

THE EAST GRONINGEN MASSIF – DETECTION OF AN INTRUSIVE BODY BY MEANS OF COALIFICATION

D. KETTEL¹

ABSTRACT

Kettel, D. 1983 The East Groningen Massif – Detection of an intrusive body by means of coalification. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): Petroleum geology of the southeastern North Sea and the adjacent onshore areas (The Hague, 1982) – Geol. Mijnbouw 62: 203-210.

Coalification data measured in Late Carboniferous strata are available from wells in the Ems estuary and in the southern part of the German North Sea.

The grade of maturity was calculated for the surveyed horizons using Lopatin's method, from the burial history, present temperature gradient and surface temperature, and these calculated data were compared with the measured ones. Positive differences (measured value higher than calculated) indicate the presence of a heat anomaly probably caused by a buried intrusive body, the 'East Groningen Massif'. The shape of this anomaly coincides with the present and past regional structural trend in this area. The same applies for a positive aeromagnetic anomaly in this area.

It can be assumed that the age of the East Groningen Massif is around the Jurassic-Cretaceous boundary, i.e. Late Kimmerian.

INTRODUCTION

In exploration for oil and natural gas, it is important to have information about the maturity of specific horizons, especially in areas where no coalification data are available.

For this reason various methods have been developed, to calculate the degree of maturity of rocks – expressed as vitrinite reflectance (R) – from the burial history (B) and the present-day temperature gradient (T). This is only meaningful, however, when the present temperature gradient is the same as in the geological past, i.e. if the influence of the palaeotemperature gradient (P) is zero.

$$B + T + P = R \quad (1)$$

$$B + T = R, \text{ when } P = 0 \quad (2)$$

This assumption is generally not valid. Therefore, with reference to Equation (1), either the maturity can be calculated directly if the palaeotemperature gradient is known, or if the maturity has been measured (R_{meas}) for a

given horizon then the influence of the palaeotemperature gradient (P) can be calculated.

$$P = R_{\text{meas}} - (B + T) \quad (3)$$

Several authors have attempted to calculate the regional temperature gradients in this way for certain parts of the stratigraphic sequence in wells for which a complete coalification survey has been carried out. In the author's opinion this leads to problems for the following reason: the relatively small variations of the regional temperature gradient in the geological past are hardly detectable by vitrinite reflectance measurements using LOPATIN's model, which, for the case of a continuously subsiding basin, assumes a small influence of temperature on maturation in the geological past. Only a very sharp rise in the local palaeogeothermal gradient, such as might be caused by magmatic heating, can still be detected on a short coalification profile.

Calculations using Equation (3) have been applied to the area of the Ems estuary and the southern part of the North Sea where exploration is still in progress. The available maturity data (R_{meas}) consists of some short coalification profiles and some single measurements carried out on Upper Carboniferous samples. The influence of the palaeotemperature gra-

¹ Niedersächsisches Landesamt für Bodenforschung, D-3000 Hannover 51. Present address: Wintershall A.G., P.O. Box 104020, D-3500 Kassel, Germany.

dient (P) is expressed as:

$$\Delta R = R_{\text{meas}} - R_{\text{calc}} \quad (4)$$

where $\Delta R \hat{=} P$ and $R_{\text{calc}} = B + T$

For the reasons mentioned above, it can be expected that negative differences ΔR ($R_{\text{meas}} < R_{\text{calc}}$) due to a lower geothermal gradient in the geological past remain very small, whereas positive differences ΔR ($R_{\text{meas}} > R_{\text{calc}}$) may, in the case of magmatic heating, be infinitely large.

In the following account these differences, ΔR , are plotted and an interpretation is presented.

THE METHOD

LOPATIN's method, which was modified by WAPLES (1980), is used to describe the relationship between the temperature (expressed as T and P), time (expressed as B) and maturity (expressed as R). Suitable parameters for use with this method have recently been determined for the maturity range of the oil window (0.6 – 1.2% VR) in the Northwest German Basin (Fig. 1) (KETTEL, 1981).

In the relationship

$$TTI = \sum_{n \text{ min.}}^{n \text{ max.}} (\Delta T_n) (r^n)$$

TTI is the maturity of a sediment and ΔT is the time spent by the sediment in the temperature interval n . The temperature factor (r) was given the value of 2 by WAPLES (1980) after evaluation of a world-wide compilation of TTI values and measured reflectivities. A value of $r = 1.6$ was chosen by KETTEL (1981) for the maturity range of the oil window after evaluation of the data from selected wells in North Germany. This value of r is used here, since it is certain that, for the wells employed for its selection, the palaeogeothermal gradient was not appreciably higher than it is today, i.e. $P = 0$ in Equation (1). In addition, a new relationship was established linking TTI and the vitrinite reflection R_m (see KETTEL 1981, Fig. 11).

MEASURED COALIFICATION VALUES AND THE PRESENT-DAY TEMPERATURE FIELD

The coalification measurements used were obtained from the laboratories of the Geological Survey of North Rhine-Westphalia in Krefeld, the Rheinelbe Company, the Federal Institute for Geosciences and Natural Resources in Hannover and the NAM in Assen by courtesy of the German North Sea

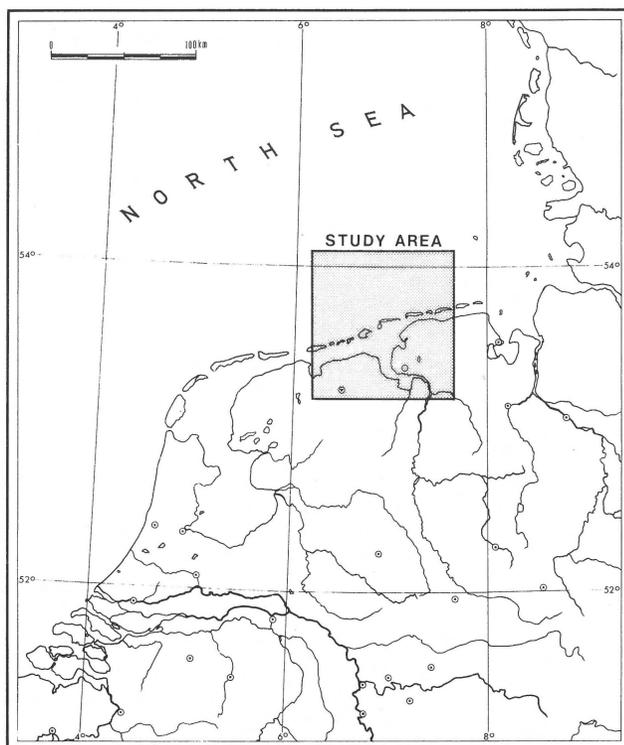


Fig. 1
Location map.

Consortium, Mobil Oil A.G. and NAM.

About half of the coalification data belong to relatively short coalification profiles determined over sections of about 100 m of Carboniferous strata, for which gradients can be drawn on a semilogarithmic plot closely fitting the points. The individual measurements show an error of less than $\pm 0.2\%$ VR, with the exception of the highly coalified material from one well, the values of which vary by a considerable amount over a vertical distance of about 200 m. The other values are individual measurements from the Carboniferous; these can deviate from the coalification gradient within about the same limits.

On a plot of the coalification gradients (Fig. 2), it is noteworthy that the coalification values for approximately the same stratigraphic unit (Westphalian C) to which most of the samples belong, fall into 3 main fields:

- a) a field of low coalification ($< 1.5\%$ VR, in the central part of figure 2) caused by the small depth of burial in the area between the Groothusen and Greetsiel-Uttum gas fields;
- b) a field of higher coalification ($< 1.5\%$ VR, in the lower part of figure 2) caused by deep burial, in the area to the NE of (a);
- c) a field of still higher coalification ($> 1.5\%$ VR, in the upper part of figure 2) in spite of a smaller amount of subsidence than case (a), to the SW and W of (a).

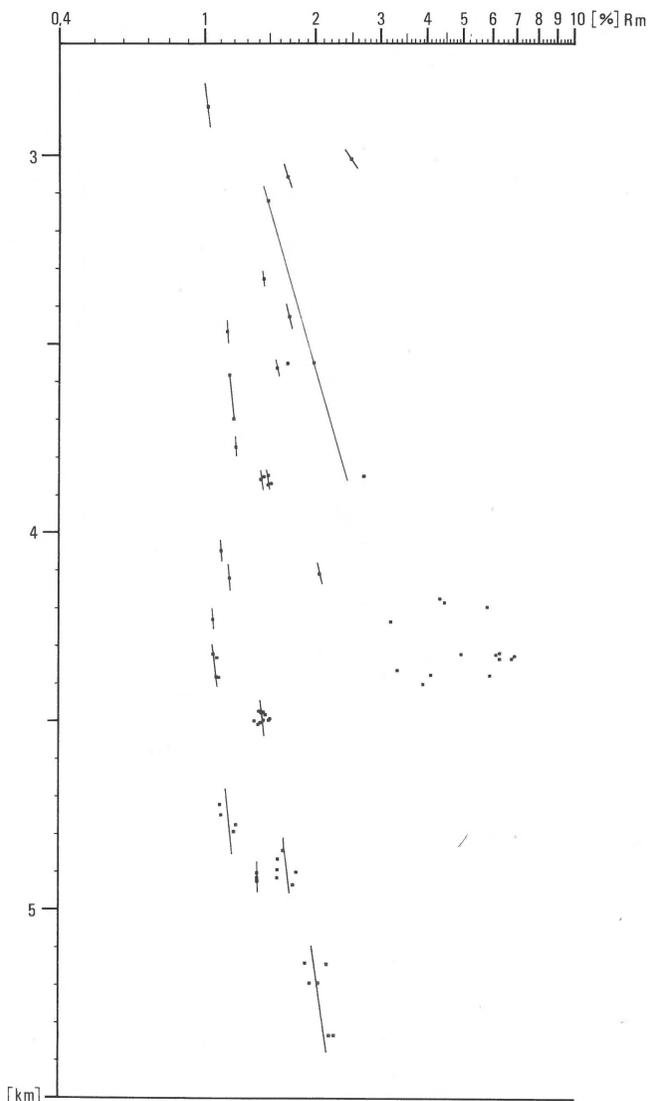


Fig. 2
Vitrinite reflection gradients in the studied area.

The present-day temperature field was taken from the temperature atlas of HÄNEL (1980) in which it is plotted for different depths. The temperature gradient generally decreases with depth. Therefore, temperature gradients were calculated using the temperature atlas taking into account the present-day depth of burial of the Westphalian, since, according to LOPATIN, temperature at deepest burial, which in this case is its present depth, has the greatest influence on the maturity.

THE COALIFICATION ANOMALY

The grade of coalification was calculated for all wells and horizons for which coalification measurements were available, using LOPATIN's method modified by WAPLES (1980) and KETTEL (1981) as a function of the burial history, the current

temperature gradient and the surface temperature. The calculated value was compared with the measured value. There are three possibilities:

- the calculated value agrees with the measured value ($\Delta R = \pm 0$ in figure 3);
- the measured value is larger than the calculated value by an indefinite amount (positive ΔR in figure 3);
- the calculated value is larger than the measured value, but the difference does not exceed 0.25% VR (negative ΔR in figure 3). (A negative coalification difference is referred to as a coalification deficit).

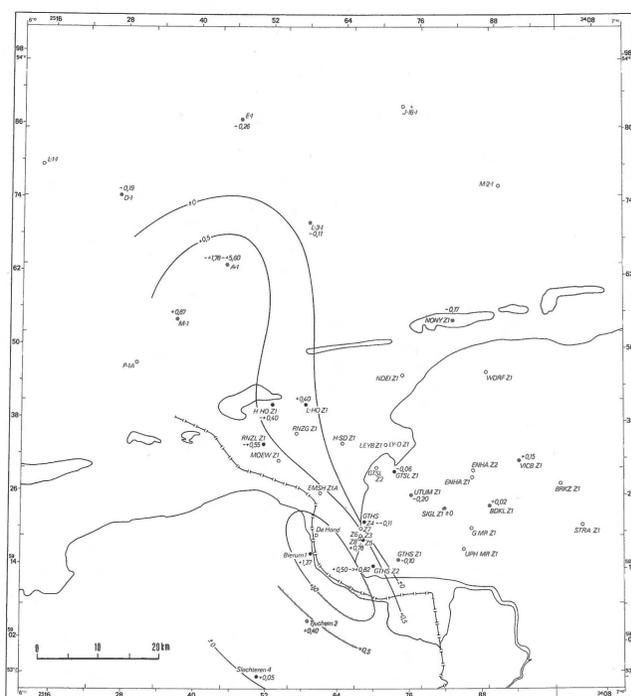


Fig. 3
Plot of the difference between measured and calculated coalification values (First approach).

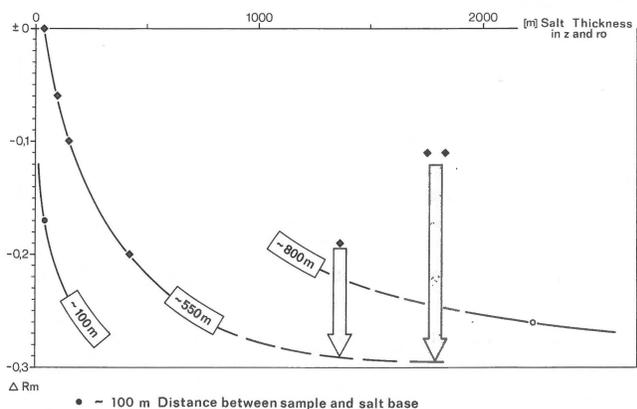


Fig. 4
Relationship between coalification deficit, salt thickness and distance between sample and base of salt.

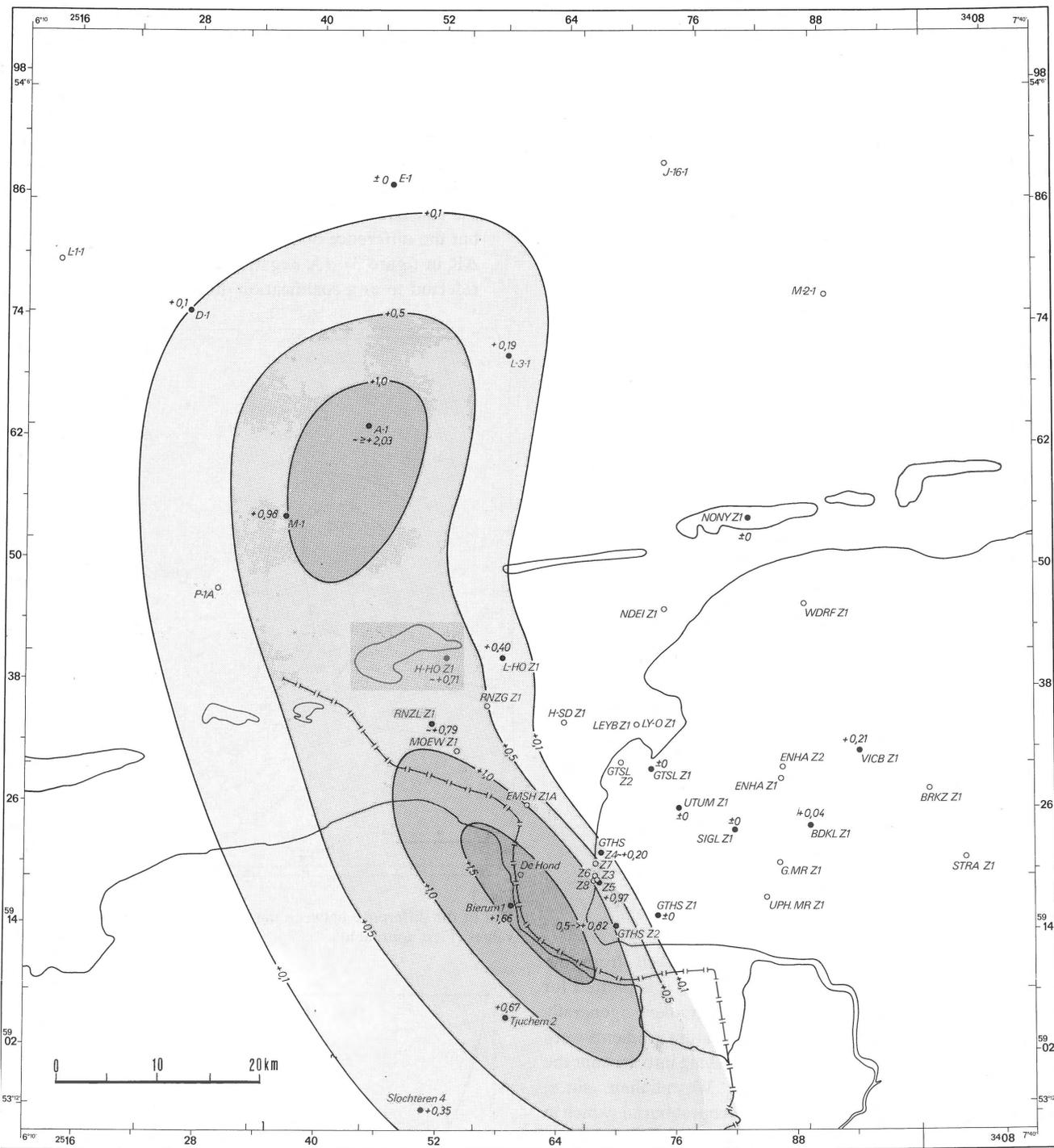


Fig. 5
Positive coalification anomaly due to the heating effect of the 'East Groningen Massif' (Second approach).

The positive differences are so large that they could not have been caused by an elevated regional palaeogeothermal gradient (see above). They have certainly been caused by the presence of a magmatic intrusion. The isolines of positive coalification difference in figure 3 outline in first approximation the postulated 'East Groningen Massif'.

In spite of the fact that the negative differences fall within the limits of error of the method, an attempt has been made (see figure 4) to find an explanation for the coalification deficits. There appears to be a definite relationship between negative coalification differences in Upper Carboniferous horizons, the thickness of rock salt in the overlying Rotlie-

gendes and Zechstein, and the distance of the Upper Carboniferous sample to the base of the salt. It is known that salt accumulations can disturb the temperature field by causing overheating of the overlying strata and cooling of the underlying beds. The magnitude of this effect on any given horizon depends on the thickness of the rock salt accumulation and the vertical distance between the horizon and the salt, or in the case of a cooling effect, the base of the salt. It is shown in figure 4 that a certain relationship exists between the coalification deficit of Upper Carboniferous horizons caused by cooling over a fairly long period, and the thickness of the overlying Rotliegende and Zechstein rock salt. The nearer the given horizon is to the base of the rock salt, the more pronounced this effect becomes. JONES ET AL. (1972) have already found a coalification deficit in sections beneath strata with a relatively high thermal conductivity.

Three wells in the central part of figure 4 do not fit this relationship, the coalification deficit is too low in regard to the thickness of overlying salt. But all these wells lie on the edge of the field of positive coalification differences in figure 3, so that it can be postulated that these particular rocks were warmed up by the East Groningen Massif. If, in figure 4, the 3 points are shifted onto the appropriate curve corresponding to their distance from the base of the salt, then the shift in ΔR represents the degree of heating due to the massif.

It is likely that in all wells showing positive coalification differences, the cooling effect of the salt overlaps the warming effect of the massif. Thus all positive coalification differences are treated with the 'salt correction'. This procedure permits a map of positive differences (Fig. 5) to be drawn which portrays only the net warming effect of the massif, i.e. its thermal aureole, as accurately as is possible at present. The differences represent the proportion of the total coalification due to the heating effect of the massif, at a depth of about 4000 m.

EVIDENCE FROM THE TECTONIC HISTORY

The most important structure-forming events since the Variscan movements in the region-under-discussion took place during the Late Kimmerian deformation and intra-Cretaceous tilting. Structural analysis was used to obtain the probable pre-Late Kimmerian (i.e. Jurassic) structure of the top of the Rotliegende. This was achieved by removing the effects of the probable intra-Cretaceous and Late Kimmerian movements in NE-SW sections across the strike (an example of such a section is given in figure 6). In the SW part of the section in figure 6, it is possible to recognise the rise to the Groningen High which can be traced back to Cretaceous times. In the Jurassic, the SW-dipping flank of a high region northeast of the present Groningen High occupied this position. This flank was uplifted during the Late Kimmerian movements and developed into part of the Groningen High itself.

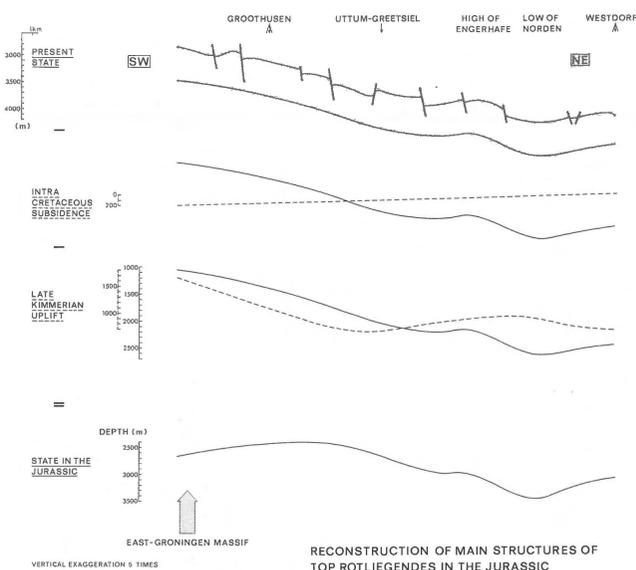


Fig. 6
Reconstruction of the general shape of the Top Rotliegende in Jurassic times.

Figure 7 shows the structure contours of the top of the Rotliegende for Jurassic times together with the coalification anomaly which is delineated by means of the $\Delta R = +0.5$ and $+1.0\%$ VR isolines. It is particularly noticeable that the crest of the coalification anomaly occurs exactly below the SW-dipping flank of the Jurassic high, namely at the site where Late Kimmerian uplift took place subsequently. This suggests that the Late Kimmerian uplift, that formed the Groningen High, was genetically connected with the intrusion of the East Groningen Massif, and that the East Groningen Massif was intruded around the Jurassic-Cretaceous boundary.

THE MAGNETIC ANOMALY

Figure 8, which is compiled from VELDKAMP (1951) and the BGR (1976), shows a positive aeromagnetic anomaly in the area of the Ems estuary and the German-Dutch border. The coalification anomaly is also shown in figure 8. Both the coalification and the magnetic anomalies are split into two maxima, a northern and a southern one, which are separated by a line roughly through the Friesian Islands. Both anomalies describe an arc which runs approximately parallel to the general strike of the present-day structures. The two southern maxima (coalification and magnetic) coincide closely and support the idea of a buried igneous mass in this position. It is significant that chalcocite, bornite and covellite, probably due to secondary mineralization, occur in Upper Carboniferous and Zechstein strata in Grootghusen (pers. comm. Dr. M. Wolf, Aachen, with the courtesy of the Brigitta und Elwerath Betriebsführungs-Gesellschaft Company).

The two northern maxima are not coincident, i.e. the coalification maximum lies on the SW edge of the magnetic

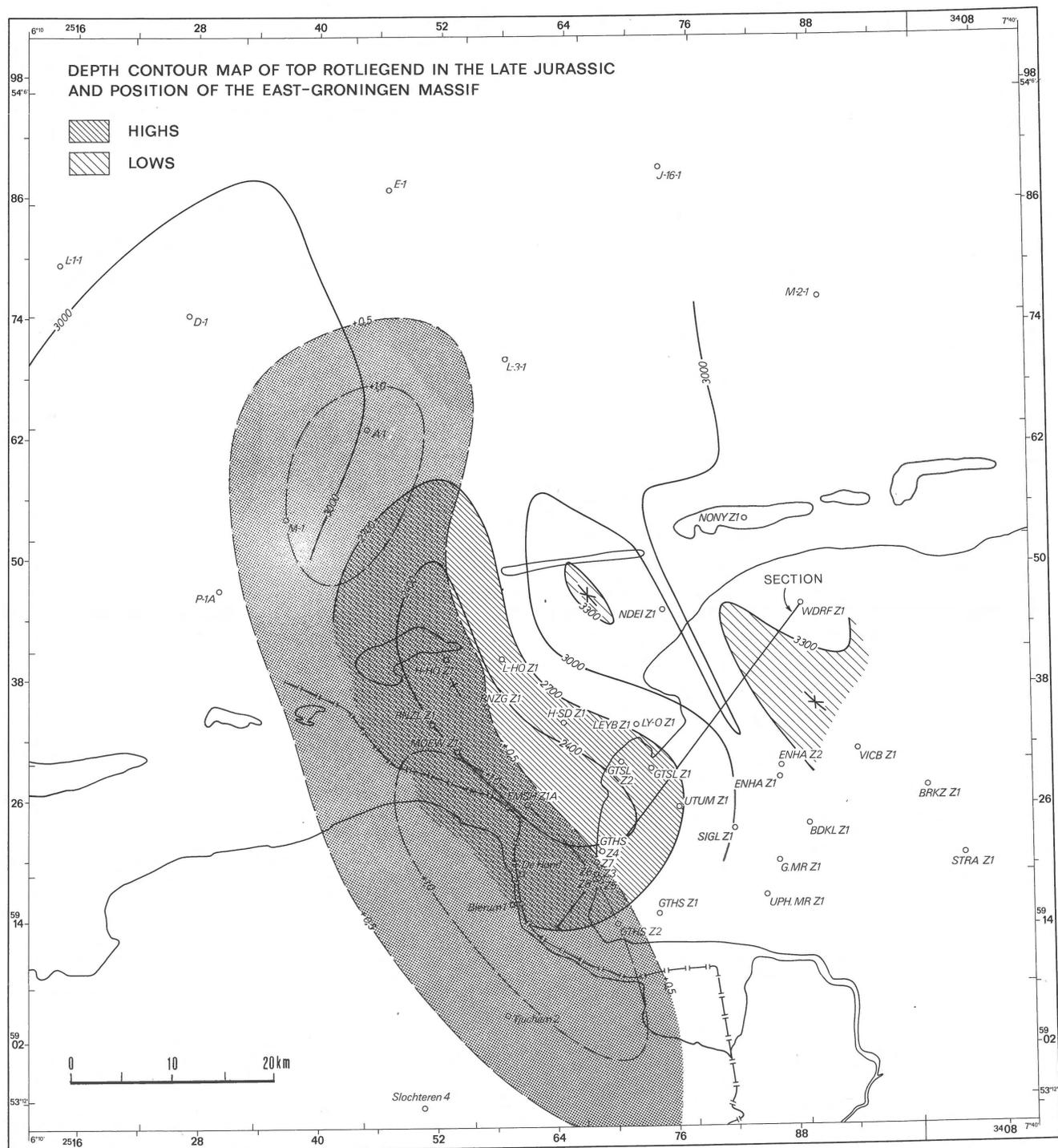


Fig. 7 Structure contour map of the Top Rotliegendes in Late Jurassic times and the position of the positive coalification anomaly (taken from Fig. 5).

maximum. In view of the wide variation in the coalification values in this area, it might be inferred that the northern coalification maximum is due to a dyke swarm which may have originated from an intrusive body lying to the northeast. In each case the northern anomalies are weaker than those in the south.

VAN WIJHE ET AL. (1980) point to the existence of magnetic anomalies in the eastern part of the Groningen Field which are interpreted as being due to an igneous intrusion; they are associated with abnormally high coalification values in the Upper Carboniferous (see also VAN WIJHE & BLESS, 1974). These authors infer an Early Rotliegendes age for the

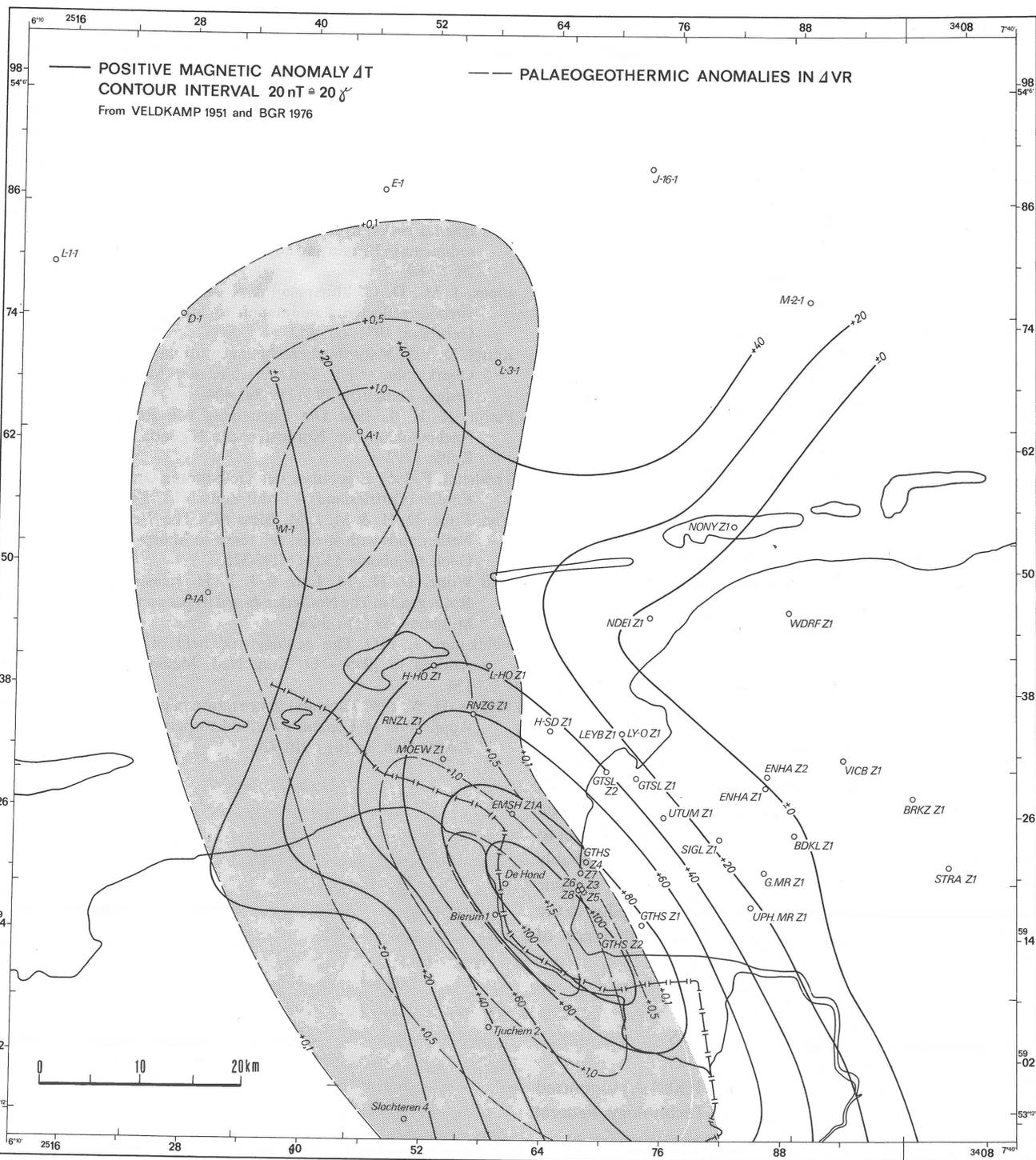


Fig. 8
The positive magnetic anomaly and the positive coalification anomaly (taken from Fig. 5).

intrusion.

DISCUSSION OF THE AGE AND SHAPE OF THE MASSIF

The nearest point to the East Groningen Massif where

extrusive igneous rocks have been dated is the onshore Zuidwal-1 well in North Holland. They are trachytes, phonolites, phonolitic basanite, i.e. alkali-rich, intermediate to basic volcanic rocks with solidification ages of 144 ± 1 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, DIXON ET AL., 1981) and 145 Ma (K-Ar, HARRISON ET AL., 1979). Age determinations ($^{40}\text{Ar}/^{39}\text{Ar}$) on nephelinites

and basanites from the Andel 2, Andel 4 and Loon-op-Zand 1 wells in South Holland by DIXON ET AL. (1981) gave ages close to the Jurassic-Cretaceous boundary. The volcanic rocks extend into the Dutch sector of the North Sea (K 14-FA 103, L 13-3 and Q 7-2 wells).

This evidence, together with that from the structural history (see above) suggests a Late Kimmerian age for the intrusion of the East Groningen Massif. An Early Rotliegendes age for the intrusion cannot be ruled out, however, since abnormally high values of coalification were determined for Zechstein and older rocks from Groothusen.

In figure 5 it is noteworthy that the isolines of positive coalification difference tend to be close together on the NE flank of the southern maximum. The closing of the isolines coincides with the important Groothusen fault if the trace of this fault is determined at present depth of the Westphalian. Towards the northwest, where the Groothusen fault apparently dies out, the sharp boundary between the high and the areas of normal coalification becomes less pronounced and changes its trend to northeast. This observation suggests that the crest of the intrusion has risen to a considerable height beneath the NE flank of the southern maximum, intruding upwards along the Groothusen fault, apparently possessing a relatively low heat capacity.

CONCLUSIONS

Three lines of independent evidence, the coalification anomaly, the aeromagnetic anomaly and the structural evolution of the area, provide a picture of an igneous intrusion beneath the Ems estuary and the southern part of the North Sea. The intrusive mass is elongated and has a curved trend parallel to the general strike. The East Groningen Massif was probably intruded during the Late Kimmerian which caused tectonic uplift of the cover rocks. The high heatflow density due to the intrusive mass gave rise to the abnormally high grade of coalification of the Late Carboniferous strata.

ACKNOWLEDGEMENTS

This study forms part of a project (No. ET 3054 A) supported by the Federal Minister of Research and Technology, Federal Republic of Germany.

REFERENCES

Bundesanstalt für Geowissenschaften und Rohstoffe 1976 Karte der Anomalien der Totalintensität des erdmagnetischen Feldes in der Bundesrepublik Deutschland.
 Carstens, H. & K. G. Finstad 1981 Geothermal gradients of the northern North Sea Basin, 59-62°N – Petroleum Geology of the Continental Shelf of North-West Europe, Institute of Petroleum, London: 152-161.

Dixon, J. E., J. G. Fitton & R. T. C. Frost 1981 The tectonic significance of post-Carboniferous igneous activity in the North-Sea Basin – Petroleum Geology of the Continental Shelf of North-West Europe, Institute of Petroleum, London: 121-137.
 Haenel, R. 1980 Atlas of subsurface temperatures in the European Community, Hannover.
 Harper, M. L. 1971 Approximate geothermal gradients in the North Sea Basin – Nature 230: 235-236.
 Harrison, R. K., C. V. Jeans & R. J. Merriman 1979 Mesozoic igneous rocks, hydrothermal mineralisation and volcanogenic sediments in Britain and adjacent regions – Bull. Soc. Surv. GB 70: 57-69.
 Jones, J. M., D. G. Murchison & S. A. Saleh 1972 Variation of vitrinite reflectivity in relation to lithology – Adv. in Org. Geochem. 1971: 601-612.
 Kettel, D. 1981 Maturitätsberechnungen für das nordwest-deutsche Oberkarbon – ein Test verschiedener Methoden – Erdöl-Erdgas-Zeitschrift 79 (11) : 395-404.
 Patijn, R. H. J. 1964 Die Entstehung von Erdgas infolge der Nachinkohlung im Nordosten der Niederlande – Erdöl und Kohle 17: 2-9.
 Trusheim, F. 1959 Ergebnisse der Tiefbohrung Groothusen Z 1 bei Emden (Ostfriesland) – Erdöl-Zeitschrift 75 (7): 273-278.
 Van Wijhe, D. H. & M. J. M. Bless 1974 The Westphalian of The Netherlands with special reference to Miospore assemblages – Geol. Mijnbouw 53 (6) : 295-328.
 Van Wijhe, D. H., M. Lutz & J. P. H. Kaasschieter 1980 The Rotliegend in The Netherlands and its gas accumulation – Geol. Mijnbouw 59 (1) : 3-24.
 Veldkamp, J. 1951 The geomagnetic field of The Netherlands reduced to 1945 – O. Kon. Ned. Meteorologisch Instituut 134.
 Waples, D. W. 1980 Time and temperature in petroleum formation: Application of Lopatin's method to petroleum exploration – AAPG Bull. 64 (6) : 916-926.