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The distribution of Pre-Westphalian source rocks in the North German Basin – Evidence from magnetotelluric and geochemical data

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Abstract

For the first time this project attempts to directly correlate magnetotelluric and geochemical data with the aim of creating a model on the regional distribution of potential pre-Westphalian source rocks deposited in marine environments in the North German basin.

Analysis of the magnetotelluric data shows, that there is a deep good conductor at the north-eastern fringe of the North German basin around the islands of Rügen and Usedom and on the mainland north east of the Anklam Fault. Through integration with seismic data and the offshore well G14 the conductor can be correlated with the Cambro-Ordovician Scandinavian Alum shales. To the south an adjoining area approximately corresponding to the depo-centre of the Rotliegend basin lacks a deep good conductor. Therefore it can be assumed that a regional distribution of comparable source rocks is unlikely. Another excellent and important conductor starts to the south west of the Lower Elbe Line extending along the Dutch-German border into the North Sea, and into the Münsterland. Its place in the local stratigraphy has not been adequately established. It is most likely that this good conductor corresponds to the black shales of the Early Namurian and the Dinantian, which is the case in the boreholes Münsterland 1 and Pröttlin 1 for example. In this paper they are collectively called Rhenohercynian Alum shales. On the Dutch-German border a transition into the "Bowland Shale" facies or equivalents is to be expected. It cannot be ruled out that even stratigraphically older black shales, possibly from the Cambro-Ordovician could contribute to the high integrated conductivity of the deep good conductor.

The evidence of highly conductive layers in the deep subsurface poses the question whether these layers could be potential source rocks for the gases in the north German gas fields. This question can be answered with a clear yes. Gas and isotope geochemical studies on gases from producing Rotliegend deposits have shown that Rhenohercynian Alum shales have been a significant source for these fields. This will be illustrated in detail using the gas fields from the production province "Ems Estuary" as an example.

Key words: Good conductors, Alum shale, Dinantian, Early Namurian, Cambro-Ordovician, carbon and nitrogen isotopes

Introduction

In the past 10 to 15 years the interest in the deep subsurface of the North German basin and its oil and gas potential has grown considerably. Geophysical studies on the geological-tectonic structure of the deep basin, its genesis and development as well as the time-spatial distribution of hydrocarbons have concentrated primarily on reflection seismic. However, at depths below the prominent Zechstein (Z)-base reflector only few structural details can be distinguished (e.g. Dohr 1989). Besides other potential methods providing information at this depth range, e.g. magnetics and gravimetrics, the magnetotelluric (MT) method is well suited to investigate the electrical conductivity distribution, a method rarely used for hydrocarbon prospecting.

The study of the conductivity distribution in the North German basin goes back to the late fifties (e.g. Schmucker 1959). By means of inductive-magnetic measurements ("geomagnetic depth sounding") the *North German Induction Anomaly*, a zone of high conductivity in the upper crust, which runs from northwest Germany to central Poland, was detected (this was, by the way, the stimulus to start similar projects throughout the world). Magneto-telluric measurements were undertaken mainly in the sixties and seventies, independently in East and West Germany, aiming at understanding the origin of this anomaly (Porstendorfer 1965; Losecke et al. 1979; Jödicke 1984; Göthe 1990). In the former GDR, conductivity measurements have also been used in the search for hydrocarbons (Porstendorfer 1984).

The main result of the early, widely spaced measurements in northwest Germany was the unexpected high conductivity of the Mesozoic-Cenozoic sedimentary cover on the one hand, and on the other the existence of a deep, highly conductive zone in the pre-Permian. This pre-Permian feature occurs, as far is known, in the area between the river Elbe, the North Sea coast, the river Ems and the Münsterland basin. The two features explained the inductive effect of the *North German Conductivity Anomaly* (Weidelt 1978). The high conductivity of the near-surface layers is clearly caused by electrolytical conduction through brine-filled open pore space. By contrast laboratory measurements on black shale samples from the Münsterland 1 borehole indicated a quasi-metallic conduction mechanism to prevail (Jödicke 1984; Duba et al. 1988). This is consistent with an advanced state of organic metamorphism for the deep conductor (pre-graphite). This relationship between deep conductors and potential source rocks indicated a previously unrecognised deep gas potential.

This deep gas potential below the currently active Permian and Upper Carboniferous plays in northern Germany has been studied in an integrated manner by the Federal Institute for Geosciences and Natural Resources (BGR) during the years 1990 – 1995 (e.g. Stahl et al. 1996; Gerling et al. 1999). In this study geological, geophysical and geochemical data were fully integrated. It could be demonstrated that highly mature source rocks (> 5.5% Rmax (max. vitrinite reflectance)) containing type III kerogen still have a gas generating potential. Moreover, hydrous pyrolysis experiments revealed, that methane generation is even possible for some types of black shales at Rmax values of over 5% if sufficient water is available (Everlien 1997).

Since 1993 new MT measurements in northeast and northwest Germany, with the objective of exploring for hydrocarbons, have been conducted by the BGR in co-operation with the Institute of Geophysics, University of Münster. The aim was:

- to delineate deep conductors which may be regarded as deep source rocks still producing some gas,
- to establish the regional extent of these layers,
- to determine their stratigraphical positions, and
- to integrate electrical parameters derived from magnetotelluric results into geological-tectonic modeling as a contribution to understanding the paleodynamic development of the deep subsurface of the North German basin.

The magnetotelluric method

The magnetotelluric method, which relies on measurements of long-period natural electric and magnetic field variations, was used to study regional structures, in particular to identify deep electrical conductors. MT "transfer functions" describe amplitude and phase relations between orthogonal components of the induced horizontal electric field $\underline{E} = (E_x, E_y)$ (in [mV/km]) and the horizontal magnetic induction $\underline{B} = (B_x, B_y)$ (in [nT]) (Fig. 1). These parameters contain all available information about the electrical resistivity distribution. Furthermore, this information depends on the penetration depth of the electromagnetic fields ("skin depth"). This may vary from 10 – 15 km in the North German basin due to the high conductance (conductivity × thickness) of the sedimentary cover, to more than 100 km over more resistive, e.g., crystalline basement areas. As a result of da-

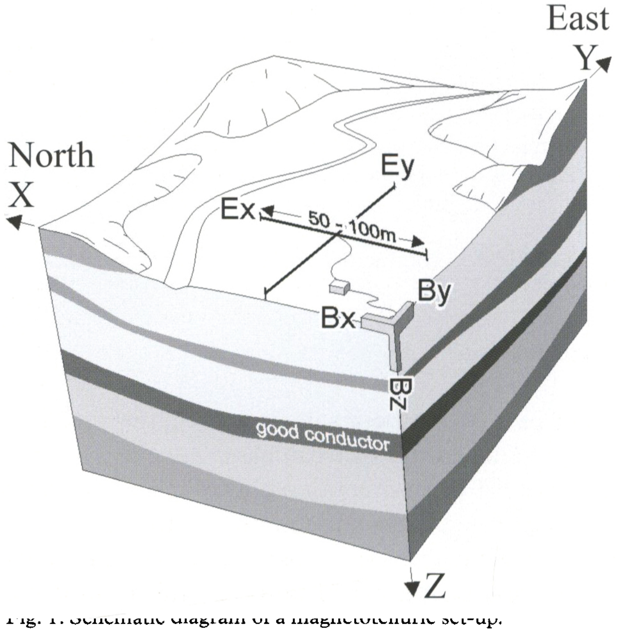


Fig. 1. Schematic diagram of a magnetotelluric set-up.

ta analysis, two apparent resistivity curves ñ$_{axy}$(T), ñ$_{ayx}$(T) and two phase curves $_{xy}$(T), $_{yx}$(T) ("sounding curves"), as functions of period T are displayed. Subscript xy denotes the set of curves derived from the induced field component E_x, and the inducing components B_x, and B_y, while yx denotes the corresponding set derived from the components E_y, B_x, and B_y. The apparent resistivity curves ñ$_a$(T) resemble geoelectric sounding curves but with period length instead of spacing L/2. The phase curves contain independent information.

For model calculations, the sounding curves have to be rotated from measured geographic (x,y) orientation to electrical strike directions. If the conductivity distribution at depth is assumed to be strictly two dimensional, a (x′,y′) co-ordinate system of complete decoupled pairs $E_{x'}$, $B_{y'}$ and $E_{y'}$, $B_{x'}$ with orientation of the E′-components parallel (E-polarization) or perpendicular (B-polarization) to strike is attained by this rotation. E and B-polarization curves differ depending on whether a two or three-dimensional subsurface structure is being surveyed. The curves are identical only in the case of a one-dimensional underground. Along profiles, the E-polarization curves vary continuously over lateral boundaries because of steady electrical boundary conditions, while B-polarization curves may change discontinuously. In model calculations, the four curves of the E and B-polarizations have to be fitted simultaneously.

The magnetotelluric measurements

MT measurements with a total of 88 soundings have been carried out along three long and four short profiles crossing the eastern part of the North German basin perpendicular to its axis (for location see Fig. 7). Along these lines the MT sites had a separation of approximately 10 km each. The field campaign was conducted by the companies Metronix (Braunschweig) and Geophysik GmbH (Leipzig), and the Institute of Geophysics (University of Münster), all using Metronix equipment including 3-component induction coils for the measurement of the magnetic and kalomel probes for the electric field. The period range covered 1/256 s (in part 1/4 s) – 4096 s and the recording time was 2 – 3 days, sometimes one week, to ensure sufficient data quality at long periods. Recently, this data has been complemented by new profiles comprising 36 soundings parallel to the river Ems near the Dutch-German border in the western part of the North German basin (Fig. 7). Since data analysis and model calculations are still in progress here, only preliminary 1D results will be presented.

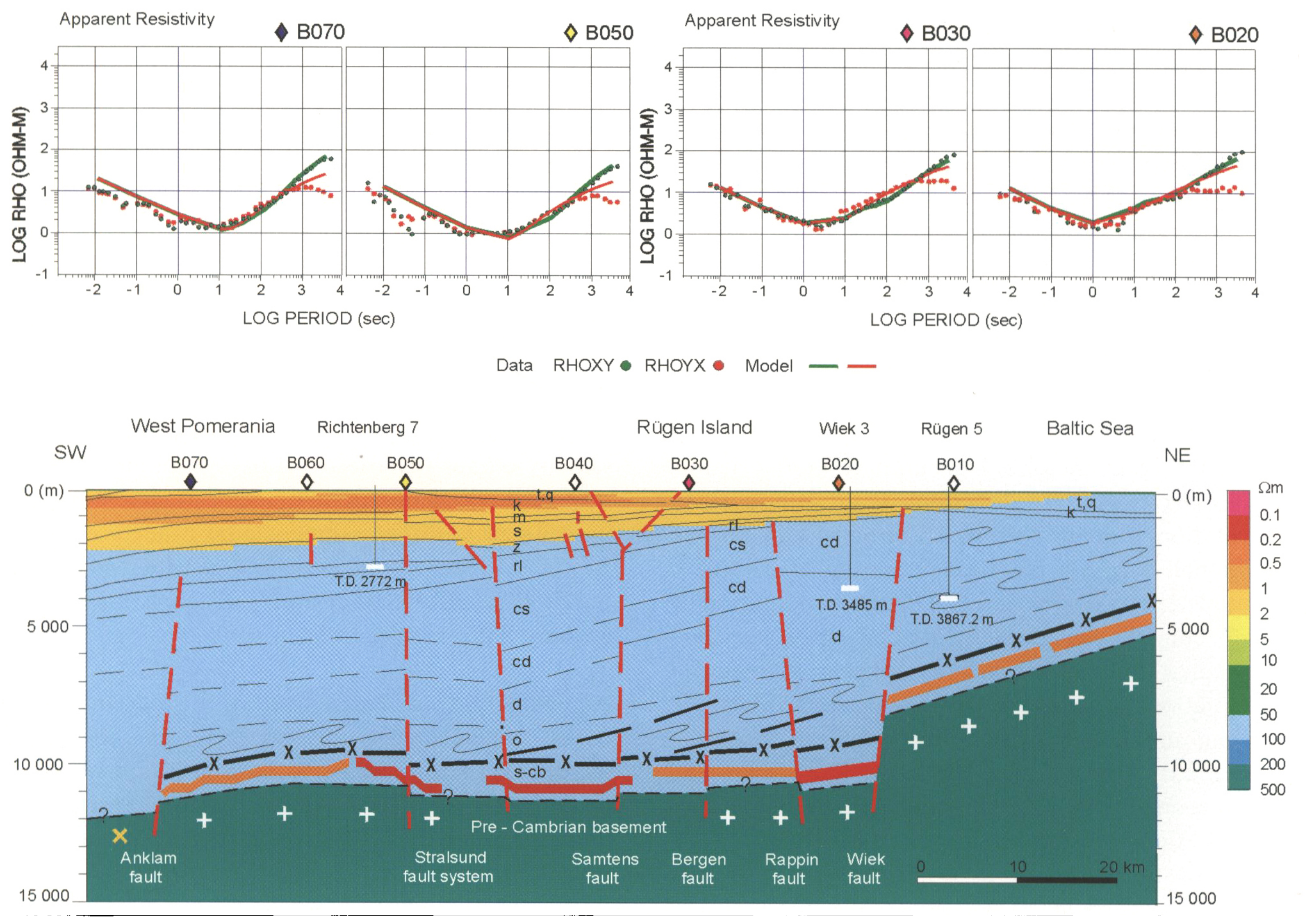
The distribution of pre-Westphalian conductors in the North German basin

The results of two-dimensional magnetotelluric forward modelling are compiled in the form of magnetotelluric-geological cross sections. Portions of two sections are presented here as examples, the first running from the island Rügen in the Baltic Sea to the mainland of West Pomerania (sites B010 – B070) (Fig. 2), the other crossing the river Elbe connecting the north-western with the north-eastern part of the North German basin (sites F040 – F120) (Fig. 3, for location see Fig. 7). A selection of corresponding resistivity curves together with best fit model curves is displayed above the models. These models were built utilising previous one-dimensional modelling results as well as seismic, magnetic and gravimetric studies, borehole measurements and geological information as input data (Hoffmann et al. 1998).

All profile sections located within the North German basin proper show sequences of layers with similar features in their upper parts, but significant variations in the resistivity pattern at larger depth which are of main interest here (cf. Figs. 2 and 3):

- 1st layer medium resistive, small thickness (not displayed in Fig. 2),
- 2nd layer conductive to highly conductive, thickness up to 5 km,
- 3rd layer resistive, several km thickness.

All models have a basal deepest layer with an undefined lower boundary and an upper boundary defined by a gradual increase in resistivity – a so-called halfspace. Due to inherently limited depth resolution of resistive layers in MT we assume, that the top of the halfspace coincides with the top of the crystalline basement. However, the data can also be interpreted as a gradual increase of resistivity. Most strikingly, above this resistive basement the presence of deep highly conducting layers is evident in some parts of the North German basin. Such a conductive layer is detected in northeast Germany at a depth of 7 – 10 km below the island of Rügen. Its depth increases to 10 – 11 km below the mainland, where it disappears south of the Anklam fault (Fig. 2). The presence of basement and good conductor rocks towards the northeast is controlled by additional test calculations and corroborated by seismic data. The good conductor can be traced further to the east where it is found between the island of Usedom and the Anklam fault at about the same depth.



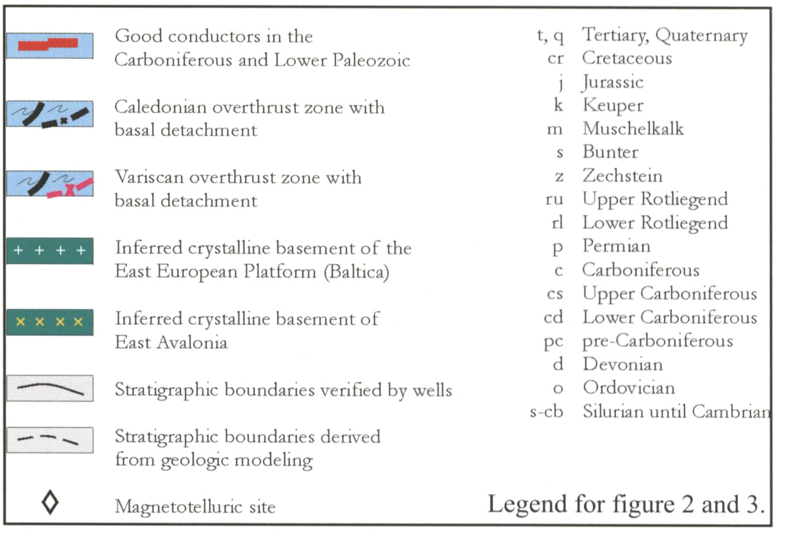


Fig. 2. Geological section between sites B010 and B070 (see Fig. 7 for location). Upper part: apparent resistivity curves of selected sites with 2D model fit; E-polarisation green, B-polarisation red. The deep good conductor correlates with the Cambro-Ordovician 'Scandinavian Alum shale', encountered in Baltic offshore well G14.

While deep good conductor rocks are absent in the Rotliegend depocentre of the North German basin, i.e. the area between Anklam fault and Lower Elbe Line, another deep conductor is encountered at a depth of 8 – 10 km between the river Weser in the south west and some ten kilometres north of the river Elbe (Fig. 3). To the southwest, the conductance of this layer increases steadily, reaching its maximum of over 5000 S, north of the river Aller close to the position of the *North German Conductivity Anomaly* (Gurk et al. 1996). There is no doubt that the conductor outlined along this section is identical to the prominent conductor, which controls the conductivity distribution of the deep subsurface between North Sea coast, Dutch-German border and Münsterland as mentioned above.

The 2D model fit is on the whole adequate or good in the medium frequency range (upper parts of Figs. 2 and 3). As the prime objective was to delineate the

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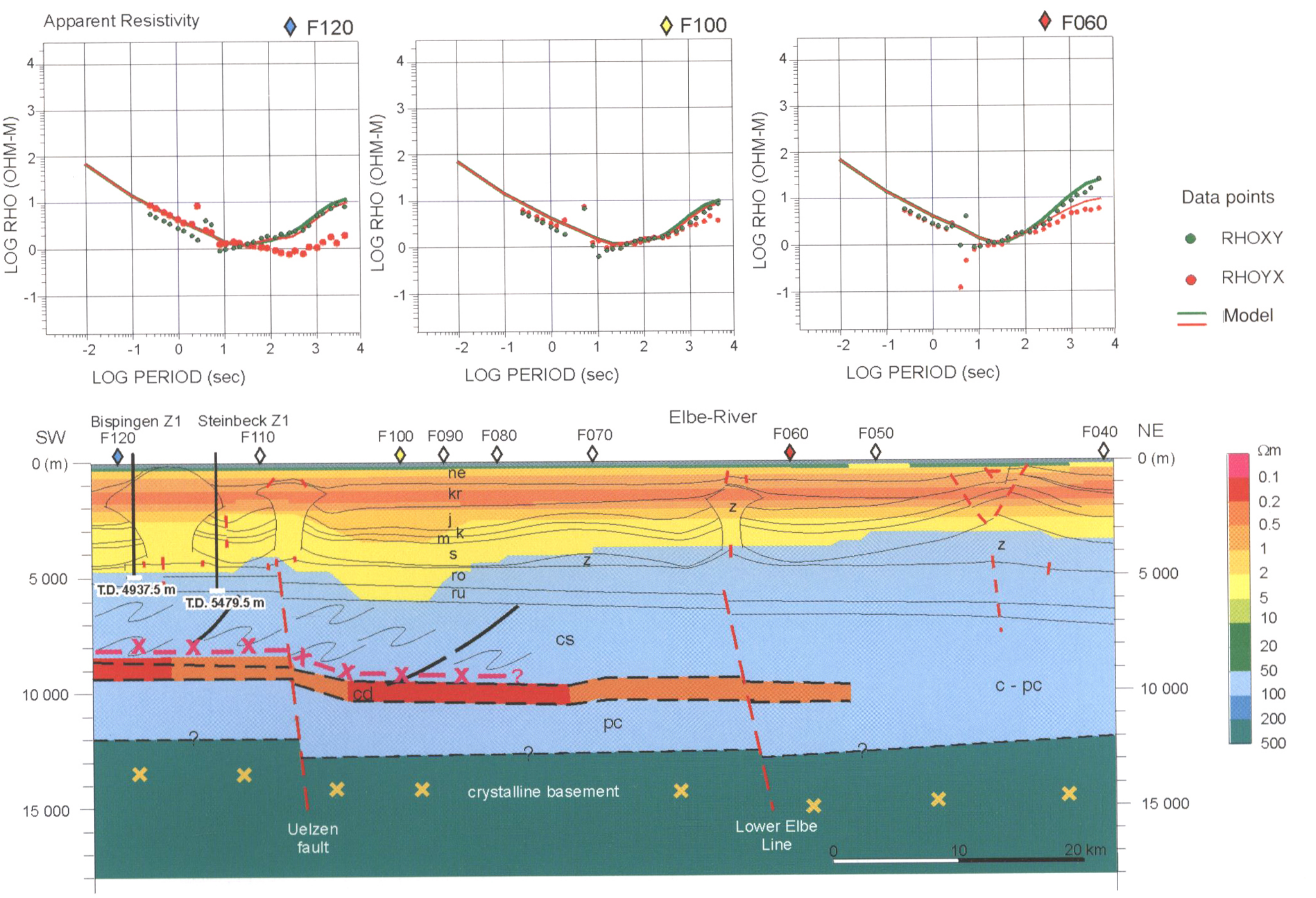

Fig. 3. Geological section between sites F040 and F120 (see Fig. 7 for location). The deep good conductor correlates with the Dinantian and Lower Namurian sediments ('Rhenohercynian Alum shale'), encountered in boreholes Pröttlin 1 and Münsterland 1.

resolution of the deep conductors, it was not intended to optimize the fit of the sounding curves at highest and lowest frequencies. At highest frequencies, the results of 1D modeling could be used for the corresponding near-surface layers (< 1 km) because of the almost perfect 1D behavior of most data in that frequency range. Only the origin of the anisotropy at the lowest frequencies, which is a characteristic feature at most sites within the North German basin, remains ambiguous. For some parts of the profiles, this anisotropy could convincingly be modeled by assuming very deep conductors (>20 km) as inferred from magnetic and gravimetric anomalies, e.g. the Pritzwalk anomaly (Hoffmann et al. 1998). An alternative, more general interpretation is that these anomalies originate from electrical anisotropy of the lower crust. However, this cannot be resolved from the available data (Strobeck 1998).

For the recently measured "Ems" profiles near the Dutch-German border only a preliminary but representative 1D model of site H250 is shown in Figure 4 (for location see Fig. 7). The general resistivity-depth distribution described above can be recognized again except for the low resistivity of the deepest half space layer for which 2D modeling is required. The conductor at 10 km depth is clearly identified from its marked minimum around 500 s in the apparent resistivity curve. The minimum at 1 s indicates the near surface conductor of Cainozoic and Mesozoic sediments. The Ems region is part of the area in north west Germany where the deep conductor has previously been delineated by early widely spaced MT measurements (Losecke et al. 1979; Jödicke 1984).

Black shales and the interpretation of deep conductors

The interpretation of the nature of deep conductors has long been a matter of debate in the electromagnetic community. The most common assumption being, that brines produce conductive zones throughout the crust. Consequently, in early interpretations, the high conductance of the pre-Westphalian layers in northern Germany was explained as being due to electrolytic conduction through open pores (Knödel et al. 1979). However, this required either unrealistically high porosities or unrealistic thicknesses of the conductive layers, even if the presence of oversaturated brines was assumed. Some years later, petrophysi-

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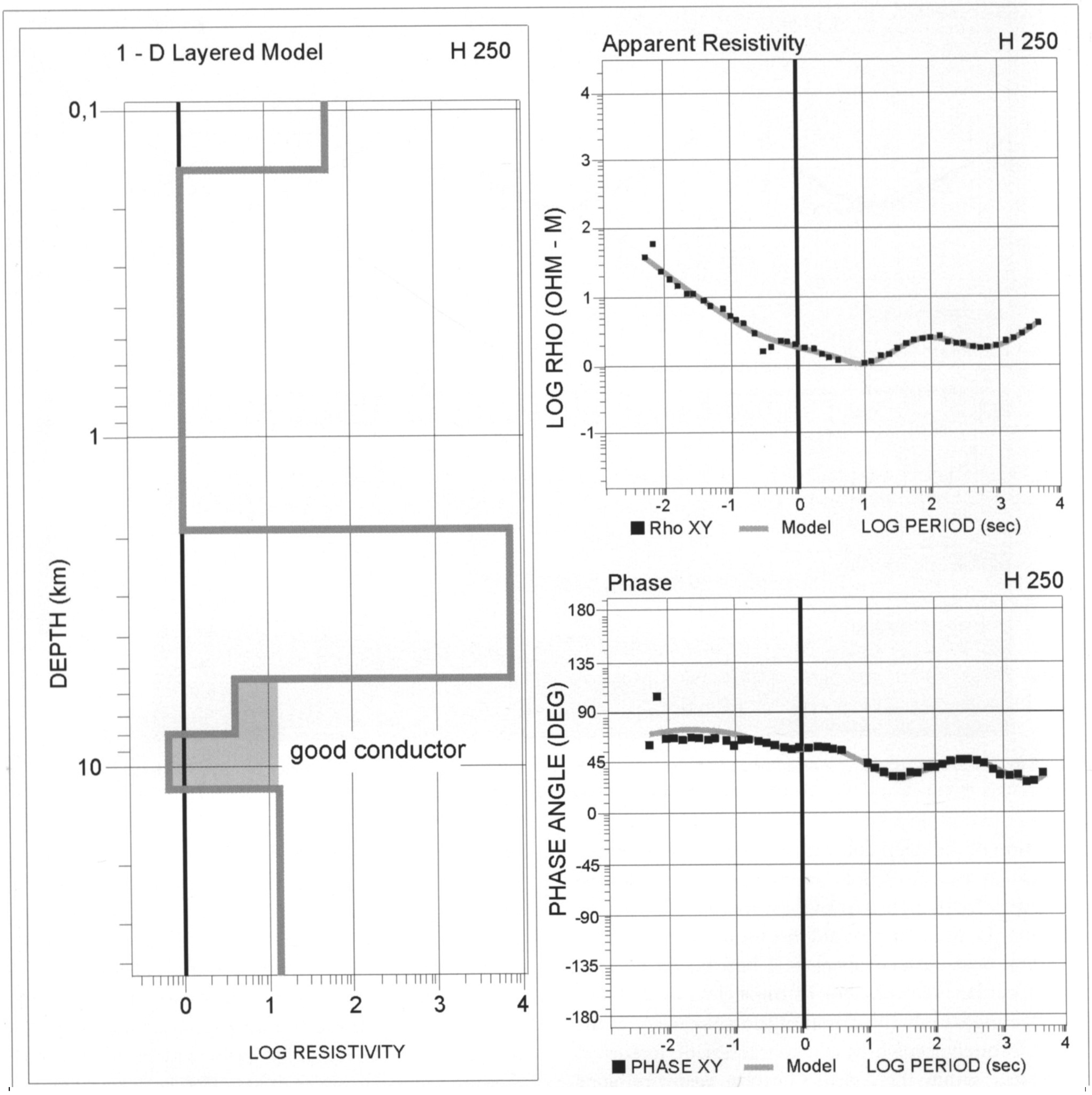

Fig. 4. Magnetotelluric sounding curves (apparent resistivity and phase angle) and layered resistivity model of site H250, located near the Dutch-German border. The good conductor occurring at a depth of about 8- 10 km is either related to the 'Rhenohercynian Alum shale' or the 'Bowland shale facies'.

cal analyses of highly coalified, TOC-rich and in part also pyrite rich, air-dried black shales from the Early Namurian of the borehole Münsterland 1 demonstrated the prevalence of quasi-metallic conduction in pre-graphitic carbonaceous matter after reaching the stage of meta-anthracite (Rr > 3.5%, Rmax > 4%) (Jödicke, 1984; Duba et al., 1988). In complex electrical measurements the quasi-metallic behavior is readily shown by its almost perfect frequency independence together with very low resistivity valeus at frequencies between 10^{-3} and 10^{6} Hz and phase values close to 0° between 10-3 and 104 Hz (Fig. 5). The decreasing phase values at frequencies > 104 Hz may be due to some water still remaining after drying the sample.

The importance of this alternative conduction mechanism may be illustrated by the resistivity-depth distribution of the Münsterland 1 borehole (Fig. 6): Below the near-surface good conductor of the Upper Cretaceous marls (200 – 1500 m) and the more resistive Cenomanian limestones (1500 – 1800 m) an Upper Carboniferous sequence of alternating shales, siltstones, and sandstones is present. Accordingly, the

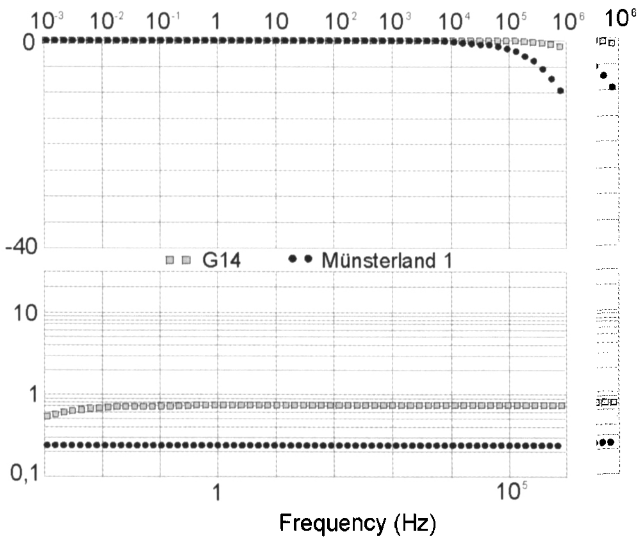

Fig. 5. Bode plot of impedances measured on dry black shale samples using a 2-pole array (Markfort 1998).

laterolog exhibits alternating resistivity values with an overall, clear and almost linear depth trend to higher values (dashed line). This is interpreted as a compaction-related decrease of porosity with depth (e.g. Schön 1983). The depth trend of increasing resistivity, which is the same as means decreasing electrolytical conductivity, reverses around 4000 m. At that depth coalification has reached the transition from the anthracite to the meta-anthracite stage (Teichmüller et al. 1979). Below 4500 m good conductors appear unexpectedly. These are interpreted to be TOC-rich shales (indicated by arrows in Fig. 6). The most important of these deep conductors occurs at 5400 – 5500 m depth and is characterised by resistivities lower than those of the near-surface electrolytical conductor. It consists of black shales and Alum shales of the Dinantian and Early Namurian Kulm facies also known as *Rhenohercynian Alum shales* (Hoffmann et al. 1998). The highly conductive quasi-metallic Münsterland 1 sample shown in figure 5 was taken from a core from the "Hangende Alaunschiefer". The sample from a depth of 5415 m has a TOC-content of 5 to 8% and vitrinite reflectance values between 4.5 and 6.4% Rr (Teichmüller et al. 1979).

The transition to highly conductive carbonaceous matter seems to occur relatively abruptly in the meta-anthracite stage. It correlates with the "pre-graphitization step" as indicated by optical properties that marks the onset of reflectance anisotropy (Teichmüller et al. 1979). At this stage the irreversible transition from amorphous carbon to crystalline carbon starts; first true graphite crystals become observable in X-ray and REM analyses (e.g. McCartney and Ergun 1965). To cause high conductivity in a rock, interconnectivity of the carbonaceous/graphitic matter is also an essential prerequisite. In highly coalified black shales the required conductive pathways appear to be formed by submicroscopical films of kerogen relics covering grain surfaces. These kerogen films result from adsorption of dissolved organic carbon onto clay mineral surfaces during deposition and from impregnation of the rock matrix with substances similar to humic acids at a very early stage of diagenesis (Tis-

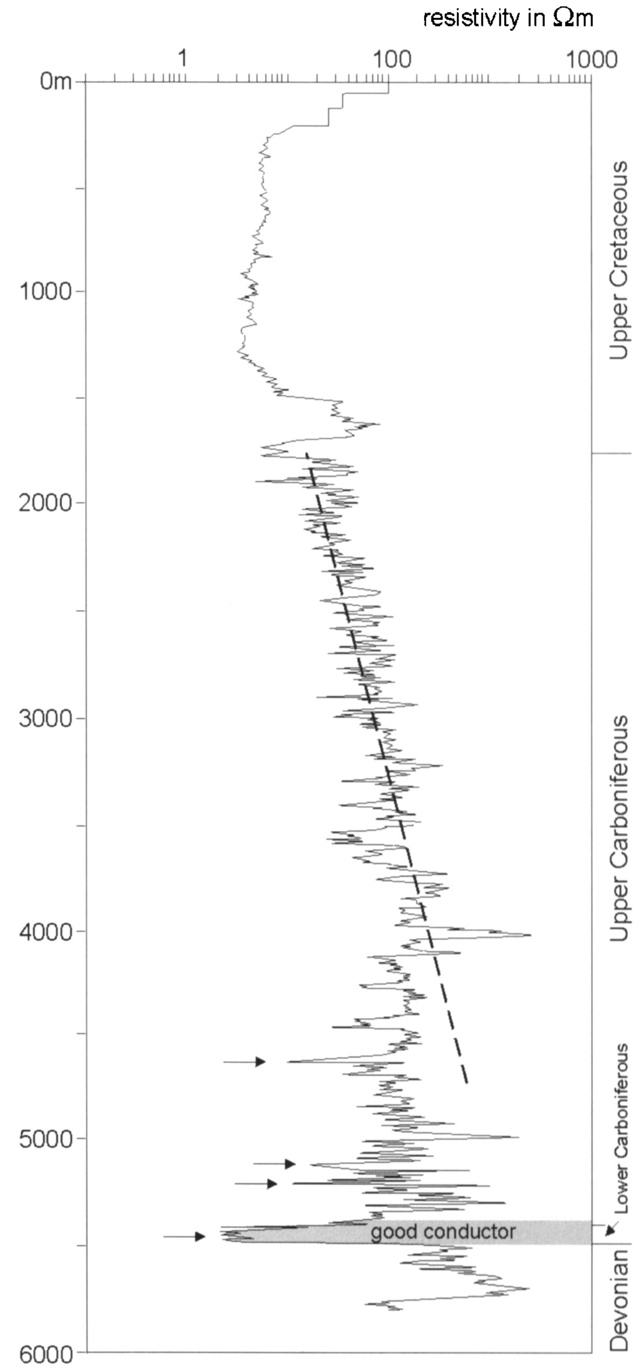

Fig. 6. Resistivity-depth distribution of the Münsterland-1 borehole compiled from geoelectric sounding (0-200 m) long normal lateral (200-1800 m), and laterolog (1800-5800 m) (after Richwien et al. 1963; Jödicke 1992).

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sot and Welte 1984). At low temperature diagenesis these impregnations can be visualised by fluorescence methods (Stach et al. 1982). Because of steady loss of kerogen compounds with increasing coalification, the films become thin and can hardly be identified by optical methods once the meta-anthracite stage has been reached. To maintain the interconnectivity of the films or, respectively, the high conductivity, the TOC-content has to exceed approximately 3% for meta-anthracitic black shales. Pulverising the samples destroys the conductive pathways, and artificially compacted powder samples are resistive.

The interpretation of deep conductors in the North German basin as highly coalified black shales allows to identify their stratigraphical position. For instance, the deep conductor extending from the islands of Rügen and Usedom to the Anklam fault in the south (Fig. 2) is correlated with the Cambro-Ordovician Alum shales. These *Scandinavian Alum shales* were penetrated at a depth of 1.6 km in offshore well G14, 40 km north east of the island of Rügen in the Baltic Sea (Franke et al. 1994). These shales are very extensive, e.g. in Sweden as highly resistive mature oil shales (Anderson et al. 1985). Close to the southeastern edge of the East European Platform, e.g. in the G14 well, they exhibit vitrinite reflectance values sufficient to cause high conductivity in this TOC-rich

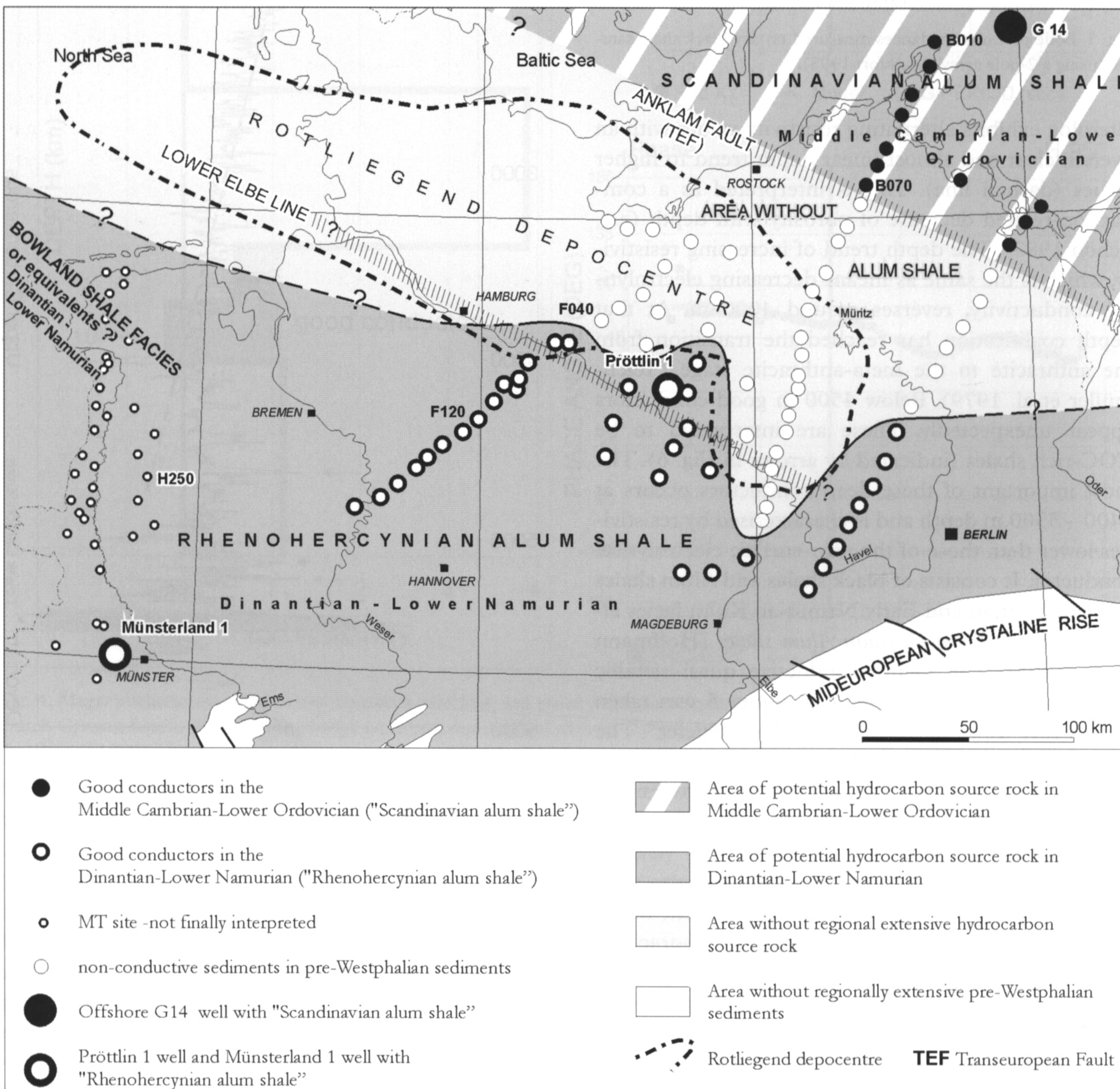

Fig. 7. Regional distribution of potential pre-Westphalian gas source rocks in the deeper subsurface of the North German basin as derived from electrical conductivity and geochemical data.

horizon (Buchardt and Lewin 1990). This was indicated by complex electrical measurements of a sample stemming from a depth of 1600.2 m in well G14. This sample is representative of a 30 m thick series of the Middle to Late Cambrian Alum shales. Containing up to 9% TOC at reflectance values of 4.5 – 5% Rr the low resistivity dry sample clearly displays the predominance of the quasi-metallic conduction mechanism (Fig. 5).

In the area between the Anklam fault and the Lower Elbe Line, there are no indications for the presence of good conductors within the pre-Westphalian sediments. Therefore, we conclude that no black shales of regional extent have been deposited in the area of the Rotliegend depocentre. The *Scandinavian Alum shale* is probably absent as this area forms part of the Caledonian magmatic arc, which originated from the collision of East Avalonia with Baltica during the Ordovician to Early Devonian. This zone is characterised by positive magnetic and gravimetric anomalies (East Elbian Massif). The absence of the *Rhenohercynian Alum shale* is probably due to the fact that during the Lower Carboniferous this area was not a poorly oxigenated, starved basin but probably a carbonate platform (Kohlenkalk facies).

South of the Lower Elbe Line, good conductors appear at depths of 7 – 10 km in northern Brandenburg, southwestern Mecklenburg and Lower Saxony, i.e. in the external Variscan zone. Based on a comparison with geological sections (Kockel 1996) the deep good conducting layer most probably correlates with the *Rhenohercynian Alum shales* as encountered in the Münsterland 1 and Pröttlin 1 boreholes. Similar, stratigraphically older horizons of possibly Cambro-Ordovician age, that cannot be resolved through magnetotelluric modelling, may contribute to the conductance. This also holds true for the deep conductor near the Dutch-German border. Here, a connection with the Early Namurian *Bowland shale formation* or equivalents, which may extend from the Anglo-Dutch basin into the study region, should not be excluded (Cameron 1993).

The interpretation of deep conductors in the North German basin as being due to a quasi-metallic conduction mechanism in highly coalified carbonaceous matter is considered an important result. However, it is not yet clear how the huge conductance values (1000 S north of the Anklam fault, 5000 S in the center of *North German Conductivity Anomaly*) should be explained. Hoffmann et al. (1998) summarized arguments that the *in-situ* conductivity of black shales may be systematically under-estimated as laboratory tests are not done under in situ conditions. Furthermore, accumulation of graphite in shear fracture zones developed within meta-anthracitic black shales could substantially increase total conductance. Given these assumptions, the deep conductor in north west Germany may be interpreted as a series of black shales with a total thickness of 100 – 250 m, and the deep conductor north of the Anklam fault by the presence of a 40 – 50 m thick black shale (Hoffmann et al. 1998).

Organo-geochemical indications for the presence of active pre-Westphalian source rocks

Given the maturity of organic matter at the Top pre-Permian level (cf. Fig. 8), the thickness and the distribution of the Palaeozoic sediments, as well as the type of organic matter, the Namurian and Dinantian source rocks are considered as potentially active gas generators. Dinantian sediments only contain black shales with TOC-contents as high as 12%. The organic matter in Namurian sediments can be subdivided in a lower, predominantly marine part with TOC-contents as high as 2% (NB – the basal Namurian hot shales (Bowland shales and equivalents) have TOC-contents as high as 60%) and an upper, predominantly paralic to deltaic facies – beginning in Lower Namurian B – with intercalated coal measures or dispersed coaly matter (Kessel 1994, Everlien & Wehner 1994, Gerling et al. 1999).

Since these source rocks have only rarely been drilled, indirect methods are needed to detect the presence of active, deeply buried source rocks. One method is the identification of gas from pre-Westphalian sources in producing reservoirs. A detailed understanding of gas generation is the basis for this approach. Figure 9 shows how gas generation is simulated during open, dry, non–isothermal pyrolysis experiments (e.g. Krooss et al. 1993). The most important hydrocarbon gas, methane, is generated during a distinct temperature/maturity interval. Peak methane generation occurs at a temperature of approx. 550° C which corresponds to a maturity of 1–2% vitrinite reflectance. Beyond this temperature/maturity window, methane generation decreases and nitrogen generation increases continuously until the gas generated is pure nitrogen. This general "recipe" (disregarding diagenetic processes and without taking into consideration other hydrocarbon gases and carbon dioxide) is valid for all types of organic matter. However, the maturity level at which the change from a methane–dominated gas composition to a nitrogen-dominated one occurs is

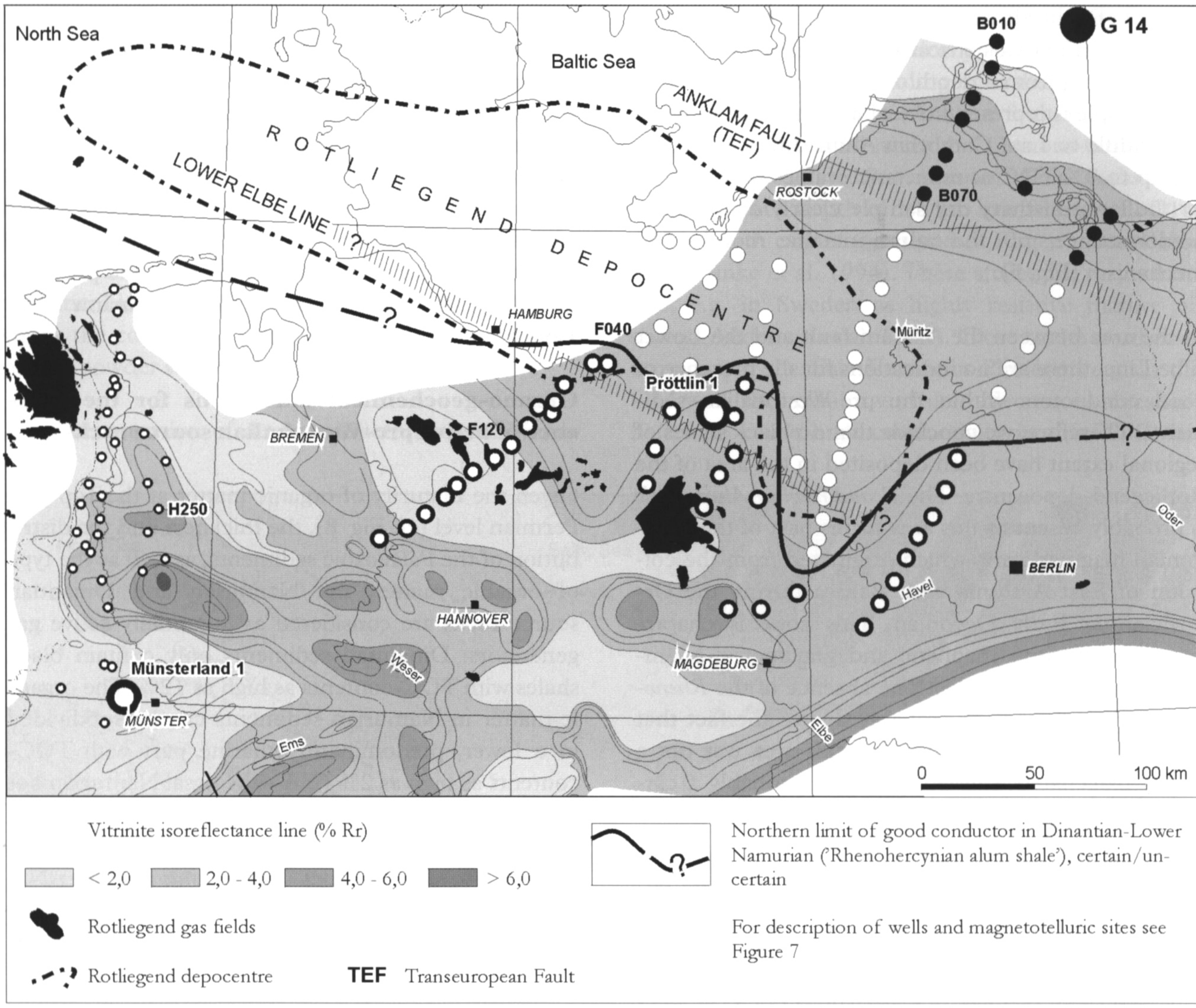

Fig. 8. Source rock maturity at the pre-Permian surface (after Koch et al. 1997), shown in combination with the regional distribution or electrical conductivity (after Hoffmann et al. 1998) and the occurrence of Rotliegend gas fields (after Lokhorst et al. 1998).

different for different source materials. It is highest for type III kerogens (coal). To differentiate gases sourced from various kerogen types, analysis of stable carbon and nitrogen isotope ratios in the gases is the key tool.

Stahl (1968) and Stahl & Carey (1975) were the first to qualitatively use the stable carbon isotope ratios of methane through propane reservoir gases to characterize type and maturity of the generating source. Subsequently numerous other researchers offered further suggestions on how to use stable carbon isotopes of gases in hydrocarbon exploration. In this paper, the variable methane/ethane type–maturity lines proposed by Berner & Faber (1996) are used. Figure 10 presents type–maturity trends for sapropelic and for terrestrial organic matter. The source type–maturity trends have to be adjusted to the carbon isotope ratio of the kerogen occurring in the area under study.

If a hydrocarbon gas contains only co-genetically generated methane and ethane from one of these sources, the corresponding pair of data should plot directly on or nearby a source type–maturity trend depending on the maturity of the source. However, very often natural gas has not been generated from a single source

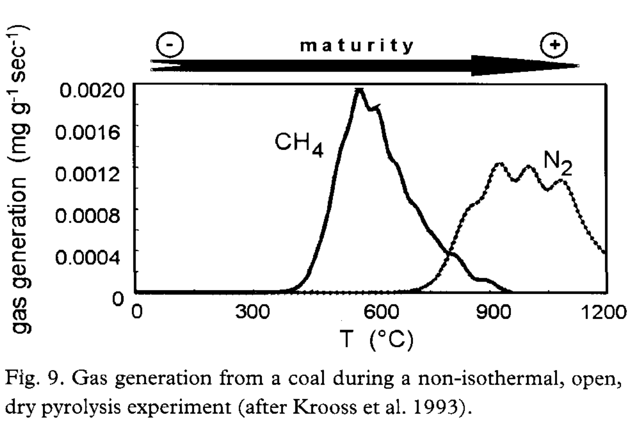

Fig. 9. Gas generation from a coal during a non-isothermal, open, dry pyrolysis experiment (after Krooss et al. 1993).

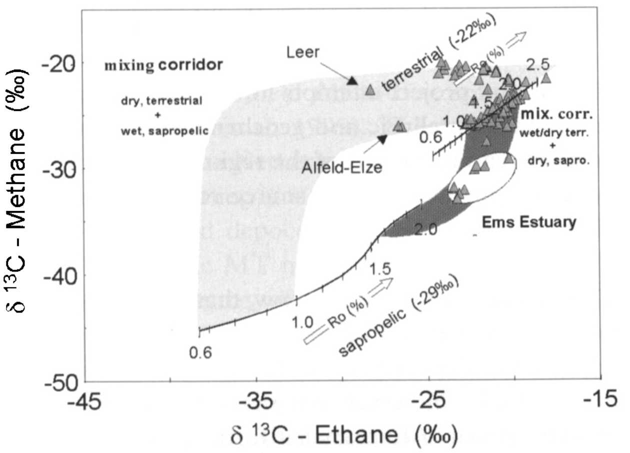

Fig. 10. Stable carbon isotope ratios of methane and ethane reflect type and maturity of the gas generating source rock. However, natural gases are very often a mixture from two or more sources. In such cases gases plot along intermediate trends.

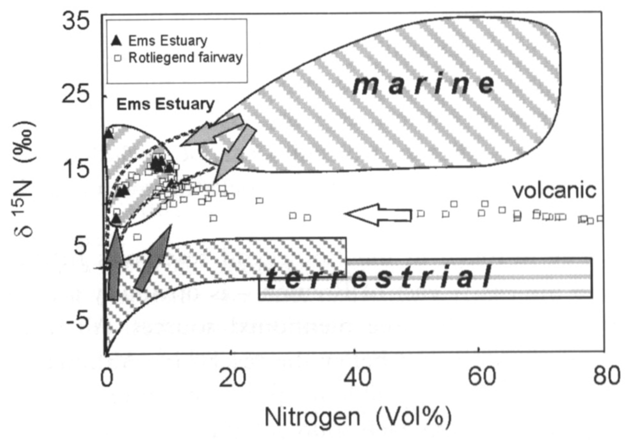

Fig. 11. Diagnostic plot for the genetic interpretation of nåitrogen gas (after Gerling et al. 1997).

rock but was derived from two or even more sources. In the case of two sources, isotope data generally plot off the source type–maturity trends. Using the molecular composition (e.g. methane / (ethane + propane)) and the stable carbon-isotope ratios of the individual end members, it is possible to calculate the proportions of gas derived from either sources.

Moreover, considering the variability of source types and maturities, two distinct mixing corridors (cf. Fig. 10) can be established. If the gas mixture is a product of a dry gas from a relatively high maturity coal and a wet gas from a relatively low maturity sapropelic precursor, it always plots in a band above the two-source type–maturity lines. If the gas mixture consists of a rather wet gas sourced from a low maturity coal and a dry gas from a higher maturity sapropelic source, it plots in a band below the source type–maturity trendlines.

Applying this diagnostic plot to the natural gases from the Rotliegend fairway in northern Germany (see Fig. 8), it is clear that most gases have been generated from a terrestrial source rock at various stages of maturity. For decades it has been established that the Westphalian coal is this source (e.g. Patijn 1964, Stahl 1968). The source rock maturities shown on figure 10 fit satisfactorily with the measured coal ranks shown in figure 8. However, some gases obviously contain a proportion of wet gas from a relatively low maturity sapropelic source. It has been shown by Gerling et al. (1999) that these admixed gases are derived from marine organic matter in Zechstein sediments. The proportions have been calculated to be less than 1% in case of the Altmark gases and about 10% in the case of the natural gas from the Leer field.

This result indicates, that none of these trapped hydrocarbons contain an admixture from a pre-Westphalian source.

However, all natural gases produced from reservoirs in the 'Ems Estuary' production province clearly indicate a mixed origin, with hydrocarbons predominantly generated by a rather mature marine source. Taking into account the low maturity at the Top pre-Permian (Fig. 8) and the distribution of pre-Westphalian source rocks, the Bowland shales or equivalents from the Base Namurian are the most probable source of these gases. Moreover, all reservoirs contain varying amounts of hydrocarbons generated by Westphalian coal seams. It should be noted that most Rotliegend gases from the Netherlands and from the southern North Sea show similar compositional mixtures (Lokhorst et al. 1998, Gerling et al. 1998).

After methane, nitrogen is the second most abundant gas in Rotliegend reservoirs. It may locally comprise up to 80% of the gas. Nitrogen isotopes are well suited to identify nitrogen from different sources. Isotopic and molecular nitrogen data from pyrolysis experiments, from autochthonous Zechstein source-reservoir combinations, and from Zechstein salt dome gases are the basis for the diagnostic plot shown in figure 11. It is evident that the nitrogen in Rotliegend reservoirs from North Germany represents neither a purely terrestrial origin nor a purely marine organic origin. Only the nitrogen gases from the Altmark area are uniquely identifiable as virtually pure volcanic nitrogen. All other nitrogen gases are mixtures derived from two or even from three sources.

– All nitrogen in reservoirs in the 'Ems Estuary' area

are a mixture of a minor amounts of nitrogen from the low maturity Westphalian coal and major amounts of nitrogen derived from a higher maturity marine source, e.g. the Base Namurian hot shales. Rotliegend volcanics can be excluded as a possible source since these rocks do not occur in this area.
- The nitrogen in the Rotliegend reservoirs further to the east – east of Bremen – is obviously a mixture from all three mentioned sources. All three sources do occur below the reservoirs. Although it is currently impossible to specify which proportion is derived from each source, figure 11 shows that a certain amount of nitrogen is derived from a pre-Westphalian marine source as a post–Rotliegend gas source is most improbable regarding their isotopic composition.

What do the above observations imply for the quality of the source rocks?

The relatively low maturity Westphalian coals (~ 1% vitrinite reflectance) in the 'Ems Estuary' area generated a high calorific (rather wet) natural gas with very small amounts of nitrogen, probably below 1 vol%. The basal Namurian hot shales (Bowland shale or equivalents) contain marine organic matter, which is still within the dry hydrocarbon gas window albeit with elevated nitrogen contents. A mixture of these two gases occurs in the Rotliegend reservoirs in this area. Rotliegend volcanics are not present in the 'Ems Estuary' area.

The Altmark gas field lies directly above a thick sequence of Rotliegend volcanics which unconformably overlie discordantly on Namurian sediments containing dispersed coaly matter. The maturity is > 2% Rr. About 99.5% of the hydrocarbon gases is derived from this dispersed coaly matter, the remaining 0.5% is derived from organic matter in the Staßfurt-carbonate (Zechstein). However, the main nitrogen source, is the thick volcanic sequence directly underlying the reservoir rocks. Admixtures from pre- and post-Rotliegend organic sources play a minor role.

The reservoirs in between these two areas only received their hydrocarbons from the relatively high maturity Westphalian coal seams (~ 2% Rr). This source also generated some nitrogen with ä^{15}N-values < +5‰. The basal Namurian hot shales are already 'overcooked', meaning, that they generate only nitrogen with ä^{15}N-values >> +10‰. A moderately thick sequence of volcanic rocks directly below the reservoir rocks probably also contributed some nitrogen.

Conclusions

The present project attempts for the first time to integrate magnetotelluric and geochemical data with the goal of creating models of the regional distribution of potential pre-Westphalian source rocks in the North German basin.

The magnetotelluric data show, that areally extensive pre-Westphalian source rocks are unlikely to be present in the depocentre of the North German Rotliegend basin. However, northeast of this area Cambro-Ordovician Alum shales form good conductive layers. These Alum shales have been encountered in boreholes and outcrops in Scandinavia. The good conductive layers to the south of the central Rotliegend basin can be correlated with Dinantian and Early Namurian black shales whose presence has been established in boreholes.

Pyrolysis experiments indicate that the highly mature Cambro-Ordovician source rock only has a very minor residual gas generation potential. However, the Dinantian/Early Namurian source rocks still have generating potential. Depending on the source rock maturity, these rocks still generate gas of differing quality along the Rotliegend fairways. Such gases have been identified in several gas fields using gas and isotope geochemical tests.

Based on these results the following conclusions are drawn:
- Magnetotelluric measurements provide new paleogeographical and tectonic information on the deep subsurface.
- The presence and gas generation capacity of pre-Westphalian source rocks can be evaluated based on gas and isotope geochemical data from gas reservoirs. Magnetotelluric data can be used to put this information into a regional context.
- An excellent example of this are the results for the 'Ems Estuary' gas province: The presence of good conductive layers in the pre-Westphalian sequence correlates with the gas and isotope geochemical indicators of the pre-Westphalian marine source rocks having been a major source of hydrocarbon gas in the Rotliegend gas fields.
- The same conclusion is drawn for the fields in the Rotliegend fairway further to the east. As these pre-Westphalian marine source rocks are already post-mature, they are the main source of nitrogen in those fields.
- The whole area with Dinantian-Namurian source rocks is prospective for deep gas. This is also valid

for other areas than the presented study area. Gas sourced from pre-Westphalian source rocks is assumed for the gas field Alfeld-Elze south of Hannover (Gerling et al. 1999). The same holds for large areas of the Netherlands and for the southern North Sea (Gerling et al. 1998).
- The Rotliegend depocenter is not prospective for deep gas as the MT measurements failed to indicate the presence of extensive pre-Westphalian source rocks.

This preliminary integrated study has yielded very promising results. Further work should help to delineate the distribution of deeply buried marine source rocks.

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