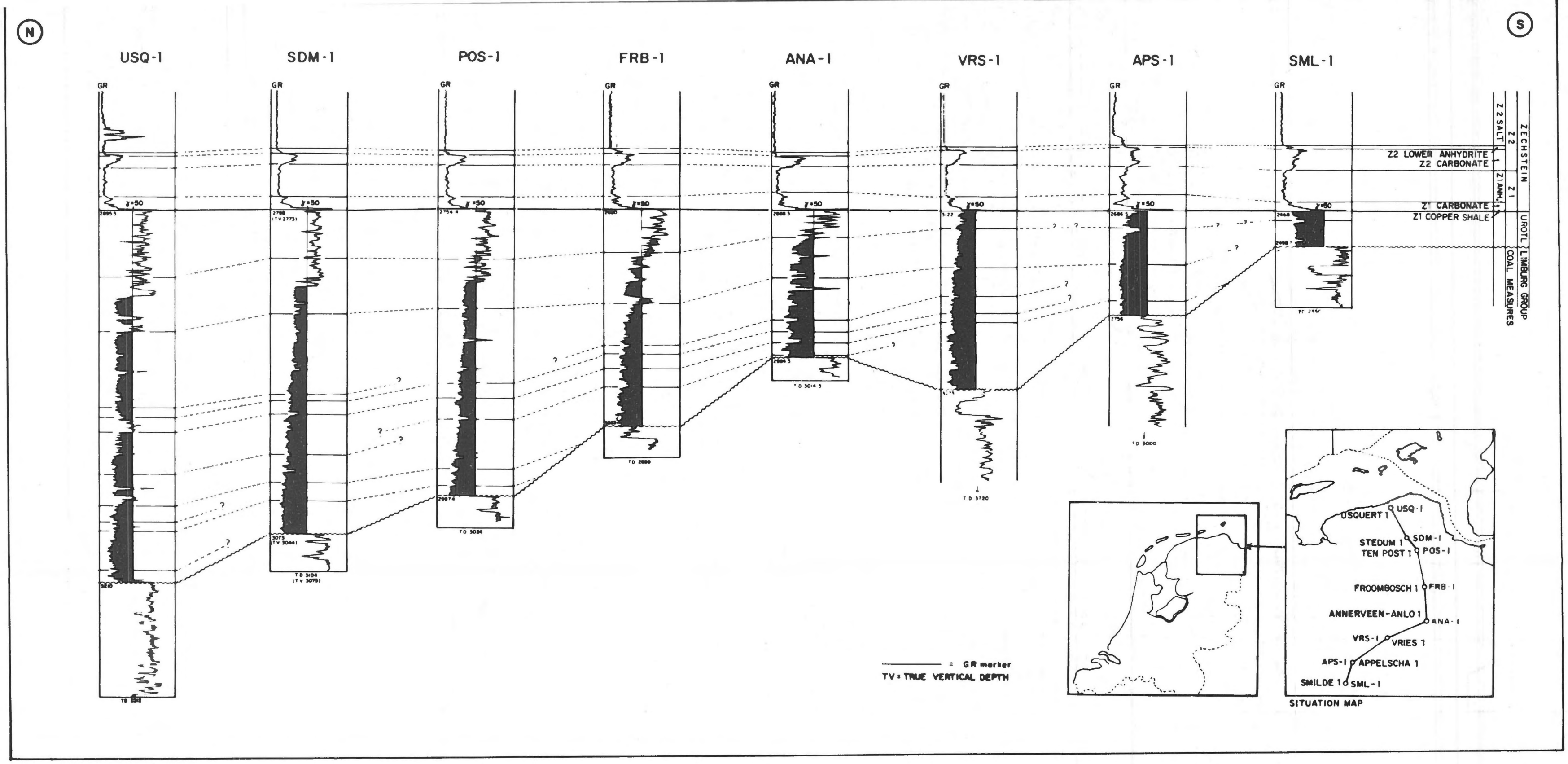


Fig. 8
Rotliegend stratigraphic section Smilde-1 – Usquert-1 based on correlation of gamma-ray logs.

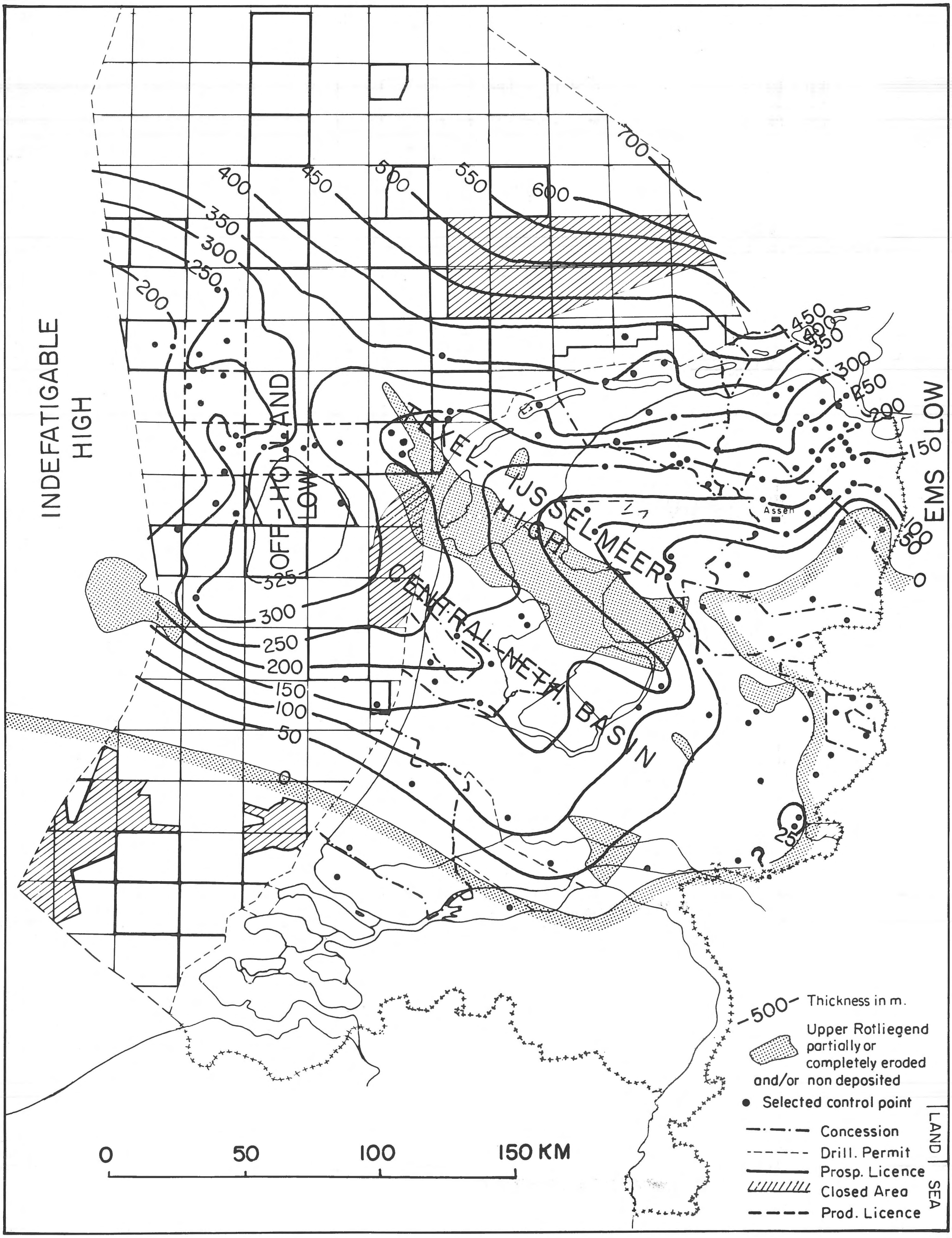


Fig. 9
Total thickness of the Upper Rotliegend.

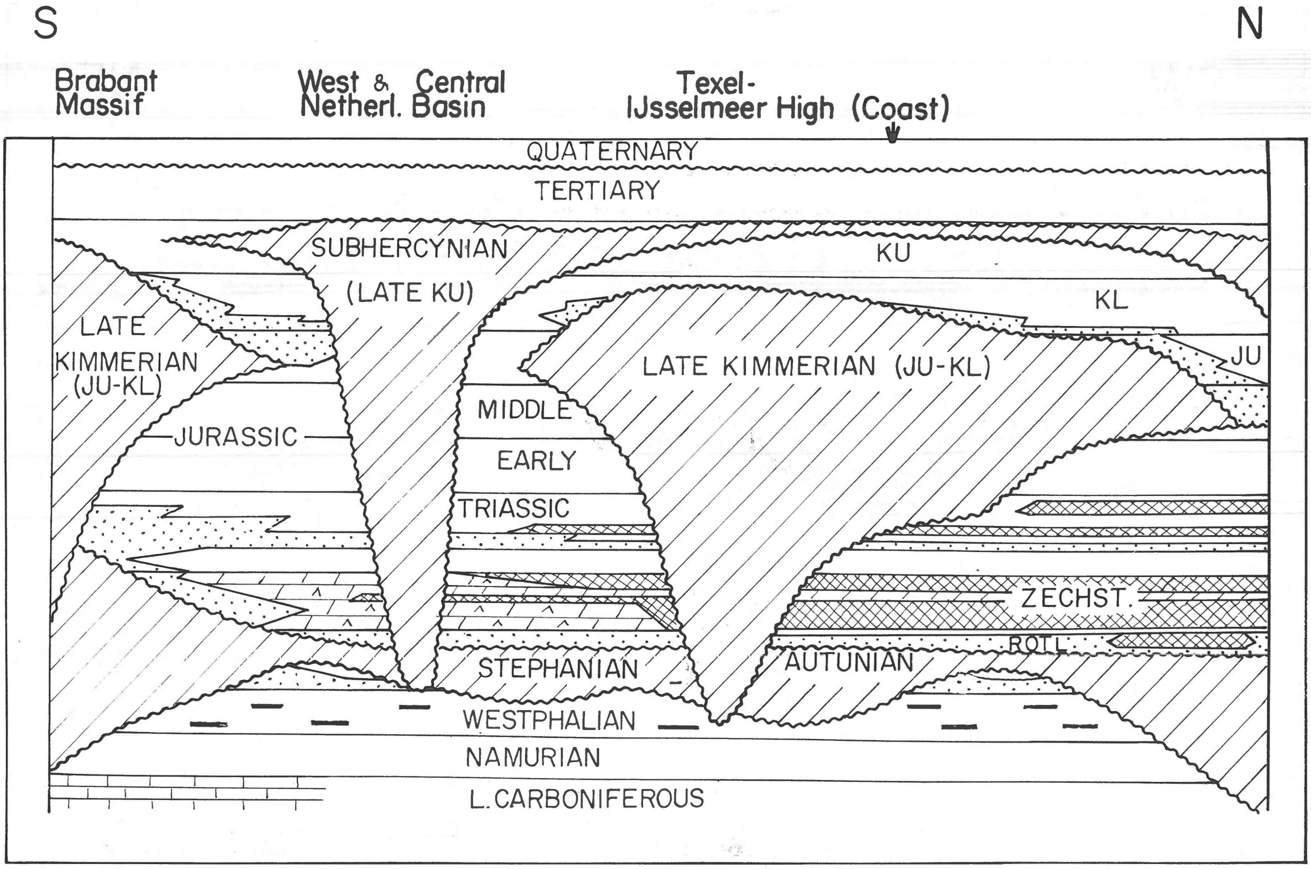


Fig. 10
Structural-stratigraphic synopsis of The Netherlands showing influence of main unconformities.

the basal Zechstein. These sediments are commonly referred to as 'Rotliegend lag deposits'. It is not excluded, however, that some of these beds represent basal Zechstein clastics, the 'Zechstein Konglomerat' of German authors.

The delimitation of the Upper Rotliegend Basin is particularly uncertain in the Achterhoek (eastern Netherlands) in view of some occurrences of Upper Rotliegend sandstones outside the indicated boundary of the basin (Fig. 9). For example, in the recently drilled well Lievelde-1, 37 m of Rotliegend sandstone have been penetrated. Furthermore, in the well Gelria-IV, 25 m of sandstones, in description similar to Rotliegend clastics, were found. In this area, Rotliegend sedimentation probably took place in isolated areas. Similar isolated occurrences are not uncommon in western Germany, and might be expected to be observed more frequently in The Netherlands as well control increases.

The post-Rotliegend history of the Mid-European Basin – The post-Permian history, described by ZIEGLER (1978) and other authors (BOIGK, 1968; HEYBROEK, 1974; KATZUNG, 1972; TRUSHEIM, 1971) is summarized below (Figs. 10, 11).

During the Late Permian large amounts of evaporites, mainly salt, were precipitated in the Zechstein basin. This evaporite sequence forms the seal for all important Rotliegend gas accumulations. Through the Late Permian (Zechstein) and Early Triassic the depositional area widened but the Rotliegend structural configuration essentially persisted.

The E-W trending Mid-European Basin remained the dominant structural element. Its southern border was subdivided by a number of N-S trending swells and lows, most of which were already present during the Rotliegend deposition.

Within the area of thick Zechstein evaporites, salt movements exerted a marked control on the thickness distribution of the Middle and Lower Jurassic and locally even of the Upper Triassic. At approximately the beginning of the Late Jurassic a number of NW-SE striking basins began to subside rapidly, e.g. the Sole Pit and the Central Netherlands Basins. Concurrently, up to 1500 m of Middle Jurassic – Carboniferous strata were removed from the adjacent highs, e.g. the Texel-IJsselmeer High.

During the younger part of the Late Cretaceous the basins, especially their central areas, were strongly uplifted and formed mega-anticlinoria. The former highs subsided and were covered by a thick uppermost Cretaceous sequence (HEYBROEK, 1974; VOIGT, 1963).

Following a regional uplift at the beginning of the Cenozoic, a new basin developed which covered the southern North Sea

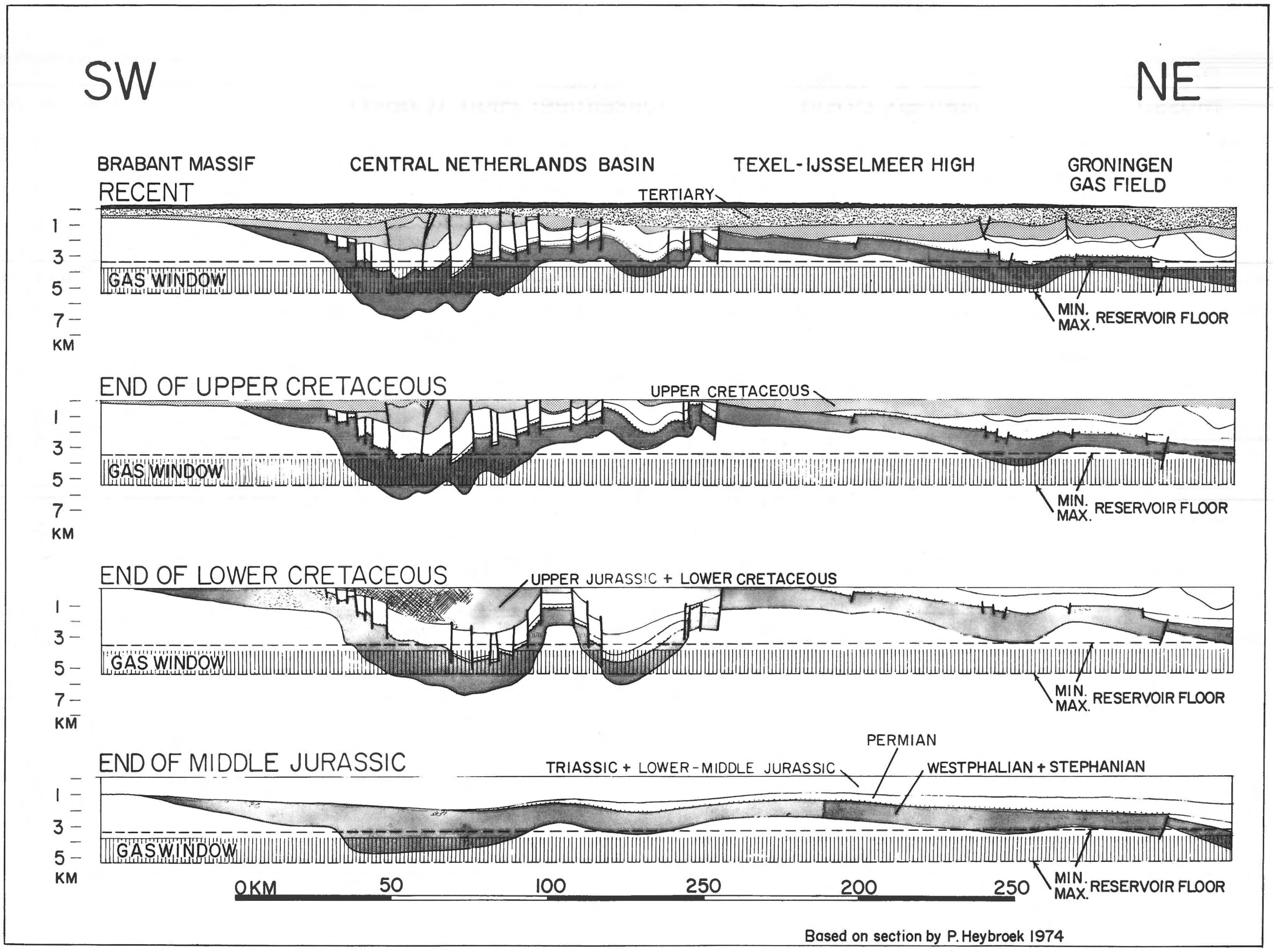


Fig. 11
Reconstruction of the post-Palaeozoic overburden in 4 stages, schematically indicating depth of reservoir and gas-source rock maturity through geological history (for location of section see Fig. 3).

and large parts of The Netherlands and NW Germany. The Mesozoic highs and lows subsided at similar rates and more than 2500 m of sediments accumulated through the Tertiary and Quaternary. Towards the south and east, deposition was negligible and uplift and erosion prevailed.

GAS ACCUMULATIONS IN THE DUTCH ROTLIEGEND

Origin of gas

Source rocks – Based on geological and geochemical data, the Late Carboniferous (essentially Westphalian) Coal Measures are regarded as the main source of the natural gas encountered in the Rotliegend (HECHT ET AL., 1962; HEDEMANN ET AL., 1971; PATIJN, 1964; TRUSHEIM, 1959). This has been corroborated by C-isotope investigations (COLOMBO ET AL., 1968; BOIGK ET AL., 1976).

Within the area under discussion only a few wells have deep penetration into the Coal Measures. These few data points indicate a thickness of about 2000-2500 m for the area between the Weser river in West Germany and the British part of the North Sea (FABIAN, 1971; THIADENS, 1963). Coal beds form approximately 3% of the total section. (HEDEMANN ET AL., 1971; VAN WIJHE ET AL., 1974).

In large parts of the Mid-European Basin variable sections of Coal Measures were removed by erosion prior to and during Rotliegend deposition. Since the thicknesses of the individual subunits of the Coal Measures are hardly known, the amount of preserved section below the Rotliegend can only be estimated.

Coalification and gas generation – The geological factors controlling coal rank and its relation to gas generation have been studied by many authors including KARWEIL (1956), PATIJN (1964) and M. & R. TEICHMÜLLER (1968). Temperature was shown to be of prime importance, geological time appeared to exert

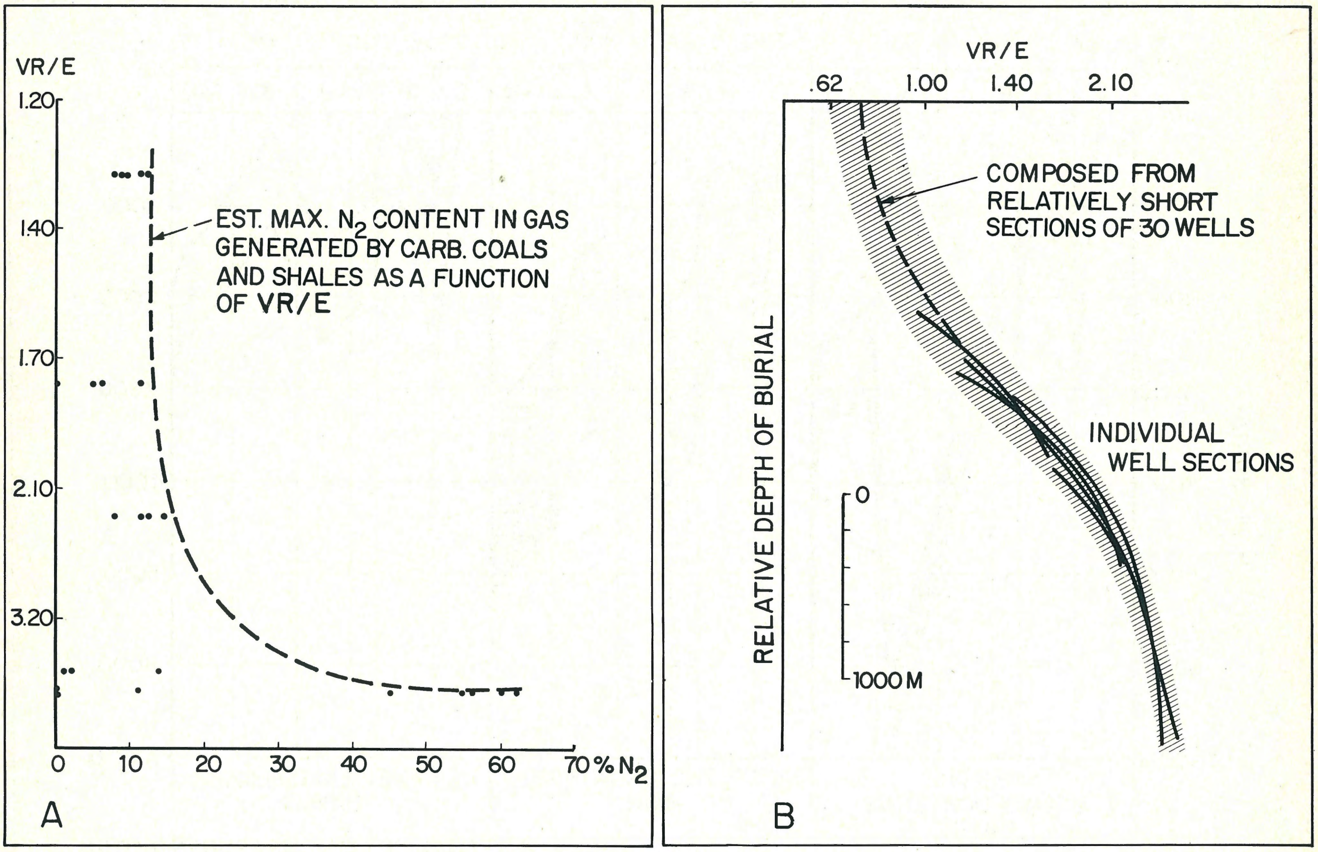


Fig. 12
A: Nitrogen content of samples from well Tjuchem-2.
B: Relative depth of burial versus degree of coalification in several Dutch wells.

less but nevertheless significant influence.

It was found that the degree of coalification (expressed in absolute vitrinite reflectance values) shows for any given area in which the Carboniferous has a similar burial history, a distinct relationship with depth. Curves that express this relationship were published by M. & R. TEICHMÜLLER (1968) for specific areas in West Germany. These graphs are very similar to the one derived from several Dutch wells (Fig. 12B; see also paragraph on time of gas generation). During the early stages of coalification, predominantly water and carbon dioxide are expelled, but above VR/E[5] 1.04 the release of methane plays an increasingly important role (M. & R. TEICHMÜLLER, 1968). Above VR/E 3.20, the amount of volatile matter expelled becomes very small for any given depth increment during further burial.

In this paper, the Coal Measures within the coalification interval of VR/E 1.20-3.20 are regarded as the main source of methane within the Mid-European Basin. The lower limit of VR/E 1.20, instead of VR/E 1.04, was chosen to account for initial losses of methane as a result of adsorption and of solution in formation fluids. This coalification interval of VR/E 1.20-3.20 corresponds to an interval ('gas window') of 1000-2000 m (M. & R. TEICHMÜLLER, 1968). In the NE Netherlands, the gas window is ± 1600 m wide (Fig. 12B). Nitrogen appears to be released in rather constant but small amounts through a large coalification range, contrary to methane generation (JÜNTGEN ET AL., 1966). Consequently, nitrogen percentages of the total amount of gas generated are relatively insignificant during the main phase of methane formation, but increase above VR/E 3.20, i.e. when methane generation is significantly reduced. This is also indicated by the high percentages of nitrogen adsorbed on high rank coals (Fig. 12A). Apart from coal and dispersed coaly matter, nitrogen also appears to be generated from nitrogen compounds and inclusions in clayey rocks during late diagenesis and early metamorphism (MÜLLER ET AL., 1973).

Temperature history of the Coal Measures – As mentioned in the above paragraph, the coalification of the Coal Measures is assumed to be largely temperature-dependent, although the influence of geological time certainly cannot be disregarded. Temperatures are controlled by depth of burial, heat flow and

---

[5] Most determinations of the degree of organic metamorphism are based on vitrinite reflectance measurements. In a few cases, however, sporomorph translucency values have been used. Both sources of information are grouped in the expression VR/E (vitrinite reflectance equivalent = Ro_{random}).

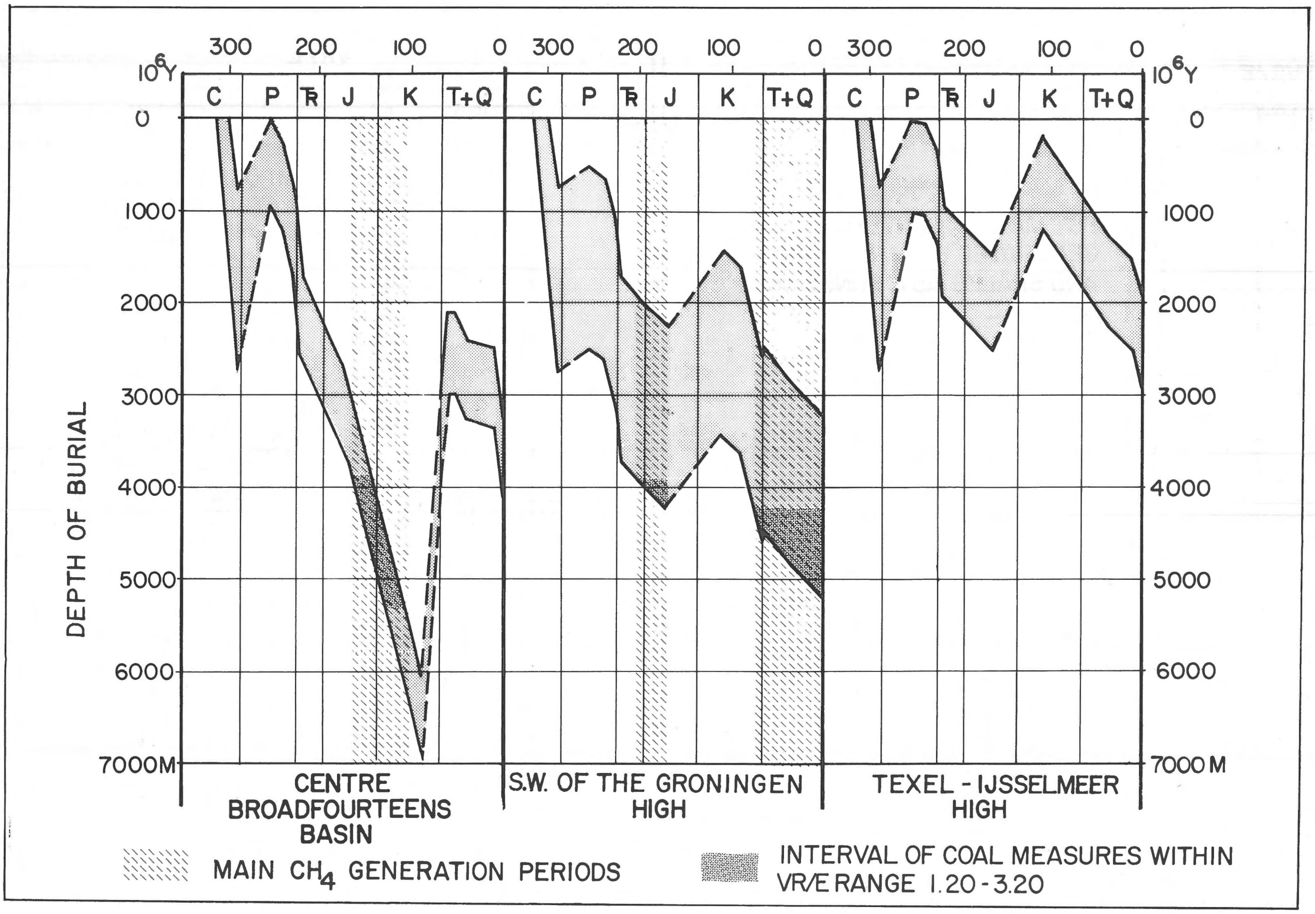


Fig. 13
Burial history of the Coal Measures (shaded) reconstructed with the aid of regional isopach maps of the overlying formations.

heat conductivity of the formations involved.

The burial depth of the Coal Measures through geologic time is controlled by the structural development of the area concerned and can be estimated with reasonable certainty, using borehole and seismic data. However, transient increases of the heat flow have locally accompanied the intrusion or extrusion of igneous rocks (VAN WIJHE ET AL., 1974).

In various parts of The Netherlands rising igneous rocks disturbed the geothermal field, especially during the Permian and Late Jurassic-Early Cretaceous. These intrusions may be accompanied by magnetic anomalies. An outstanding example from the latter period is the Zuidwal volcano at the extreme southeastern end of the Central Graben (COTTENÇON ET AL., 1974). A strong magnetic anomaly witnesses the presence of the phenomenon. Basic volcanics and/or intrusives as well as pyroclastics have been found in strata of Late Jurassic to Early Cretaceous age in several wells in the SW Netherlands Basin. From this indication of widespread volcanic activity a somewhat increased geothermal gradient may also be deduced for this basin during Late Jurassic to Early Cretaceous time.

Magnetic anomalies have also been observed in the northeastern part of the Groningen field and are similarly interpreted as being caused by intrusives. Here, the magnetic anomaly coincides with an area of abnormally high coalification of the Upper Carboniferous (VAN WIJHE ET AL., 1974). However, to date no igneous rocks have been reached by the drill and the age of this coalification is unknown. Yet, it is assumed that the intrusion took place during the Early Permian in view of the presence of Lower Rotliegend volcanics in German wells in the nearby Ems Low (FABIAN ET AL., 1962). Furthermore, the anomaly is located at a boundary fault between the Ems Low and the Groningen High (see p. 6).

Lateral changes in the heat flow may be caused by thickness variations of formations in the overburden which are particularly poor or very good heat conductors. Coal and unconsolidated water-rich clastic sediments are well-known poor conductors. Salt is a very good heat conductor and thickness variations of the Permian salts, due to halokinesis, lead to marked and lasting lateral temperature variations at their base (VAN ENGEN, 1975). As these variations decrease rapidly with depth, they will only influence the coalification in the topmost part of the Coal Measures. However, these phenomena are of special significance for the understanding of temperature-dependent diagenetic processes in the Rotliegend reservoir itself, e.g. authigenesis of illite.

Time of gas generation – In the above paragraph temperature is considered to be the dominant factor controlling gas generation. PATIJN (1964) was one of the first to relate gas generation to the burial history of the source rocks. His theory can be summarized as follows:

When the coalification process is interrupted by uplift it is only re-activated when during a subsequent downwarp the previous depth of burial is surpassed. Patijn calls this process re-coalification.

Contrary to the generation model of EAMES (1974), Patijn attributes only local influence to heat anomalies caused by intrusions. Patijn's view is fully endorsed by us and is further commented upon in the last paragraph. The beginning and the duration of the main gas generation phase(s) can therefore be derived from burial graphs for any individual location. These graphs are based on the reconstructed history of the Coal Measures and on an assumed palaeogeothermal gradient. For the presented Dutch examples a geothermal gradient of 3.2 °C/100 m has been applied (Fig. 13). The VR/E interval of 1.20-3.20 i.e. the main gas generating interval, will then be located in an approximate depth interval of 4000 to 6000 m. The actual limits of this 'gas window' may shift from one structural unit to the other depending on the burial and temperature history.

Rotliegend reservoirs

Primary reservoir distribution – The geographic distribution of the Rotliegend sandstone reservoirs and of their reservoir quality are controlled by environment of deposition (see above) and subsequent diagenetic history. Sand percentages within this southern sand belt of the Rotliegend are shown on figure 14[6].

The length and type of clastic transport (fluviatile or aeolian) controlled grain size and sorting. These factors in turn determined the primary porosity and permeability distribution (NAGTEGAAL, 1979). Rapid decreases of sand thickness and grain size, together with early carbonate cementation of the sebkha sands at the basinward edge of the clastic belt, explain the rapid deterioration of reservoir quality towards the basin centre.

Diagenesis –

(1) *General:* The primary porosity and permeability of the Rotliegend sandstones decreased during initial subsidence by mechanical compaction and early diagenetic phenomena, such as the formation of hematitic clay films around the sand grains. At greater depth, quartz solution and reprecipitation further diminished the reservoir quality. However, it is the growth of fibrous illite, a temperature-controlled authigenetic process, which reduces the diameter of the pore interconnections to such a degree that the sandstones became practically impermeable for gas movement. Even if such rock contains gas, this can probably not be produced at economic rates. These diagenetic processes in the Rotliegend were studied in detail and documented by STALDER (1973), GLENNIE ET AL. (1978), HANCOCK (1978) and SEEMANN (1979). Depth and temperature required for illite formation put a lower limit on economic Rotliegend reservoirs. Present data indicate that in the case of unrestrained illite growth this reservoir floor is located at approximately 3500 m.

Illite growth (as any secondary growth of minerals in the pore space) is apparently inhibited if the reservoir is filled with hydrocarbons. If this happens at an early stage of diagenesis, porosity may thus be preserved below the depth of the normal reservoir floor.

Similarly, the reservoir floor may be deeper than normal when the flow of compaction fluid is slowed down or inhibited by effective vertical or lateral seals. In an early stage this will prevent compaction, in a later stage it will impede the growth of authigenetic minerals like illite by slowing down the transport of the mineral constituents needed. Such a slowing-down of the flow of compaction fluids is in many cases indicated by higher than hydrostatic pressures (overpressures) in the porous reservoirs concerned. Overpressures in the aquifer therefore indicate the possibility of reservoir preservation to greater depth than expected under normal (hydrostatic) pressure conditions. Early hydrocarbon fill, or an effective retardation of the movement of compaction fluids in the reservoirs may lower the 'reservoir floor' down to, say 4.5-5.0 km. On the other hand, the base of economic reservoirs may be much shallower than the 'normal' depth of 3.5 km if the depth of the Rotliegend was once in geological history appreciably deeper than at present.

The occurrence of producible Rotliegend gas accumulations is, therefore, normally restricted to those areas where the Rotliegend sandstones were never buried deeper than the reservoir floor, i.e. 3.5-5.0 km.

In order to predict the degree of diagenesis to be expected in the Rotliegend reservoir at a given location, it is therefore important to know the maximum depth of burial, the relationship of depth and temperature to diagenesis, as well as the presence and magnitude of any factor which could disturb this relationship. Two relevant aspects will be discussed in some detail, viz. the determination of the maximum depth of burial and the recognition of areas where the permeabilities may be preserved by restriction of formation water flow in the reservoir.

---

[6] This map is based on sand counts from the gamma-ray log. Sand counts were established according to an empirically established formula:

$$\text{net SST thickness} = \text{GR }75 + \frac{\text{GR}_{50} - \text{GR}_{75}}{2} = \frac{\text{GR}_{50} + \text{GR}_{75}}{2} \quad \text{whereby}$$

GR 75, GR 50 = thickness of intervals with a gamma-ray radiation of less than the 75%, and less than the 50% sand line, respectively. The 75% and 50% sand lines are interpolated between a 100% and a 0% sand line, drawn at the radiation level of clean sandstone and pure claystone intervals, respectively (see Fig. 4, gamma-ray log). Net sand thicknesses evaluated with this method have been shown to differ by not more than 10% from those determined by a full petrophysical evaluation using a cut-off porosity of 0%.

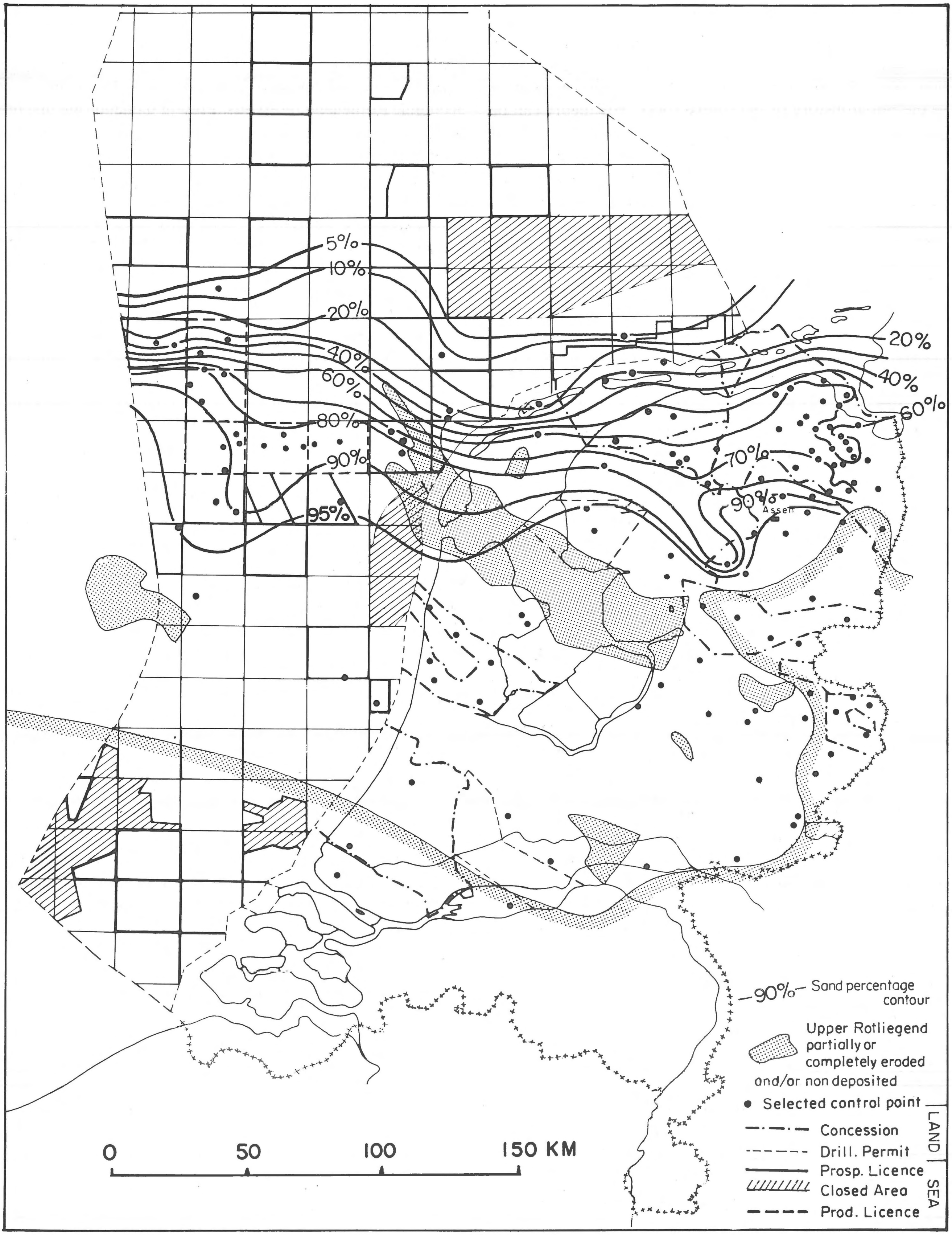
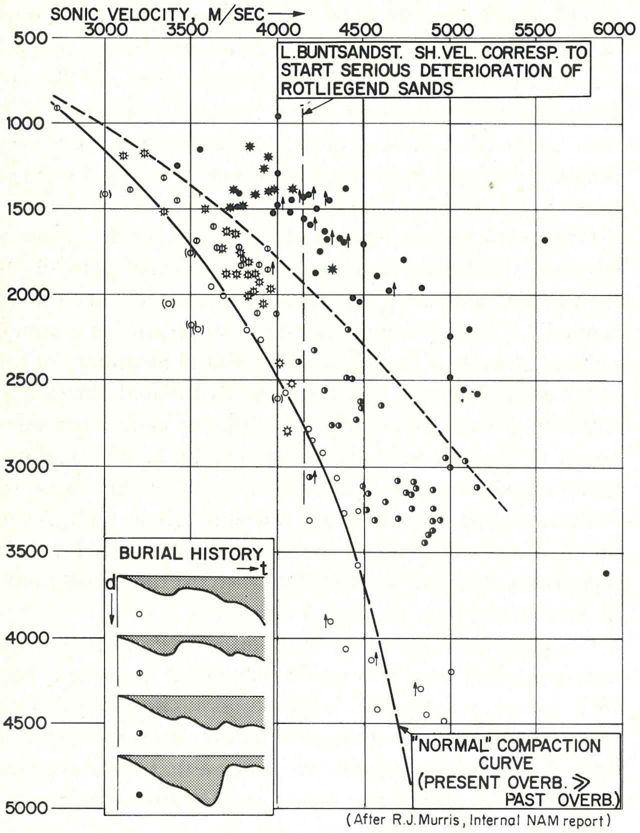


Fig. 14
Sand percentage map based on sand occurrences throughout the Upper Rotliegend.



(After R.J.Murris, Internal NAM report)

Fig. 15
Main Claystone (Lower Buntsandstein) sonic velocity versus depth subdivided into four classes, each of which corresponds to a distinct burial history. The dashed upper line separates the fourth class (past overburden considerably larger than present overburden) from the other three classes. The vertical dashed line through sonic velocity 4150 m/s separates gas discoveries (starred symbols) from gas shows (arrow) and gas-bearing tight sandstones.

(2) *Determination of maximum depth of burial:* To determine the maximum depth of burial, use was made of the fact that with increasing depth of burial and compaction, sonic velocities of uniform shale sections increase, and that this increase is irreversible. Such a uniform shale section of wide lateral extent is present in the Lower Buntsandstein. By crossplotting sonic log-derived velocities and depths of the Lower Buntsandstein for many wells which are known to be today at their maximum depth of burial, a normal compaction curve can be constructed. By comparing the sonic velocity of the Lower Buntsandstein of a given well with the normal curve, its maximum depth of burial can be estimated; the difference between the present depth and the depth indicated by the normal curve equals the uplift of the Lower Buntsandstein since its maximum burial (Fig. 15). This method has been applied earlier for Early Jurassic claystones of the Gifhorn Trough (F. R. of Germany) by PHILLIP ET AL., (1963); it has been discussed and illustrated for the Lower Buntsandstein of NW Germany by JOHN (1975).

By adding to the maximum depth of burial of the Lower

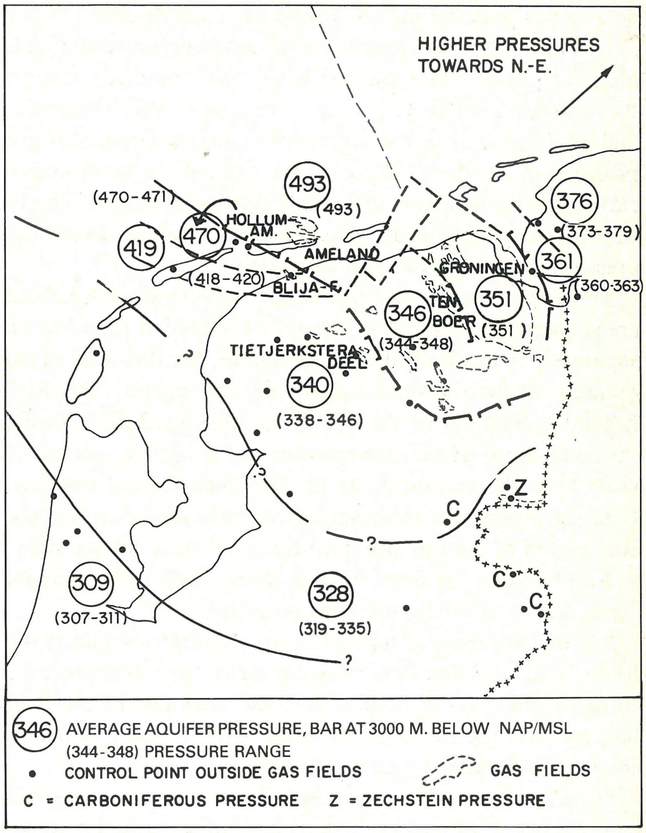


Fig. 16
Upper Rotliegend aquifer pressures.

Buntsandstein the thickness of the underlying Zechstein sequence (taking into account salt movements where appropriate) and, if present, Rotliegend shales and evaporites, the maximum thickness of the overburden which has affected Rotliegend reservoirs can be estimated.

(3) *Restriction of formation water flow in the Rotliegend reservoir:* Pressures higher than hydrostatic have been reported from water-bearing Rotliegend reservoirs for several wells in the northern Netherlands. As such high pressures in waterfilled sandstones may be indicative for reservoir preservation to greater depth than can be expected under normal (hydrostatic) pressure conditions (see above), data on the pressures in the Rotliegend aquifer have been compiled.

Aquifer-pressure data at a common reference level of 3000 m MSL/NAP which were either available directly from tests in water-bearing intervals or calculated from measured gas pressures are plotted on figure 16[7]. This figure shows that pressures generally increase from south to north by up to 180 bar. Yet, over substantial areas, the calculated pressures are similar; significant pressure changes occur discontinuously between wells only a few kilometres apart. The quality of the

---

[7] Based on an unpublished report by J. P. Rijnders, M. Lutz & H. Plaat.

data seems good enough to justify such a statement.

To explain the observed discontinuous pressure changes, effective permeability barriers have to be assumed between the respective wells. Given the thickness of the Rotliegend and its lithofacies in the area under consideration, it is not possible to visualize depositional barriers, e.g. extensive clayey strata between sand lenses. Faulting therefore seems to be the only geologically feasible mechanism to cause the pressure discontinuities just described.

The well-documented Ameland and Hollum-Ameland areas (pressure difference 23 bar) were indeed found to be separated by a seismically mapped fault, the throw of which exceeds by far the thickness of the Rotliegend. The Rotliegend sandstones of the high block abut against Zechstein salt, and those of the downthrown block against essentially shaly Late Carboniferous strata. The Zechstein salts and the Late Carboniferous shaly sequence are assumed to seal the Rotliegend of the up- and downthrown blocks, respectively.

Additionally, an impermeable layer, such as a mylonite zone, may exist along the fault plane itself.

Within the Groningen Field, a fault separates similarly the Main Field, and Ten Boer pressure areas; here, however, the throw of the fault is smaller than the thickness of the Rotliegend, and the rather small differential pressure (4 bar) is thought to be held by a fault seal only.

Other pressure areas (e.g. Blija-Ferwerderadeel and Tietjerksteradeel; difference 79 bar) are not separated by obvious faults. However, the boundary between these areas could follow a transcurrent fault; such faults are often hard to prove on seismic evidence only.

While it appears to be well established that sealing normal (and possibly transcurrent) faults delimit in N. Friesland and in the province of Groningen individual 'pressure areas', it is not known how these overpressures are generated. A number of processes can be visualized which may act individually or in combination, as long as they fulfil one constraint, viz. to be effective within the confines of the isolated areas mentioned above.

– The Rotliegend reservoir may be loaded with compaction water from intercalated Rotliegend claystones, or underlying Late Carboniferous shales. As densities in the respective claystones and shales are essentially equal to densities of similar rocks in normally pressured wells of the same depth, the present stage of compaction probably has been reached before the reservoirs have been overpressured; no compaction water, therefore, was available to generate the overpressures observed.

– When montmorillonite and mixed-layer clay minerals in the Carboniferous are transformed to illite during subsidence, water is freed equal to 16% by weight of the original montmorillonite (PERRY & HOWER, 1972, p. 2017). This water is overpressured in the pore space of the claystone at the depth concerned; pressure equalization with the Rotliegend water would lead to overpressures in the Rotliegend too. However, investigations of German authors (STADLER, 1963) showed that comparable Late Carboniferous claystones with a maximum depth of burial of 2000 m are free from montmorillonite and mixed-layer clay minerals. Burial graphs for some of the wells involved indicate that such a depth was already reached in the area discussed at the end of the Middle Jurassic. Any overpressure present could not be preserved during the subsequent uplift in Early Cretaceous time.

– Overpressures are generated by aquathermal pressuring (BARKER, 1972), i.e. the pressure increase which parallels the temperature increase in any subsiding, isolated and constant, water-filled pore volume. Aquathermal pressuring is an ubiquitous process. It therefore surely played an important role in the area discussed, where effectively isolated blocks were warmed up since Late Cretaceous time by continuous subsidence. Seals, however, and especially fault seals as discussed here, are never perfect. If a pressure difference across the faults is present, some fluid will flow through the fault. A very minor flow will release the overpressure generated by aquathermal pressuring, therefore such overpressures cannot be maintained over geological times.

– Gas generated in the Late Carboniferous Productive Measures which migrated into the Rotliegend at a very late stage (see above), may cause overpressures in Rotliegend reservoirs. The magnitude of pressure differences is thought to be related to seal effectiveness. We believe that this is the main process which caused the higher than hydrostatic pressures observed.

Seal

The salts of the Late Permian Zechstein form the main seal for most of the Rotliegend gas accumulations. The distribution of these salts is determined by primary depositional patterns as well as by later halokinetic movements and/or later erosion and subsurface solution.

In the basinal Zechstein facies, however, the salts are directly underlain by approximately 50 m of dense carbonate and anhydrite which often act as an additional seal.

Traps

The gas-filled structures in the area under discussion differ considerably in size. The Groningen structure is a large regional uplift with a closed area of hundreds of km^2, whereas others are rather small dip- and fault-closed traps superimposed on regional structural units, e.g. the many small- to medium-sized accumulations in the northern Netherlands and the Dutch offshore region with closed areas of only some tens of km^2 or less.

The age of many regional structural units can generally be deduced from the thickness pattern of the post-Zechstein stratigraphic units. For example, the Texel-IJsselmeer High apparently was in a high position relative to its surroundings almost continuously from the Late Carboniferous to Early Cretaceous (Fig. 13). In contrast, the large uplifts in the centre

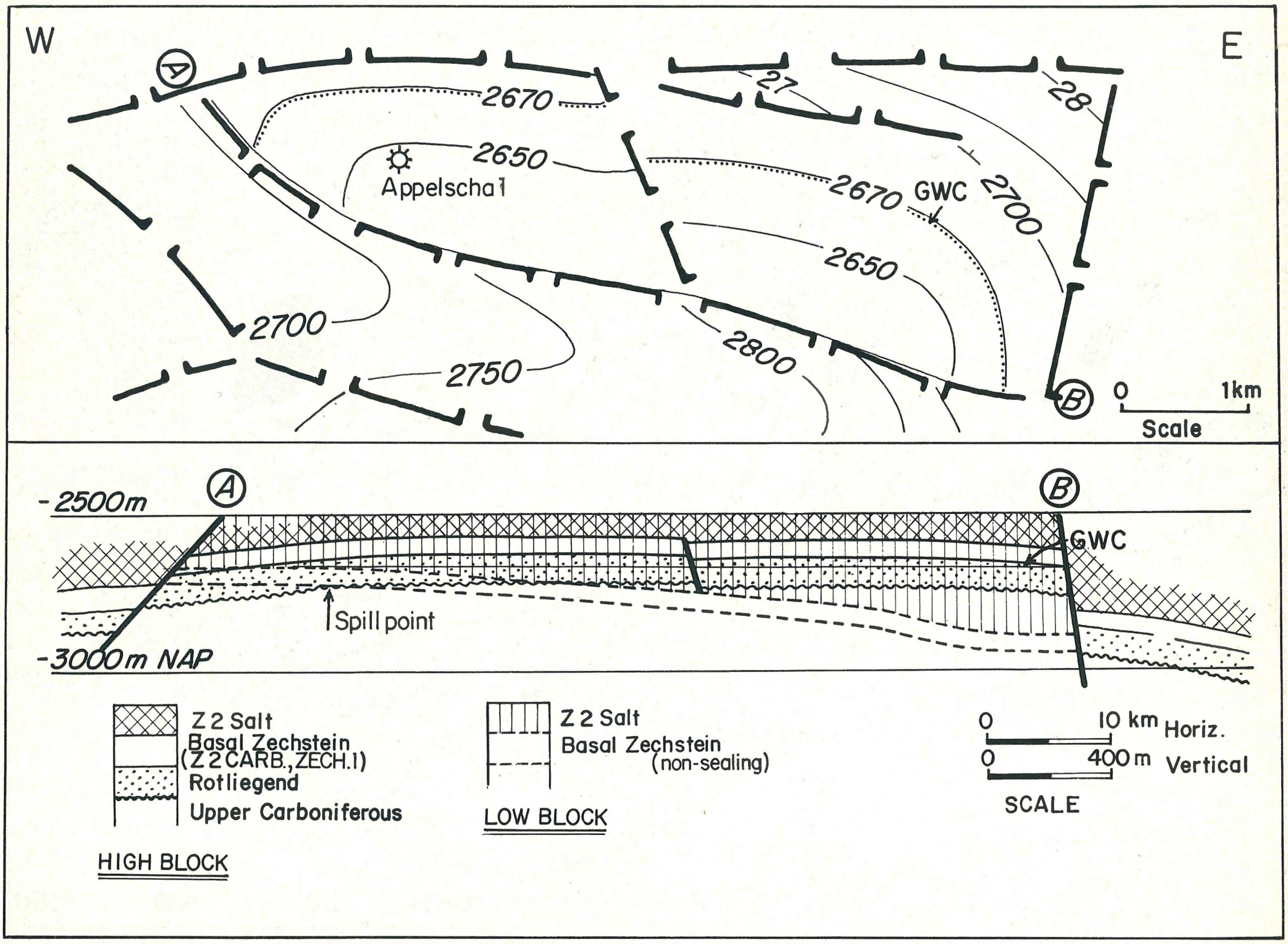


Fig. 17
Appelscha structural analysis. Fault-plane projection (AB) showing gas water contact (GWC) to correspond with spill point.

of the Late Jurassic – Early Cretaceous basins were only formed in the latest Cretaceous. The formation of individual structures, however, can in most cases hardly be dated. The thick Zechstein salts usually drape the Rotliegend structures and by their halokinetic movements have often controlled the thicknesses of the overburden which, therefore, often reflect rather accurately the movements of the salt but not of its substratum.

Migration and accumulation

Migration and gas composition – Empirically and experimentally it has been shown that both the length of the migration path and its permeability strongly influence the gas composition (MAY ET AL., 1968; FABER ET AL., 1979). In particular, during migration the relative amounts of nitrogen tend to increase. It is well-known that in any given structure with superimposed accumulations, gases in the Buntsandstein (Early Triassic) reservoirs are generally of high nitrogen content compared with the gases in the deeper Zechstein, Rotliegend and/or Carboniferous reservoirs (BOIGK ET AL., 1971; FABER ET AL., 1979).

Time of migration versus structural and diagenetic history – It is assumed that the primary migration was almost contemporaneous with generation. Therefore, the age of the primary migration is linked directly with the structural history of any given part of the Mid-European Basin. The burial history of the western part of this Basin indicates a first generation phase during the Early and Middle Mesozoic (Fig. 13). Gas migration took place towards the flanks of the basins present at those times and gas was trapped along the high margins or in intermediate positive structural elements. Due to Late Cretaceous inversion of most of these basins, remigration of the gas was set in motion. This secondary migration was directed towards the newly formed structures in the centre of the former Early-Middle Mesozoic basins. However, due to deep burial, the reservoir properties, especially permeability, of the Rotliegend in these structures are strongly deteriorated, mainly by the authigenetic growth of fibrous illite and chlorite in the pore spaces (STALDER, 1973). Consequently, although attractive amounts of gas can be trapped in such structures,

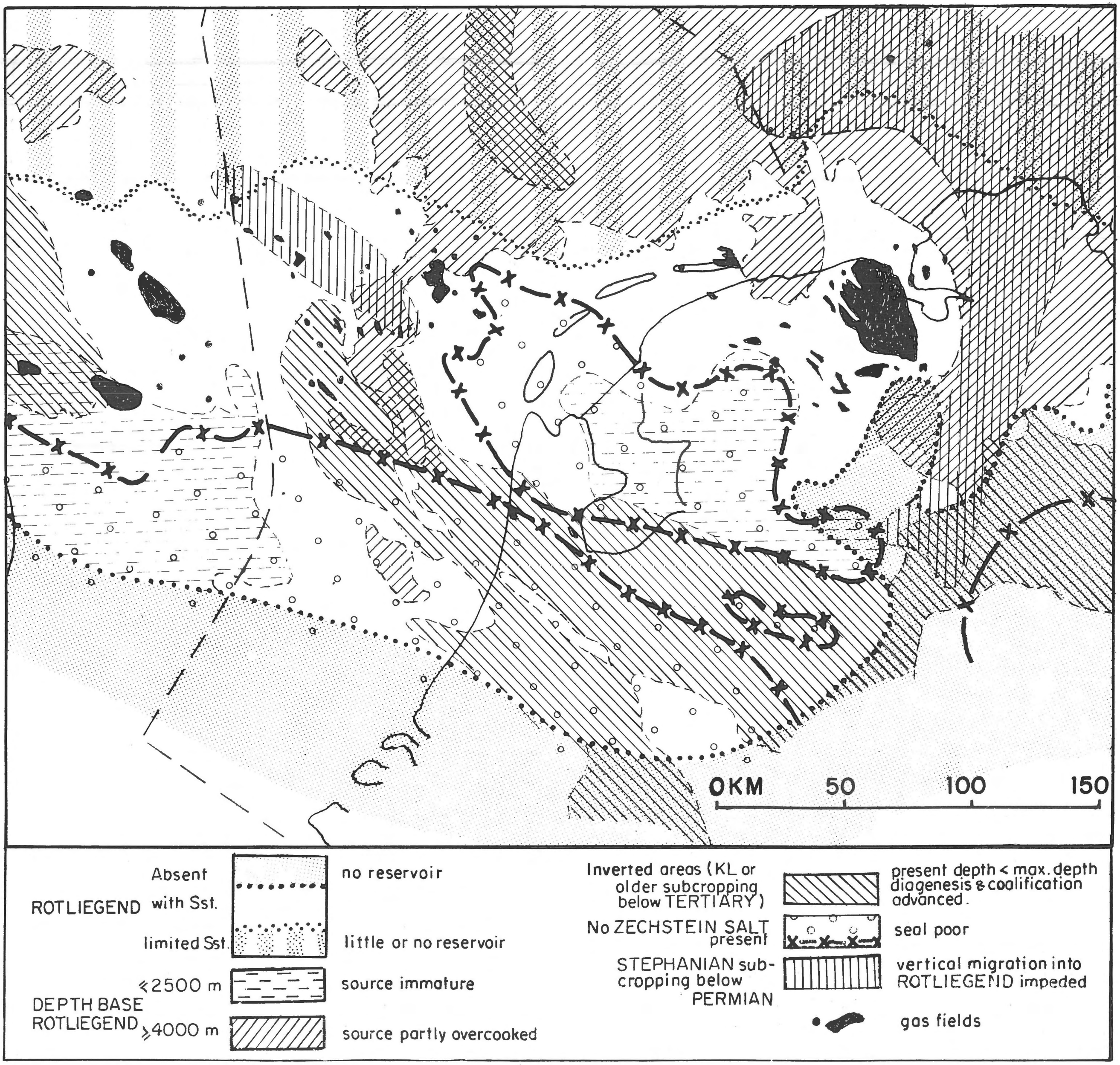


Fig. 18
Hydrocarbon prospect map of the Upper Rotliegend.

economic production is hampered, as found in a number of wells in the Dutch offshore.

In areas where diagenesis was less intense, presumably because of less burial, economic accumulations could be formed in and around such inverted basins, e.g. the Leman Bank and Sole Pit fields in the British offshore (Fig. 18).

During the Tertiary-Quaternary, the southern North Sea basin underwent pronounced subsidence after a Late Cretaceous – earliest Tertiary period of uplift. In many places a second phase of gas generation and migration occurred (Fig. 13). The same process was described by PATIJN (1965) and called re-coalification. Such young migration effects are demonstrated by most of the better known structures in the northern Netherlands and the adjoining parts of the Dutch offshore. These structures, although subjected to continued Cenozoic subsidence, are all filled to structural spill point.

Figure 17 demonstrates how the spill point of a fault-closed structure can be determined. Of the three boundary faults of the Appelscha-1 structure, fault AB has the smallest throw. The structural spill point should therefore be found along this fault, provided that the fault plane itself has no sealing capacity. The spill point is located at ± 2670 m, since down to this level the Slochteren Sandstone of the high block is sealed by salt on the low block. The petrophysical evaluation of

Appelscha-1 indeed confirmed this spill point by establishing the gas-water contact at the same depth. In early-filled structures, subsequent subsidence would have caused considerable compression of the gas resulting in a partial fill. Consequently, the complete fill of a structure is only possible by renewed, late gas generation.

Figure 18 summarizes all factors controlling the Upper Rotliegend gas accumulations. The distribution of adverse parameters is indicated by shading, leaving the most favourable areas white. Note that all large and methane-rich accumulations are within or near the white areas. Accumulations in the shaded areas are small and/or rich in nitrogen.

CONCLUSIONS

The large Rotliegend gas accumulations in the Dutch and other parts of the Mid-European Basin are the result of a combination of favourable conditions of which the most prominent are:

(1) thick, good quality gas source rocks, combined with a favourable burial history, leading to the wholesale generation of methane;

(2) close spatial relationships between source and reservoirs resulting often in easy migration conditions;

(3) excellent reservoir development;

(4) first-rate seal;

(5) presence of abundant, sometimes large, Rotliegend structures which were often formed before the main gas generation period(s).

ACKNOWLEDGEMENTS

The authors are indebted to the Nederlandse Aardolie Maatschappij B.V., Shell Internationale Petroleum Maatschappij B.V. and Esso Europe for granting permission to publish this paper. They gratefully acknowledge the co-operation of companies active in the North Sea area, which has enabled them to use unpublished data. They particularly wish to thank all colleagues who have contributed to this paper.

REFERENCES

Barker, C. 1972 Aquathermal pressuring – role of temperature in development of abnormal pressure zones – Amer. Ass. Petrol. Geol. Bull. 56: 2068-2071.

Bartenstein, H. M. & R. Teichmüller 1971 Die Umwandlung der organischen Substanz im Dach des Bramscher Massivs – Fortschr. Geol. Rheinland Westf. 18: 501-538.

Boigk, H. 1961 Zur Fazies und Erdgasführung des Buntsandsteins in Nordwest-Deutschland – Erdöl Kohle 14: 998-1005.

—— 1968 Gedanken zur Entwicklung des niedersächsischen Tektogens – Geol. Jb. 85: 86-90.

Boigk, H., H. W. Hagemann, W. Stahl & Z. G. Wollanke 1976 Isotopenphysikalische Untersuchungen zur Herkunft und Migration des Stickstoffs nordwestdeutscher Erdgasse aus Oberkarbon und Rotliegend – Erdöl Kohle 29: 103-112.

Boigk, H., W. Stahl, M. & R. Teichmüller 1971 Das Oberkarbon im Untergrund von Nordwestdeutschland. b) Inkohlung und Erdgas – Fortschr. Geol. Rheinland Westf. 19: 101-108.

Brouwer, G. C. 1972 The Rotliegend in The Netherlands. In: H. Falke (ed.) Rotliegend, Essays on European Lower Permian: 34-42.

Colombo, U., F. Gazzarini, M. & R. Teichmüller 1968 Das Verhältnis der stabilen Kohlenstoff-Isotopen von Steinkohlen und kohlenbürtige Methan in Nordwestdeutschland – Z. angew. Geol. 14: 257-265.

Cottençon, A., B. Parant & G. Flacelier 1975 Lower Cretaceous gas fields in Holland. In: A. W. Woodland (ed.): Petroleum and the continental shelf of N.W. Europe I (Geology): 403-412.

Daber, R. 1969 Paläobotanische Hinweise auf eine paralisch beeinflusste Oberkarbon-Senke im tieferen Untergrund Nordwestdeutschlands – Geologie 18: 253-298.

De Booy, T. 1968 Mineral assemblages in Rotliegendes – Verhand. K.N.G.M.G. 25: 21-33.

Eames, T. D. 1975 Coal rank and gas source relationships Rotliegend reservoirs. In: A. W. Woodland (ed.): Petroleum and the continental shelf of N.W. Europe I (Geology): 191-204.

Faber, E., M. Schmitt & W. Stahl 1979 Geochemische Daten Nordwestdeutscher Oberkarbon-, Zechstein- und Buntsandsteingase.

Fabian, H. J. 1971 Das Oberkarbon im Untergrund von Nordwestdeutschland und dem angrenzenden Nordseebereich. a) Stratigraphie und Tektonik – Fortschr. Geol. Rheinland Westf. 19: 87-100.

Fabian, H. J., H. Gaertner & G. Müller 1962 Oberkarbon und Perm der Bohrung Oberlanger Tenge ZI im Emsland – Fortschr. Geol. Rheinland Westf. 3: 1057-1096.

Falke, H. 1972 The Continental Permian in North- and South Germany. In: H. Falke (ed.): Rotliegend, Essays on European Lower Permian: 43-113.

—— 1976 Problems of the continental Permian in the Federal Republic of Germany. In: H. Falke (ed.): The continental Permian in Central, West and South Europe – NATO Adv. Study Inst. Ser. C. (Math. Phyc. Sci.) 22: 38-52.

Glennie, K. W. 1972 Permian Rotliegendes of Northwest Europe interpreted in light of modern desert sedimentation studies – Amer. Ass. Petrol. Geol. Bull. 56: 1048-1071.

Glennie, K. W., G. C. Mudd & P. J. C. Nagtegaal 1978: Depositional environment and diagenesis of Permian Rotliegendes sandstones in Leman Bank and Sole Pit areas of the UK Southern North Sea – J. Geol. Soc. 135: 25-34.

Hancock, N. J. 1978 Possible causes of Rotliegend sandstones diagenesis in northern West Germany – J. Geol. Soc. 135: 35-40.

Haubold, H. & G. Katzung 1972 Die Abgrenzung des Saxon – Geologie 21: 883-914.

Hecht, F., O. Hering, J. Knobloch, K. Kubella & W. Rühl 1962 Stratigraphie, Speichergesteinsausbildung und Kohlenwasserstoff-Führung im Rotliegenden und Karbon der Tiefbohrung Hoya ZI – Fortschr. Geol. Rheinland Westf. 3: 1061-1074.

Hedemann, H. A. & R. Teichmüller 1971 Die paläogeographische Entwicklung des Oberkarbons – Fortschr. Geol. Rheinland Westf. 19: 129-142.

Hemley, J. J. 1959 Some mineralogical equilibria in the system K_2O-AL_2O_3-SiO_2-H_2O – Amer. J. Sci. 257: 241-270.

Heybroek, P. 1974 Explanation to tectonic maps of The Netherlands – Geol. Mijnbouw 53: 43-50.

John, H. 1975 Hebungs- und Senkungsvorgange in Nordwestdeutschland – Erdöl Kohle 28: 273-277.

Jüntgen, H. & J. Karweil 1966 Gasbildung und Gasspeicherung in Steinkohlenflözen – Erdöl Kohle 19: 251-258.

Jüntgen, H. & J. Klein 1975 Enstehung von Erdgas aus kohligen Sedimenten – Erdöl Kohle 28: 65-73.

Karweil, J. 1956 Die Metamorphose der Kohle vom Standpunkt der physikalischen Chemie – Z. dtsch. geol. Ges. 107: 132-139.

Katzung, G. 1972 Stratigraphie und Palaeogeographie des Unterperms in Mitteleuropa – Geologie 21: 570-584.

Kölber, H. 1968 Regionalgeologische Stellung der DDR im Rahmen Mitteleuropas. In: Grundriss der Geologie der Deutschen Demokratischen Republik 1 – Akademie-Verlag (Berlin): 19-66.

Lutz, M., J. P. H. Kaasschieter & D. H. van Wijhe 1974 Geological factors controlling Rotliegend gas accumulations in the Mid-European Basin – Proc. 9th World Petr. Congr. (Tokyo) 2: 93-103.

Marie, J. P. P. 1975 Rotliegendes stratigraphy and diagenesis. In: A. W. Woodland (ed.): Petroleum and the continental shelf of N.W. Europe I (Geology): 205-221.

May, F., W. Freund, E. P. Müller & K. P. Dostal 1968 Modelversuche über Isotopenfraktionierung von Erdgaskomponenten während der Migration – Z. angew. Geol. 14: 376-380.

Müller, E. P., K. Goldbecher & T. A. Botnewa 1973 Zur Geochemie und Genese stickstoffreicher Erdgase – Z. angew. Geol. 19: 494-499.

Mundry, E. 1971 Der Temperaturverlauf im Dach des Bramscher Massivs nach der Wärmeleitungstheorie – Fortschr. Geol. Rheinland Westf. 18: 539-546.

Nagtegaal, P. J. C. 1979 Relationships of facies and reservoir quality in Rotliegendes desert sandstones, Southern North Sea Region – J. Petr. Geol. 2: 145-158.

Ned. Aardolie Mij. & Rijks Geol. Dienst 1979 Stratigraphic nomenclature of The Netherlands – Verhand. K.N.G.M.G. (in press).

Patijn, R. J. H. 1964 Die Enstehung von Erdgas infolge der Nachinkohlung im Nordosten der Niederlande – Erdöl Kohle 17: 2-9.

Perry, E. A. & J. Hower 1972 Late stage dehydration in deeply buried pelitic sediments – Amer. Ass. Petrol. Geol. Bull. 56: 2013-2021.

Philipp, W., H. J. Drong, H. Füchtbauer, H. G. Haddenhorst & W. Jankowsky 1963 Zur Geschichte der Migration im Gifhorner Trog – Erdöl Kohle 16: 456-468.

Plein, E. 1978 Rotliegend Ablagerungen im norddeutschen Becken – Z. dtsch. geol. Ges. 129: 71-97.

Plumhoff, F. 1966 Marines Ober-Rotliegendes (Perm) im Zentrum des nordwestdeutschen Rotliegend-Beckens – Erdöl Kohle 19: 713-720.

Richter-Bernburg, G. 1955 Der Zechstein zwischen Harz und Rheinischem Schiefergebirge – Z. dtsch. geol. Ges. 105: 876-896.

Roll, A. 1969 Recent development in German exploration for oil and gas. In: P. Hepple (ed.): The exploration for petroleum in Europe and North Africa – Inst. Petrol. (London): 221-229.

Schreiber, A. 1960 Das Rotliegende des Flechtinger Höhenzuges – Freiberger Forschungshefte 82: 132 pp.

Seemann, U. 1978 Diagenetically formed interstitial clay minerals as a factor in Rotliegend sandstone reservoir quality in the Dutch sector of the North Sea – J. Petr. Geol. 1.

Smith, D. B. 1972 The Lower Permian in the British isles. In: H. Falke (ed.): Rotliegend, Essays on European Lower Permian: 1-33.

Sorgenfrei, T. & A. Buch 1964 Deep tests in Denmark, 1935-1959 – Danm. geol. Unders. 36: 146 pp.

Stadler, G. 1963 Die Petrographie und Diagenese der oberkarbonischen Tonsteine in der Bohrung Münsterland-1 – Fortschr. Geol. Rheinl. Westfalen 11: 238-292.

Stahl, W. J. 1968 Zur Herkunft nordwestdeutscher Erdgase – Erdöl Kohle 21: 514-518.

Stalder, P. J. 1973 Influence of crystallographic habit and aggregate structure of authigenic clay minerals on sandstone permeability – Geol. Mijnbouw 52: 217-220.

Stäuble, A. J. & G. Milius 1970 Geology of Groningen gas field, Netherlands In: M. T. Halbouty (ed.): Geology of giant petroleum fields – Amer. Assoc. Petrol. Geol. Mem. 14: 359-369.

Teichmüller, M. & R. 1968 Geological aspects of coal metamorphism In: D. Murchiso & T. S. Westoll (eds.): Coal and coal bearing strata – Oliver and Boyd, (London): 233-267.

Thiadens, A. A. 1963 The Palaeozoic of The Netherlands – Verhand. K.N.G.M.G. geol. ser. 21: 2-28.

Trusheim, F. 1959 Ergebnisse der Tiefbohrung Groothusen Z 1 bei Emden (Ostfriesland) – Erdöl-Erdgas Z. 7: 273-278.

—— 1971 Zur Bildung der Salzlager im Rotliegenden und Mesozoikum Mitteleuropas – Geol. Beih. 112: 51 pp.

Van Adrichem Boogaert, H. A. 1974 Outline of the Rotliegend (Lower Permian) in The Netherlands. In: H. Falke (ed.): The continental Permian in Central West and South Europe: 21-37.

Van Engen, H. 1975 An interpretation of Groningen subsurface temperature data – Geol. Mijnbouw 54: 177-183.

Van Veen, F. R. 1975 Geology of the Leman gas field. In: A. W. Woodland (ed.): Petroleum and the continental shelf of N.W. Europe I (Geology): 223-231.

Van Wijhe, D. H. & M. J. M. Bless 1974 The Westphalian of The Netherlands with special reference to microspore assemblages – Geol. Mijnbouw 53: 295-328.

Voigt, E. 1962 Über Randtröge vor Schollenrändern und ihre Bedeutung im Gebiet der Mitteleuropäischen Senke und angrenzender Gebiete – Z. dtsch. geol. Ges. 114: 378-418.

Waterhouse, J. B. 1978 Chronostratigraphy for the world Permian. In: G. V. Cohee, M. F. Glaessner & H. D. Hedberg (eds.): The geologic time scale – Amer. Ass. Petr. Geol. Studies in Geology 6: 299-322.

Ziegler, P. A. 1978 North-western Europe: tectonics and basin development. In: A. J. van Loon (ed.): Fault tectonics in N.W. Europe – Geol. Mijnbouw 57: 589-626.