Geothermal Aspects of Hydrocarbon Exploration in the North Sea Area

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A statistical analysis of the distribution of hydrocarbon phases indicates that in a time-temperature diagram these phases are restricted to hyperbola confined areas. Thus, the 'liquid-window-concept' has been improved by inferring a time correction. Based on a survey of recent temperature conditions and the reconstruction of paleo-temperatures, it has been applied to the North Sea region. Furthermore, the survey of present geothermal gradients has made it evident that the region north of the Variscan orogen is a type region of an inverted geothermal realm. This can be explained by the abundance of source beds and other sediments of low grade lithification in the subsiding areas. The maximum temperatures have been preferentially determined by the vitrinite (coal) reflectivity method; because it allows measurements without physical–chemical alterations of the organic matter and because the reflectibility depends on the gradational changes of aromatization, which is one of the significant processes during the formation of crude oil. A Table for the determination of time-corrected temperatures from vitrinite reflectivities has been added to this paper.

The relationships between recent and paleo-temperatures have been systematized and some paleo-thermal events have been interpreted:

a. The temperature high above the Bramsche Massif which formed during the Austrian orogeny.
b. The Mid-Jurassic event which led to the formation of the gas deposits in the Rotliegend of the British part of the southern North Sea.
c. The subrecent re-coalification processes responsible for the persistent formation of gas deposits in the 'Buntsandstein' beds north of the Rotliegend reservoirs.
d. The importance of the early Tertiary heat dome along the Lofoten high axis has been taken into consideration.

Many, or maybe all geothermal events affecting the North Sea region since the Cambrian, indicate a time-space relationship to the alternating phases of sea-floor-spreading along mid-oceanic ridges; respectively, compressional orogenic phases caused by plate collisions. Positive temperature anomalies formed preferentially at discontinuities. Some of them are related to the irregular course of the North Sea graben system.

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1. Introduction

The purpose of this paper is to report the results of investigations of changing temperature conditions in the North Sea region. They refer to worldwide statistical data and special experiences gained from the genetically closely related areas of Northwestern Germany as well as the Netherlands. Subsequent to an introductory discussion about the importance of the temperature parameter in the hydrocarbon genesis model, special results of present temperature measurements in the North Sea region will be presented. Finally, the genesis of hydrocarbon deposits in the North Sea region will be elucidated,

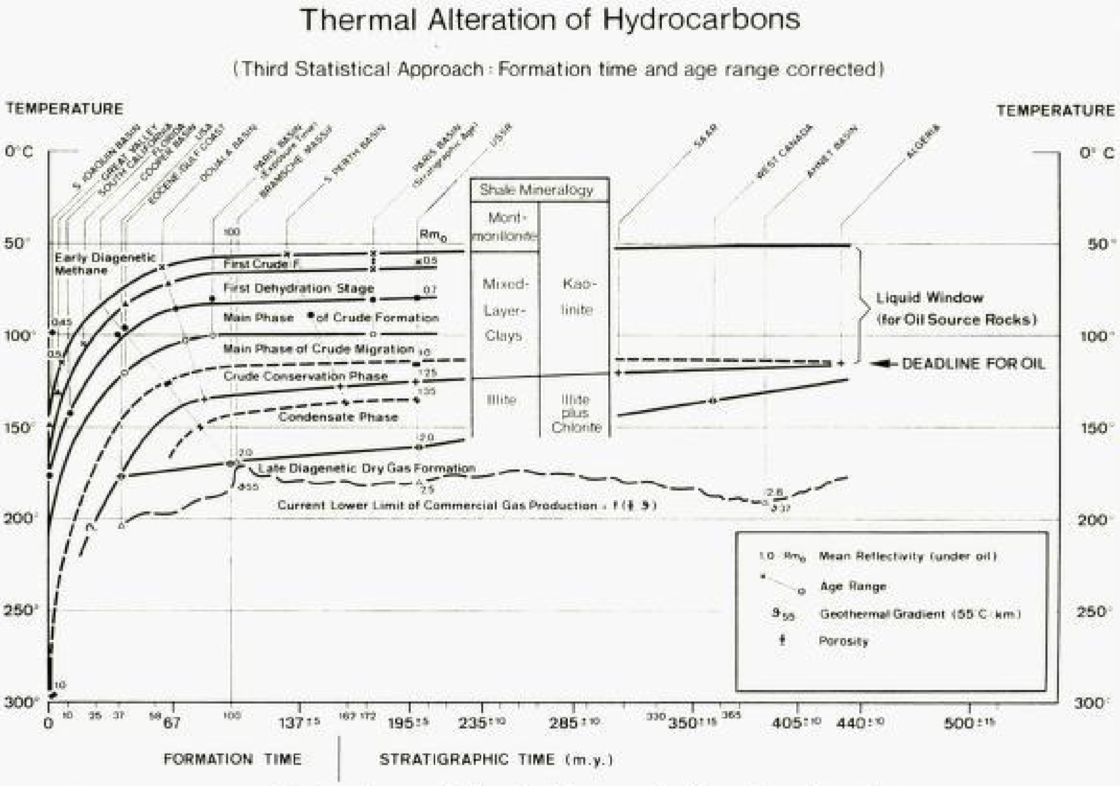

Fig. 1. Thermal alteration of hydrocarbons (third statistical approach: formation time and age range corrected).

The values of hydrocarbon alteration are taken or derived from Alpern (1969), Bartenstein et al. (1971), Castano (1973a), Correia (1969), Demaison (1973), Evans & Staplin (1970), Johns & Shimoyama (1972), Landes (1967), Leythaeuser & Welte (1969), Louis & Tissot (1967), Phillipi (1965), Price (1973), Reel & Griffin (1971), Robert (1971), Seibold (1973), Ting (1973), Wassojewitsch et al. (1969).

The 'shale mineralogy window' is based on discussions in papers by Burst (1969), Dunoyer de Segonzac (1964 & 1970), Frey & Niggli (1971), Johns & Shimoyama (1972), Kubler (1968), Leplat (1973), Ludwig & Hasse (1973), Weaver (1960), Weber (1972).

based on the determination and the evalution of maximum temperatures.

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2. The temperature parameter in the hydrocarbon formation model (Figs. 1 & 2)

Subsequent to Sokolow's (1948) publication an exponentially growing number of writers have been explaining the crude oil formation by transmutation of kerogen in the low temperature realm (Figs. 1 & 2). Kerogen is a highly

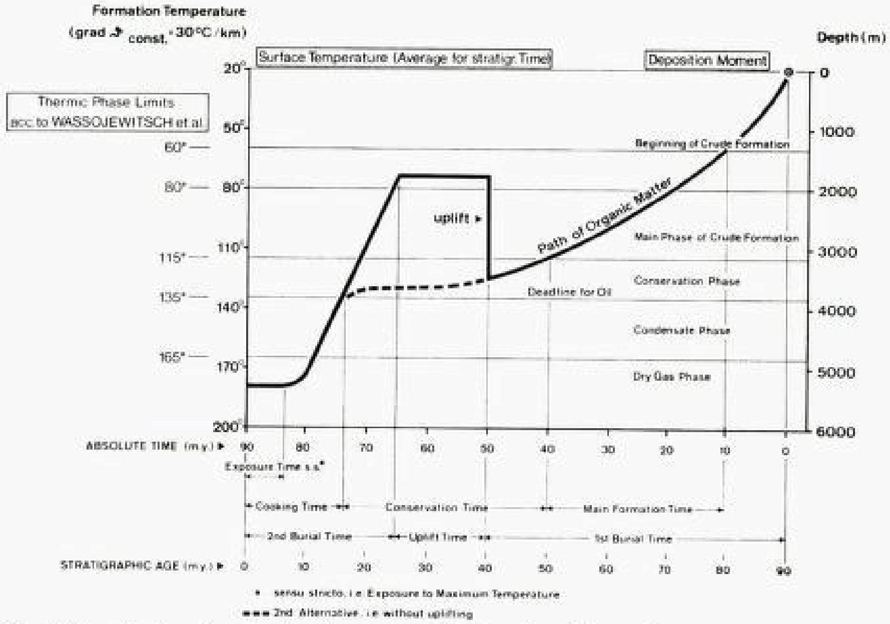

Fig. 2. Terminology for the time intervals of hydrocarbon diagenesis.

polymeric organic matter, disseminated in the sediment and insoluble by organic solvents. The maceral groups essential for the hydrocarbon formation are liptinite and to some extent, vitrinite. Heating of kerogen in an unoxidizing, hydrogen-bearing environment results in the dissociation of hydrocarbons from these macerals providing their grade of aromatization does not exceed a certain limit (Welte 1973, also 1965 and 1972, Louis & Tissot 1967, McIver 1967, Califet et al. 1969, Tissot 1969, 1971, Espitalié et al. 1973).

Pusey's (1973) 'Liquid–Window–Concept' is known as the hypothesis of the limitation of crude oil deposits to a distinctive temperature range. However, much more subtle differentiations were proposed by Landes (1967) and Wassojewitsch et al. (1969), who distinguished a number of phases confined by isotherms.

Landes (1967)		Wassojewitsch et al. (1969)	
		Early diagenetic methane	< 60°C
Oil and gas	< 93,3°C	Initial phase of crude formation	< 80°C
Light oil and gas	< 121,1°C	Main phase of crude formation	< 115°C
Mostly gas	< 149°C	Final phase of crude formation	< 135°C
Oil phase-out zone	< 177°C	Late diagenetic methane	<(180°C)

We prefer the Russian model and modify it by adding the following horizons and stages:

a. Johns & Shimoyama (1972) followed a proposal of Burst (1969) and the perception of Perry & Hower (1972), saying that the dehydration process during the illitization is set forth stepwise in two phases. Drawing conclusions from studies in the U.S. Gulf Coast Eocene, they defined the second dehydration phase as the main phase of oil migration, proceeding in a temperature range between 120°C and 130°C. Seibold (1973) claims that migration in the Douala-Basin of Cameroun begins already at temperatures around 105°C. However, careful consideration must be given to the fact that the solubility of the various hydrocarbons in water as well as their affinity to form colloidal soaps is different and, furthermore, is changing with salinity and pressure (see Chapman 1972, Berry 1973, Cordell 1973, Hobson 1973, Price 1973).

b. Robert (1971, 1973) appears to interpret the 'final phase of oil formation' as a conservation phase. We incorporate this idea, particularly as several authors believe in an upper temperature limit for crude oil formation of approximately 115°C. However, Meinhold (1972) assumes that crude oil formation processes are only extenuated around this temperature (see also Fig. 2 for the importance of the conservation phase).

c. The conservation phase is bounded by the 'deadline for oil' (M. Teichmueller 1971). The breakage of straight chain hydrocarbons will commence no later than at this isotherm (Abelson 1963).

d. The question of the 'deadline for gas' has been modified into the question for the 'current lower limit of commercial gas production' by reservoir engineers (Landes 1967). This limit depends on the porosity which is a function of the geothermal gradient (Maxwell 1964). However, we could prove that hydrocarbon impregnation will prevent a porosity decrease in quartzitic sandstones (Pernow 1969). This observation is of common interest especially since it supports M. Teichmueller's (1971) general statement that the velocity of coalification processes exceeds that of inorganic diagenetic processes.

It remains a remarkable fact that large gas deposits become scarce above temperatures of 150°–165°C (M. Teichmueller 1971, Bartenstein et al. 1971); although Meinhold (1972) places the main gas formation phase into a temperature range of ± 170°C and Geodekjan (1972) speculates about gas formation even at temperatures between 300° and 400°C. One reason for the formation of giant gas fields is the rapid dissociation of gas from fat coal and ess coal (Fig. 7); another reason is the transition of liquid hydrocarbons into gaseous ones. Conversely, the destruction of gas deposits is caused by an increase of jointing and shaly cleavage (Fourmarier 1970) yielding a loss of the sealing characteristics of overlying shales, as well as by an increase of the reservoir pressure, both resulting mainly from temperature increases ($p \cdot V/T = \text{constant}$; for additional information about problems of diffusion see Rudakow 1965, Kroepelin 1967, Nesterow & Uschatinskij 1972).

Thus, the evolution of organic matter is well known, and it can be ordered into a sequence of phases of formation and transformation; crude oil genesis has been brought into a systematic scheme of specific diagenetic and metamorphic steps: between early and high diagenesis (according to M. Teichmueller 1971 and Robert 1973); the catagenesis, principally the meso-catagenesis

(Wassojewitsch et al. 1969); the anchi-metamorphism (preceding the metamorphism sensu strictu according to Harrassowitz, see also Correns 1949); the 'initial' metamorphism of Baker & Claypool 1970), the 'eometamorphism' (Landes 1967), 'the low-grade' metamorphism (Dunoyer de Segonzag 1970), the 'very-low-stage' metamorphism (Kisch 1973, in reference to Winkler 1970). The terms of diagenesis are applied in this paper because Winkler speaks of metamorphism only above temperatures of about 200°C. (Further information about time-dependent mineral temperatures may be obtained from the remarks about the clay mineral diagenesis, as well as from the apatite fission track ages of Wagner & Reimer 1973.)

The temperature intervals, however, are not conclusive. The Anglo–American literature of the sixties was dominated by Phillipi's (1965, 1969) doctrine that crude oil formation begins at a minimum temperature of 150°C, and by the Russian findings that crude oil is still stable at temperatures between 170°C and 180°C (Hedberg 1964). On the other hand, in the Eastern Hemisphere, the concept was developed (since Louis & Tissot 1967) that crude oil formation is limited to a range between approximately 60°C and 135°C (Wassojewitsch et al. 1969). Albrecht & Ourisson (1969) shifted the base line of the 'liquid window' in the Douala-Basin even down to 105°C. Pusey (1973) expanded his 'window' concept with a statistically broader range, between 65° and 150°C in a rather pragmatic attempt to summarize the different results of various authors from various regions. In that way he made it more consistent, yet unfortunately he restricted the economic value of the whole concept.

My alternative model of the distribution of hydrocarbon phases (Fig. 1) might be considered more useful because it is based on empirical data gained from detailed investigations of approximately twenty sedimentary basins. Ten of these have the rank of case histories with two or more values from each profile, even though, in two cases, (U.S.A. and U.S.S.R.) a conclusive time-correction could not be accomplished. In two other cases (Cooper Basin and S. Perth Basin, Australia) reliable coalification values were available. Incorporation of additional vitrinite reflectivity values yielded a sufficient number of appropriate data to present a composite model, which is based on the combined evaluation of hydrocarbon as well as coal maturity values. This combination appears to be tolerable because the degradation grade of kerogen (Welte 1973), the maturation grade of crude oil (Califet et al. 1969) and the reflectivity of coal (see M. Teichmueller 1971, for details about the index of refraction) all depend on the grade of aromatization (Oelert 1972, see also Leythaeuser & Welte 1969).

The curves in Fig. 1 are isolines of maturity and diagenesis grades. We are dealing with iso-reflections, a term that has been introduced by coal petrographers (Bartenstein et al. 1971); it is synonymous with the term iso-apostilbs (Paproth & Wolf 1973). Within certain limitations, discussed later, iso-voles or iso-volatiles, i.e. isolines of volatile constituents of coal, can also be utilized (Kuyl & Patijn 1961, Patijn 1961, Boigk et al. 1971, M. & R. Teichmueller

1966, 1971a, b). In addition, the maturity grades of kerogen and crude oil can be characterized by 'iso-maturities' or 'iso-crack-values'. A superimposed term would be 'iso-aromatization grade'. The term 'geochronotherms' was introduced by Karzew in 1968 (cit. Meinhold 1972) because their loci are functions of the parameters temperature and time.

In an initial attempt to accomplish a statistical analysis, we referred to the stratigraphic position, i.e. to the geologic age of source rocks. From this it could be learned that only the source rocks from young continuously downwarping basins indicate causal relations. Thereupon the geologic ages of up to 150 m.y. old samples were corrected by the formation times. Finally, hydrocarbon distribution profiles (published from various basins) were time-corrected. (The dextrally inclined lines of the diagram indicate the age range.) These corrections yielded evenly bent hyberbolic curves which indicate the validity of an exponential function. Based on geological considerations it could be demonstrated that the Arrhenius equation (1) is valid for the formation and the maturation of hydrocarbons:

$$\frac{dC}{dt} = -C_i \cdot A \cdot e^{-\frac{E}{RT}} \qquad (1)$$

C = kerogen concentration at the process time t
C_i = initial kerogen concentration
$-$ = negative sign; becauce $C < C_i$ (degradation)
A = Arrhenius– or impact– or frequency factor (number of molecular groups reacting with each other per time unit)
e = base of the natural logarithm
E = activation energy
R = universal gas constant
T = absolute temperature (°K)

The discussion of this equation (1), based on laboratory findings and theoretical assumptions, is dealt with by Huck & Karweil (1955), Karweil (1956), Abelson (1963), Deroo et al. (1969), Hanbaba & Juentgen (1969), Karweil (1969), Phillipi (1969), Tissot (1969), Lopatin (1971), Tissot (1971), Tissot & Pelet (1971), Eglinton (1972), Tissot et al. (1972), Welte (1972), Johns & Shimoyama (1972), Bostik (1973). A detailed interpretation of the equation (1) will be presenterd on an other occasion. The reader's attention is drawn to the apparently straight line boundary between wet and dry gas. The time relationship of the clay mineral diagenesis (Fig. 1) and the water solubility of hydrocarbons is not sufficiently clarified yet. However, it can be recognized that time is gradually substituted for temperature in an exponentially decreasing mode during the first 60 m.y. of kerogen degradation. Thus, the introduction of the time factor allows a relativation of the various 'liquid-window' concepts. (Strange to say, Wassojewitsch et al. 1969 substituted time only for the geothermal gradient.) Moreover, the processes abstracted in the Arrhenius equation are irreversible and therefore their products are fossilizable.

From this point of view, the quantification of the time factor must be considered the most important task of a geologist trying to solve problems. These questions have been explained within the framework of the Russian model (Fig. 2). The crude oil formation period makes up only approximately 1/3 of the geologic history of certain source rocks. According to the Arrhenius equation degradation in a source rock during this time interval is 27%. This change of concentration can be called the recovery factor of the source rock. In the simplified model the previously formed oil accumulation remains unchanged even through an uplift phase.

Only at temperatures above 135°C is there sufficient energy supplied to initiate the cracking process of crude oil, especially of the straight chain hydrocarbons. This point marks the boundary between formation time and cooking time, the latter term here only being used for the gasification period of crude oil formation. The coal geologists consider the exposure time under maximum temperature conditions to be the most crucial factor for the mode of hydrocarbon formation. Experience has shown that the liquid phase will not be totally transformed into the gas phase if the exposure time interval of the cooking period is comparatively short. In this case the formation of deposits with a high gas/oil ratio is favoured. After all, the recovery factor increases during the cooking stage because solid kerogen in the source rock discharges additional gas during this phase.

The time intervals during which kerogen is degraded ought to be distinguished from the exposure times: in most cases the geologist can only make an estimation of maximum values from the subsidence curve. The stagnation and uplift phases ('hiati') creating a reduced energy level are mostly beyond recognition; however, they should be substracted from the periods of maximum subsidence, using 'best guess' assumptions.

The practical usefulness of the above-described geochronothermal concept lies in the fact that the temperature ranges of hydrocarbon phases can be recognized in any sedimentary basin or sub-basin, provided that the subsidence history is known. Thus, determined isotherms can be incorporated in the 'liquid-window' diagrams, where depth values relate to geothermal gradients (see, e.g., Pusey 1973). These diagrams allow a prognosis about lacking, sufficient or over-maturation, as well as crude oil qualities and gas contents; thus providing the basis for well planned drilling programmes. For instance, any kind of drilling activity will be irrelevant unless crucial temperatures for the formation of oil or gas have been reached in source rocks above the basement. The application of heavy rigs for ultra-deep wells appears to be useful only in rapidly foundered areas or in areas with a comparatively low geothermal gradient.

3. The current temperature distribution in the North Sea region

3.1 TEMPERATURE DETERMINATIONS (Fig. 3)

The geothermic specialists from various geological surveys, mining companies and geophysics departments of universities have made detailed investigations

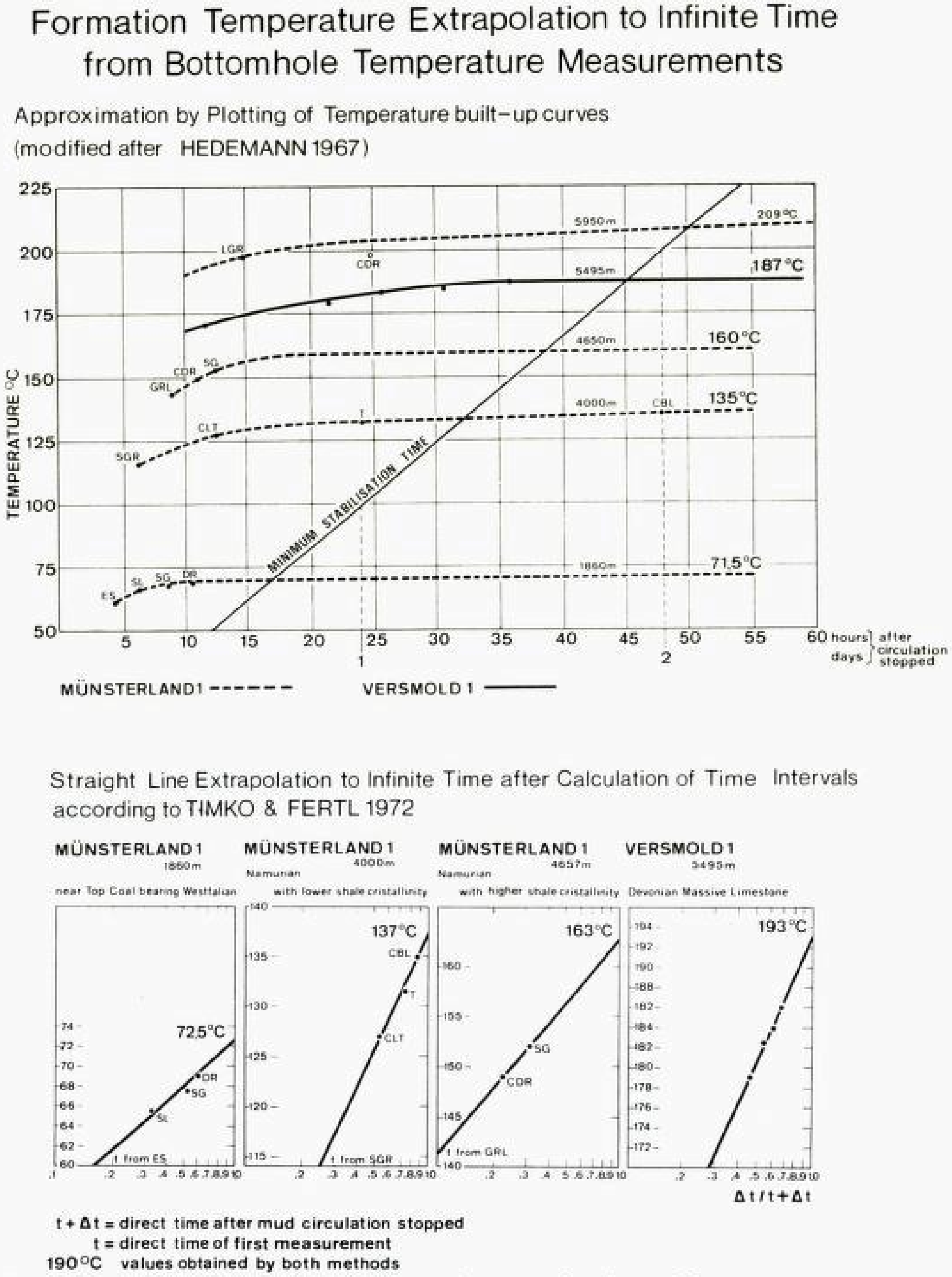

Fig. 3. Formation temperature extrapolation to infinite time from bottomhole temperature measurements.

to determine the true formation temperatures of adjacent onshore areas (e.g. Braaf & Maas 1952, Creutzburg 1964, Heine 1962, Kappelmeyer 1961, Parasnis 1971, Quiring 1936, Swanberg et al. 1972.) On the basis of their findings they handle the petroleum geologists' temperature data from deep wells with some scepticism; the justification for this might be discussed in the following. Their objections refer to the grade of accuracy and the comparability of such measurements as well as to the temperature compensation times and the depths of reference.

The results of preliminary investigations by Gelsenkirchener Bergwerks A.G. dealing with this group of questions have been summarized by Heine (1962). According to this, West Germany's Coal Mining Association presented in 1956 'guidelines for the determination of true formation temperatures' for the purpose of standardization. Gelsenberg has been using and comparing temperature-measuring devices constructed by Huegel (1942), Schlumberger et al. (1957), and the Coal Mining Ass. and Deilmann Corp. These are mercury, electric and Negative Temperature Coefficient (NTC) resistivity thermometers with a reading accuracy of ± 0.1°C. The results differed from each other by values of up to 1.6°C in general less than 1°C. Hence, the usefulness of the mapping of isotherm intervals of $< 2°C$ must be critically examined.

Recently, the Boliden Aktiebolag of Sweden produced a Hewlett-Packard quartz thermometer with a tolerance of 1/1000°C for measurements in their shallow exploration holes (Parasnis 1971). Unfortunately, such precision thermometers are scarcely ever used.

Their application is useful if all other parameters determining the true formation temperatures are under control. However, the geothermist should proceed pragmatically, i.e. he should also include less accurate data — as well as data from drilling companies with a lesser interest in geothermal problems — in his investigations providing that the density of data will be sufficient for a good geothermal evaluation of his area of study.

The results of the application of refined measuring techniques by geothermists show clearly that exact temperatures can be obtained only several years after the termination of drilling (see for instance Kappelmeyer 1961, Meincke 1966, Demaison 1973). Lachenbruch & Brewer (1959) made the statement that temperature data with an accuracy of ± 0.1°C could be obtained after 6 years, and that with an accuracy of ± 0.01°C only after as much as 50 years .However, this concept holds true only for 'dry holes' and it would be irrelevant for petroleum exploration unless these authors had proposed a method of extrapolation.

(1) Formation interval testing has shown that the temperature of the formation liquid will adjust to that of the formation within a comparatively short period, provided that the influx of uncontaminated formation water is considerably great in relation to the thickness of the reservoir interval. However, attention must be paid to the cooling effect of adiabatically expanding gas from reservoirs (Kunz & Tixier 1955) or source rocks (Heine 1962). Conversely, mud and mud filtrate disturb the natural temperature balance if the formation

is permeable. For this reason temperature logs for the location of top cement or lost circulation reveal only relative data (Hedemann 1968). Nevertheless, they give some information about changes in the thermal gradient (see chapter 3.2).

(2) Temperature data with a tolerance of ± 1 °C are considered to be precise enough to be used for the models of crude oil formation and the temperature distribution in the North Sea region as described in this article. Furthermore, the exploration geologist is obliged to develop ideas about the formation of hydrocarbon deposits immediately after drilling the first exploration well(s) in a sedimentary basin, since he cannot wait several years for the stabilization of natural formation temperatures. Where he was successful, FIT's (Formation Interval Tests) or in an annual cycle shut-in pressure measurements will provide him with reservoir rock temperatures of an accuracy tolerance of ± 0.1 °C at best. These will change within the years only for technical reasons: influx of higher temperature bottom water or of cooler injection water.

(3) The mud with an average temperature of about 30 °C — on its way down — heats the bedrock in the upper part, and cools it in the lower part of the hole. After the circulation stops the assimilation process of the mud temperature to that of the formation in a given depth will operate according to the following equation (Lachenbruch & Brewer 1959):

$$T_m = k \cdot e^{\frac{t}{t-s}} + T \quad (2)$$

T_m = temperature measured after the time t
k = inclination coefficient determinable by plotting T_m over $\frac{t}{t-s}$ on semi-logarithmic paper
t = time elapsed after reaching a definite depth respective after mud circulation stopped
s = drilling time = total drilling time ./. t
T = true formation temperature, graphically extrapolated for $t = \infty$

Equation (2) is clearly designed for measurements taken right after the termination of a well; hence, it is not applicable to the multitude of abandoned wells. Confining himself empirically to control measurements with an accuracy tolerance of ± 1 °C in observation wells after 3 days as well as several weeks, Heine (1962) found that a temperature balance had been achieved within only 3 days.

Hedemann (1963) drew graphs of the temperature build-up curves for particular logging series in the Muensterland 1 well by plotting the mercury–maximum–thermometer values (T_m) of respective sondes and runs over the times (t) elapsed after stopping the mud circulation (Fig. 3). He had to determine the true formation temperatures graphically since he used arithmetic scales for both the temperature and the time axis. Fig. 3 shows that the estimation of the asymptote is more subjective as the temperature equalization time increases. Later, Hedemann (1967, 1968) thought that from the grade of conformity of the equalization curves conclusions could be drawn as to their degree of probability in uniform facies areas. Moreover, the examples selected from the results of Carboniferous well tests in Northwest Germany demonstrate that temperature measurement data tend to assimilate to true formation temperatures around 100°C as quickly as within one day, and to approx. 200°C within about two days. From that the conclusion can be drawn that Heine could have measured true formation temperatures after less than 3 days in wells of the Ruhr District, penetrating rocks of a similar facies.

Hedemann's graphic solution is mathematically unsatisfactory. Hence, his data as well as all other bottom hole temperatures (BHT) have been revised according to Timko & Fertl's (1972) method, in which, besides T_m, only the measurement time intervals have been utilized (Fig. 3). This method has the advantage of providing a mainly graphic solution including a minimum of calculation. The values gained by applying this method on impermeable bedrocks are 1.5–3.0% higher than the graphically determined ones (Fig. 3).

This solution requires three test values. In case only two values can be obtained — as at the final depth of Muensterland 1 — an exact determination of the true formation temperature cannot be made (Fig. 3).

The slopes of the linear functions plotted on semi-logarithmic paper indicate the heat conductivity of the bedrock at the test locations: directly if it is impermeable, and indirectly if it is infiltrated by mud. Gentle slopes mean low heat conductivity: an example is that of the coal-bearing Westphalian in the upper parts of the Muensterland 1 section. At a depth of 4000 m in the coal-barren Namurian (Fig. 3) the conductivity is higher. It decreases parallel to an increase in crystallinity of the clay texture and the increasing interstitial water content probably associated with it. The steepest curve of Fig. 3 is a characteristic of a limestone of high heat conductivity.

Steep curves are also encountered in zones of lost circulation where the temperature balance process is slow. In such cases even abrupt bends can be seen on semi-logarithmic paper. They can be explained by the sudden infiltration of more strongly warmed mud which is brought about by the swab-effect of the heaving of the sonde.

A fourth objection of the critics of borehole temperature tests refers to the reference depth. In most cases, the sonde does not quite reach the bottom and, in general, the thermometer is placed a few metres above the base of the sonde; details are provided by the well-surveying companies.

3.2 TEMPERATURE PROFILES (Fig. 4)

For the construction of a well temperature profile the surface temperatures are used in addition to the true formation temperatures. The geothermists put much effort into the determination of the so-called neutral depth, referred to as the depth where daily and annual temperature variations are no longer influential. For our investigations, secular variations, i.e. variations in a scale of geologic periods and changes of the reference level by erosion or subsidence

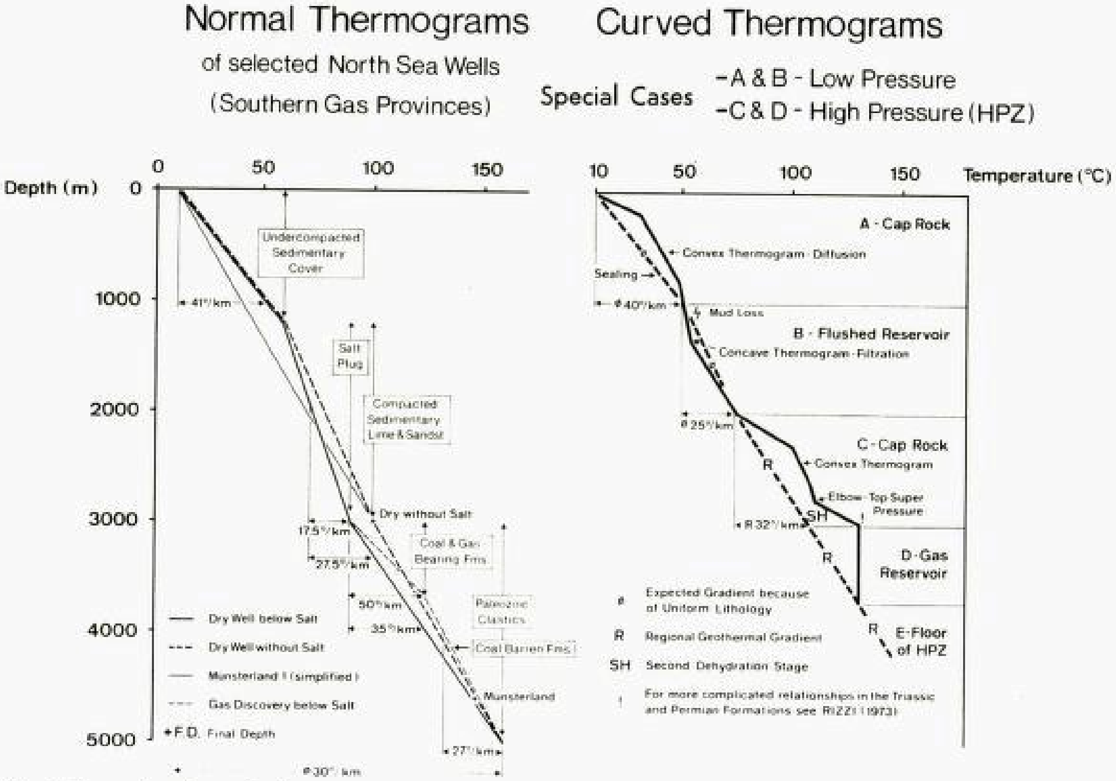

Fig. 4. Normal and curved thermograms.

(Fig. 10), are of particular interest. Relative to the accuracy tolerance of well temperature surveys, surface temperature changes of > 1.0°C are of some importance. Taking into account that in the North Sea area nearly all utilized formation temperatures were measured at depths of approx. 3000 m, it becomes clear why the determination of the neutral depth (varying between 5 m and 25 m) is mostly neglected.

In the Ruhr District average surface temperatures (T_s) are determined according to the following equation taken from Heine (1962):

$$T_s = 10.76°C - 0.006 \cdot h \quad (3)$$

where h is elevation above msl in (m), so that T_s would be 10.0°C at an elevation of 126.6 m. Accordingly, average Ruhr District soil temperatures T_s vary between 10.0° and 10.4°C. Defant (1961) published sea-floor temperatures in the North Sea of 9°–10°C in water depths of up to 25 m, decreasing to 6°C at a depth of about 100 m. On the basis of these data and following the example of Braaf & Maas (1952), as well as of Harper (1971), a standard surface temperature of 10°C is used for the design of temperature profiles in all close-to-coast lowland or shallow water wells of the North Sea region. In all other areas data from climatological atlases or from previous workers (e.g. Quiring 1936, Creutzburg 1964) have been used.

Temperature profiles — also called thermograms by hydrologists (Bredehoff & Papandopulos 1965, Sejdidow & Gawrilow 1973) — are graphic presentations of temperature changes versus depth. From these diagrams the geothermal gradients and the interval gradients can be determined for any depth. According to the known equation (4) these gradients depend largely on the heat conductivity of the various rock units:

$$q = -\lambda \cdot \vartheta \quad (4)$$

q = heat flow ($\mathrm{cal \cdot cm^{-2} \cdot s^{-1}}$), world average* of $1.5 \cdot 10^{-6}$
λ = heat conductivity ($\mathrm{kcal \cdot cm^{-1} \cdot s^{-1} \cdot {}^{\circ}K^{-1}}$)
ϑ = geothermal gradient (°C/km), world average* of 25°C/km

Heat conductivity data for rocks of the area of study have been published by Benthaus (1959), Kappelmeyer (1961), Creutzburg (1964 and 1965) and Hueckel & Kappelmeyer (1966). From the 166 mineral heat conductivity values determined by Horai (1971), theoretical heat conductivities can be calculated by a factor analysis of all minerals contributing to a rock's composition. However, such calculations always yield higher values than the effective values of porous rocks dealt with by petroleum geologists. The latter have been investigated especially by Huang (1971), subsequent to work of Meinhold (1968) and Lewis & Rose (1970). Accordingly, the heat conductivity is inversely proportional to the geothermal gradient which itself is proportional to the bulk porosity as well as being inversely proportional to the grade of compaction, but proportional to the amount of oil or gas infiltration of the sediment. In low pressure gas reservoirs the geothermal gradient attains its maximum. Complications in permeable rocks are due to the fact that the heat flow is brought about not only by diffusion but, to a larger extent, also by convection (Kappelmeyer 1968, Meinhold 1968).

On the basis of this brief introduction to the principles of heat flow, the interval gradients encountered in the North Sea region will now be discussed (Fig. 4). For the most part, the thermograms reveal a characteristic subdivision into three or four portions. In the southern North Sea and adjacent areas high gradients are found predominantly above salt plugs of high conductivity. In the central and northern parts of the North Sea region they are caused by undercompaction of the Tertiary sediments. Low gradients are encountered in the middle parts of sediment sequences characterized by a considerably high percentage of carbonates or, especially in the southern North Sea, of evaporites. The gas source rock parts of the Carboniferous are responsible for higher gradients. Finally, the sterile 'basement' — speaking in terms of petroleum geology — reveals lower gradients again.

In the southern North Sea the geothermal gradient intervals are especially well marked in gas-bearing sections. Here, the production conditions are optional if in the Carboniferous layers the amount of gas-rich coal with a low heat conductivity is high, and if the Rotliegend reservoirs are covered by salt

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* according to Lee & Uyeda (1965)

of high heat conductivity. The distribution of these reservoirs, however, must be surveyed by means other than geothermal methods.

The evaluation of the above information also enables the petroleum geologist to interpret the more complicated unpublished thermograms from oil-bearing or dry wells of the North Sea region. In this article only the curved thermogram of Fig. 4 may be discussed since they describe cases of pressure-bound convection. Case C — determination of over-pressure zones — is familiar to any petroleum engineer from the publications of Lewis & Rose (1970) and Timko & Fertl (1972). The reader's attention may be drawn to Rizzi's (1973) findings which have not yet been integrated into the Anglo–American literature. He found that not only the undercompaction of young clastic sediments but also formation water locked in clastic intercalations of evaporites could produce over-hydrostatic pressures. This holds true especially for the 'Buntsandstein' of the southern North Sea region.

Cases A and B rely on the experiences of the hydrogeologists (Sejdidow & Gawrilow 1973) and of the present author. In cases of vertically upward infiltration, i.e. especially through accelerated diffusion, and in cases of lateral migration in inclined beds as well as in cases of overlying permafrost soil, the thermograms are conversely bent. The perfect sealing capacity of a lithologically homogeneous impermeable bed is indicated when the thermogram is a straight line. Concave thermograms indicate downward infiltration, i.e. under hydrostatic pressure in a reservoir rock below dehydrated clays. Thus, lost circulation and also occasionally increased salinities of the underlying beds can be predicted. Of course such predictions can be made only if the wells are logged comparatively often, as, for instance, the first exploration well in a sediment basin, or if changes of the thermal gradient can be determined from continuous measurements of the mud temperatures. This is now a standard procedure applied by the mud engineers for the detection of over-pressure zones in undercompacted Tertiary sediments of the North Sea region.

To some extent surface soil temperatures reflect the subsurface geothermal conditions because of upward heat diffusion. This rule is applied for the geothermal prospection in marginal areas of North Sea (Paul 1935, Poley & Steveninck 1970 and 1971, Geertsma 1971). Fig. 5 shows the oldest ever published soil temperature profile above a salt plug of the Germanic basin; determined from temperature measurements from two-metre deep holes (Paul 1935). In the lower part of the figure, a profile is presented which was drawn later relying on results from deep salt and oil wells and from potassium mines (Bentz 1949, supplemented by oil field data according to Richter-Bernburg & Schott 1959).

Furthermore, the salt plug rocks have been classified after their heat conductivities, based on Creutzburg's (1964) measurements (supplemented by the estimated value for salt clay). On the surface above the plug, increased soil temperatures can be measured in zones of increased heat conductivity unless they are sealed by clay. Above subsurface pockets of clay or faults, soil temperature decreases of 2–3°C are common. Paul had matched the soil temperature minima with the flanks of the salt plug. This holds true for a

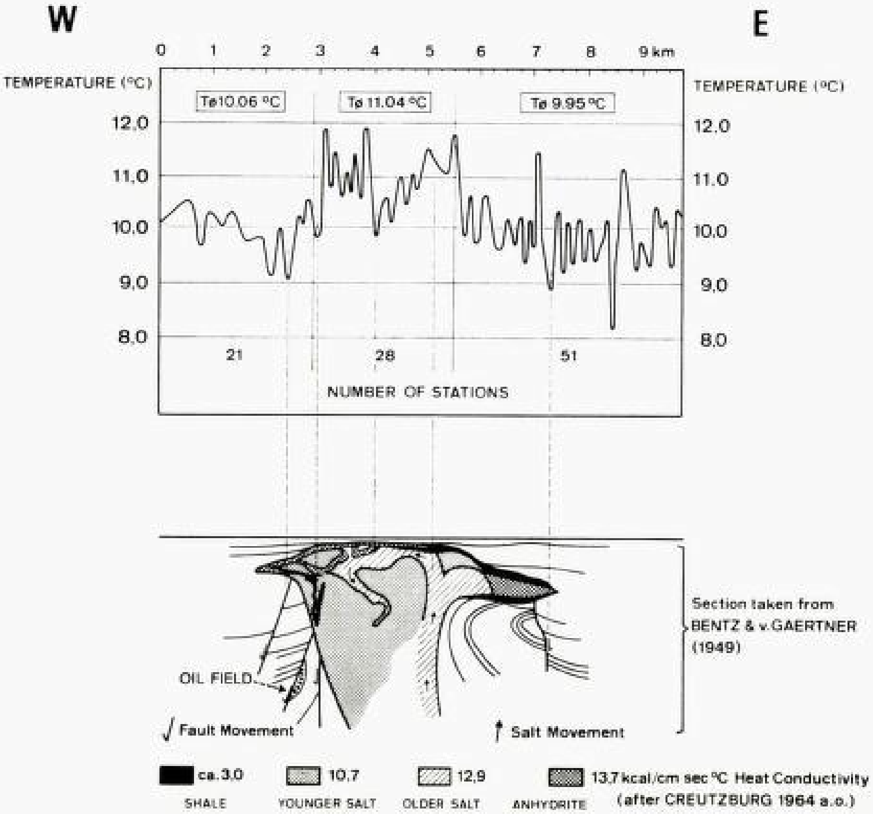

Fig. 5. Soil temperature survey over a salt plug near Hanover, Germany, by M. Paul (1935).

depth of approximately 500 metres because the salt overhangs are hard to separate from the surrounding sediment, as illustrated in Fig. 5. Accordingly, for a temperature analysis Selig & Wallick's (1966) cylindrical salt plug models can be applied even to salt mushrooms.

Near Groningen and in the Peel-Horst area (in the south-easterly continuation of the Oostzaan High, see Fig. 6), Poley & Steveninck (1970) have located salt domes and faults at depths of more than 1000 metres. As in the case of the Hannover salt plug they were indicated by temperature increases of 1–2°C, although these were unnoticeable from surface features. Originally they measured the temperature at a depth of 2 m. Later, however, they realized that anomalies can be mapped even from measurements at depths as shallow as 5 cm.

Recent remote sensing techniques allow the reconnaissance of temperature anomalies of this order from satellites. Even on simple black and white satellite photographs of N.W. Germany — published by Heuseler 1973 — some of the numerous salt plugs in this region, as well as the Northern rime of the Lower Saxonian Basin, seem to show up. Thermal infra-red pictures, however, have not yet been taken.

Geertsma (1971) explains the temperature anomalies above faults by changes of the heat conductivity along the fault planes: a decrease caused

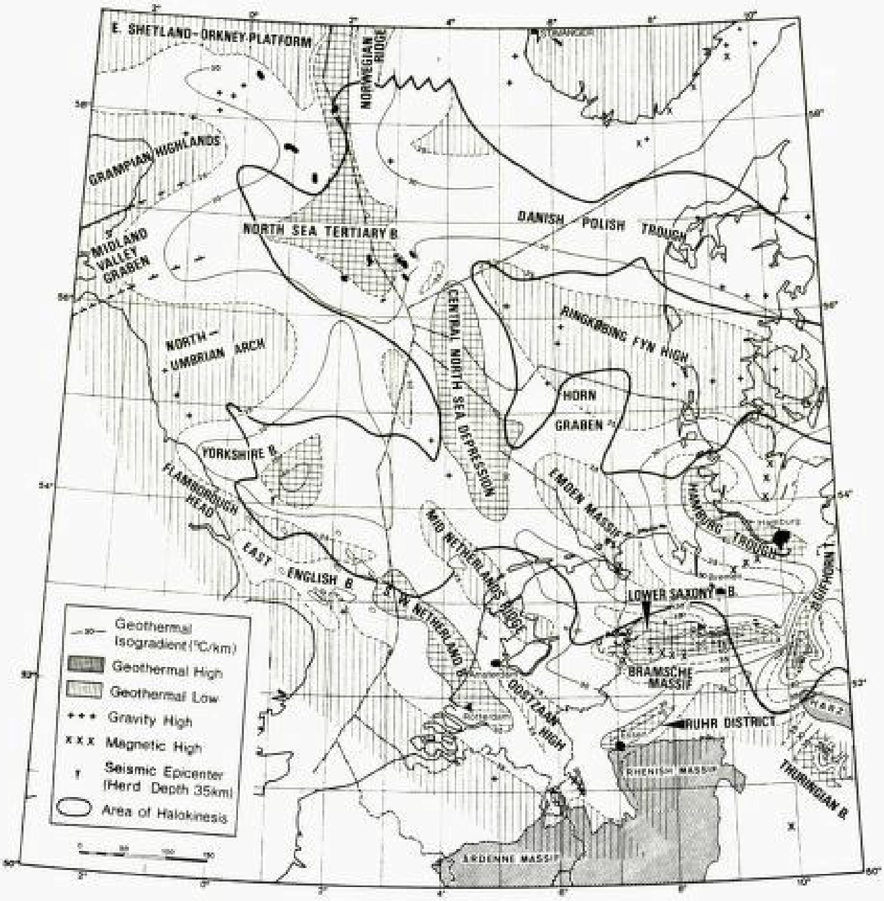

Fig. 6. Geothermal gradients, North Sea area.

by rupturing of highly lithified rocks; an increase by compaction of less lithified rocks due to shear stresses building up along the fault. An increase should also result from mineralization along the fault. These interpretations, however, are restricted to heat diffusion. Due to prevailing 'open' tensional faults in the area of study, convection is common and increases of temperatures are proportional to increases of permeabilities; in the Ruhr District and South Limburg we are even dealing with hot brines ascending along faults.

3.3 GEOTHERMAL ANOMALIES OF THE NORTH SEA REGION (Fig. 6)

Temperature surveys of the North Sea region have been published only in a few cases. From adjacent areas geothermal isogradient maps of the Saar District have been presented by Hückel & Kappelmeyer (1966), and of the Thuringian Basin by Meincke (1966). The first specific geothermal gradient map of the North Sea region was presented by Harper (1971). It is based on mean gradients, which were determined from bottom hole temperatures (BHT) building up over a maximum time interval of 48 hours. This map covers the North Sea up to 59° N, and the Dutch onshore lowland. A maximum accuracy was obtained by plotting 2°C/km intervals (see above 3.1).

The author's map (Fig. 6) is also based on mean gradients. Offshore, they have been gained exclusively from BHT's, mostly from wells with depths of around 3000 m. True formation temperatures could be extrapolated from BHT's only in rare cases when operating companies took sufficient interest in geothermal problems. For the author's map, 2°C/km intervals were also utilized; however, the map was simplified by plotting only 5°C/km intervals (Fig. 6) which does not, in the author's opinion, alter its essential value.

Hardly any difference can be observed between the author's and Harper's map concerning Norwegian and British waters. This is good support for his assumption that gradients can be determined from unextrapolated temperatures with an accuracy tolerance of less than 10%.

In many wells, according to explanations given in chapter 3.1, standstill periods of 48 hours were even sufficient for the regeneration of true formation temperatures. Furthermore, for these parts of the North Sea the author had available only a limited amount of supplementary data. Of these data the Ekofisk field reservoir temperature of 129.4°C from an average reservoir depth of 3.170 m has been of special interest because the calculated gradient of 39°C/km as well as the published gradient of 36.8°C/km (OGJ) could be effectively incorporated into the map.

Apparently, in the Dutch, German and Danish waters as well as in the adjacent continental areas, the author had many more data available than Harper. In addition, the author was able to incorporate preferentially precise measurements from various oil fields and mines in this area. The majority of these data have been taken from the publications of Quiring (1936), Braaf & Maas (1952), Fabian (1955, 1963, Benthaus (1959), Patijn (1961, 1964), Heine (1962), Hecht et al. (1962), Stheeman (1963), Hedemann (1963, 1967, 1968), Creutzberg (1964), Lee & Uyeda (1965), Simmons & Horai (1968), Kimpe (1973) and Tunn (1973).

Lee & Uyeda's (1965) data from the British Isles and Swanberg et al.'s (1972) data from Norway have not been incorporated into the map because they are outside the North Sea Basin, and because their number is insufficient for a special survey of these inhomogeneous continental areas. The British values are around 32.3°C/km, the Norwegian ones around 15°C/km. The latter gradients vary in a range between 9.45° and 22.39°C/km (Swanberg, personal communication).

In the southern North Sea and the easterly adjacent continental areas of our map, the density of data is sufficient; whereas in the central part of the North Sea — south-west of the Montrose–Ekofisk line — it can be considered fairly sufficient. From the Norwegian part of the North Sea, north of the 58th latitude, only scattered data are available.

In addition to the isolines of geothermal gradients, regional geological informations, e.g., basement highs and depocentres, have been entered in the map including information from structural analyses of Ahorner et al. (1972), Bartenstein et al. (1971), Boigk (1968), Gunn (1973), Kent & Walmsley (1970), Lindström (1971), Ramberg (1971), Sorgenfrei (1969) and Thiadens (1963). Comparisons with other articles in this volumes indicate that the British nomenclature for structural units in some cases has been changed; however, this does not require a revision of the essential structural information.

The isolines of geothermal gradients delineate the regional geological units. Usually thermal highs coincide with subsiding areas, whereas thermal lows can be encountered above basement highs; this implies that elevations of the basement are inversely proportional to the geothermal gradients. For this reason the North Sea region can be considered as an inverted geothermal realm, contrary to normal geothermal realms like, e.g., the Rocky Mountains (Klemme 1972) or the Sirte Basin. South of the northern margin of the Variscan orogen is a normal geothermal realm (Fig. 6, detailed information concerning the Thuringian Basin).

Second order structural elements such as anticlines and synclines yield normal temperature distributions within the basins of an inverted temperature realm. This is even more evident in the Ruhr District, which has been more thoroughly investigated than offshore areas in the North Sea region. In the Ruhr District, for instance, deeper shafts can be sunk in synclines because they have lower gradients than the anticlines. The major reason for high gradients in anticlines must be selective heat flow, parallel to the bedding planes. In addition, convection along faults, which is indicated by hot brines, might be taken into account. Such faults coincide with anticlines as in South Limburg and in the Peel Horst. Also, the Ekofisk anticline appears to be distinguished from its surroundings — with a temperature gradient of approximately 35°C/km — by having a considerably higher gradient of approximately 39°C/km. However, this observation can not be generalized as long as reliable temperature values are available only from reservoirs and structural highs of the North Sea. As previously mentioned in chapter 3.2, heat flow parallel to bedding planes, as well as the special situation over salt domes with high heat conductivities and heat-damming below insulating undercompacted clays, may be of some importance.

Thus, details of the geothermal situation can be explained; but what about a synthesis? According to Ahorner et al. (1972) the focus of the 1931 Doggerbank earthquake was at a depth of 35 km (Fig. 6), indicating the crustal thickness in the whole North Sea region. Relying on Neuhaus's (1968) assumption that temperatures at the Moho are around 900°C, a mean gradient of approx. 25°C/km can be extrapolated for the North Sea crust; this corresponds to gradients over basement highs in our map.

Heat conductivities in such consolidated basement blocks outside the coal-bearing Variscan orogen can be considered uniform. In the latter area, however, and in areas of more recent subsidence with a considerable content of heat insulating Jurassic and Paleocene source rocks as well as undercompacted clays (especially Eocene tephra), thermal gradients are higher. Contrary to the Upper Rhine Graben (Haenel 1970) and other rift systems of the earth, crustal thinning does not seem to be responsible for the increase of gradients; especially since mean gradients of 35°C/km in subsiding areas of the North Sea are low in comparison with those of 60°C/km in genuine rifts. So the explanation through heat-damming remains feasible, as earlier suggested by Harper (1971).

The situation in the southern and eastern parts of Harper's map was so different to our's that a revision of his interpretation appeared to be necessary:

a) Harper offers no structural or stratigraphic explanation for the thermal anomaly east of Yorkshire. Yet reference should be made to the earthquake centre at its southern margin, as well as to the coal content of the northern shallow syncline, which subdivides geothermically the Central North Sea High ('Northumbrian Arch').

b) According to Harper the Permian evaporite basin is characterized by a uniform E–W striking negative thermal anomaly. In Fig. 6 this trend can no longer be recognized since it appears to be dismembered by a series of NW–SE striking anomalies. Furthermore, halokinesis covers a much larger area within abundant positive heat anomalies.

c) The central North Sea depression can also be traced geothermically into the area of the Dutch oil discovery F 18–1 from where it continues to Lower Saxony through NE Holland.

d) The central North Sea depression is separated from the SW Netherland Basin (which possibly continues into the Rhine Graben through the 'Niederrheinische Bucht' and the Rhenish Massif) by the Mid-Netherlands Ridge.

More structural details, which are not actually discussed here, can be gathered from the map. High gradients of up to 55°C/km in the Lower Saxony Basin and the Gifhorn Trough cannot be explained by heat-damming alone. In the case of the Lower Saxonian tectogene (Boigk 1968) a supply of fossil heat by upwarping of the basinal infill from a higher to a lower temperature level could be taken into consideration (Fig. 13). In Fig. 6 several gravimetric and magnetic highs have been entered on the map which, as in the case of the Oslo Graben (Ramberg 1971), indicate crustal thinning and the formation of heat domes during the geologic past. The relationship between recent and previous temperature fields of the North Sea region will be discussed in chapter 5.

4. Determination of maximum temperatures (Figs. 7-9)

There are many methods and even more literature on this particular subject. In 1971 the Commission on Petrography of Organic Matter in Sediments and Application to Geology was founded by coal petrologists of the ICCP. Initially the purpose of this Commission was the measurement of coalification ranks encompassing analyses of hydrocarbons (particularly n-paraffins and CP-indices, cit., e.g., Welte 1965, Leythaeuser & Welte 1969, Leplat 1973, who studied samples from the discussed area, among others) and of their melting or boiling points (Jacob 1967, Silverman 1971). For calibration there are utilized: shale mineralogy (Fig. 1), mineral temperatures, electron-spin-

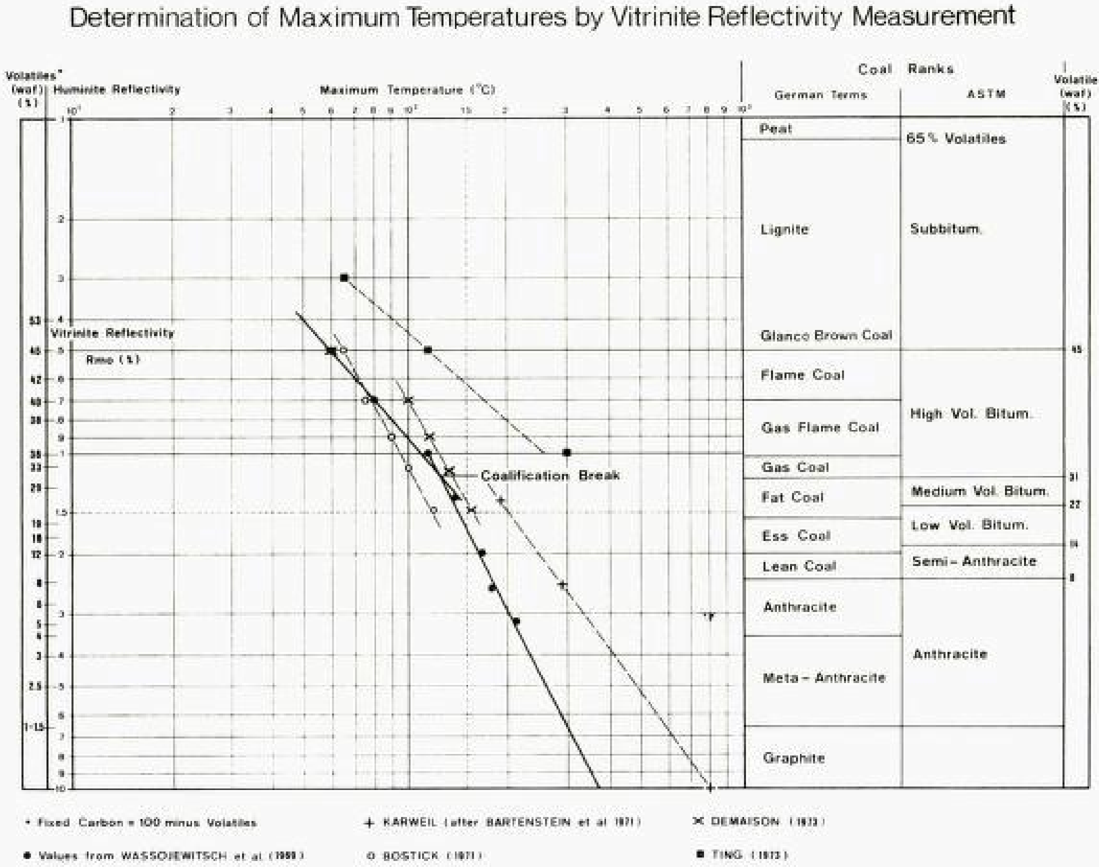

Fig. 7. Determination of maximum temperatures by vitrinite reflectivity measurement.

resonance (ESR, Pusey 1973), pyrolysis (Wehner & Welte 1969, Leplat 1973, Somers et al. 1973) and fission-track-ages (Wagner & Reimer 1973). According to our experience, the usefulness of the methods is limited to those which are based on a laboratory treatment by which the physicochemical state of the sample is modified and in which equation (1) as well as the geologic time factor are not taken into account (cit., e.g., Hanbaba & Juentgen 1969). Consequently, pyrolysis yields maximum temperatures, which are always too high, and ESR temperatures compare to those determined from coalification ranks only for samples from young and continuously down-warped basins.

As early as 1873, Hilt, a mining engineer from Aachen, published his coalification rule according to which the volatile percentage of pit coal decreases with increasing depth: near Aachen by 1%/100 m. Today, the coal petrographers prefer the optical measurement of the mean reflectivity under oil of polished vitrinite-bearing samples. The reflectivity values are correlated to the volatile percentage of the coal as determined in the laboratory. Compared with other methods the vitrinite reflectivity measurements have the advantage of not being bulk analyses for all coal macerals and all organic constituents

In addition, they allow a differentiation of the various coalification ranks of vitrinite. The youngest population can be interpreted as autochthonous only if the constituents are not exclusively represented by reworked matter.

From the bibliography of the above-mentioned Commission the following references are recommended for a basic study of the matter and/or for a study of the particular relevancy to the North Sea: Alpern (1969, 1970), Alpern & M. Teichmueller (1971), Alpern et al. (1972), Ammosov (1967), Bartenstein et al. (1971), Boigk et al. (1971), Bostik (1973), Castano (1973b), Caye & Ragot (1972), Hedemann & R. Teichmueller (1966), Jacob et al. (1970), Jones et al. (1972), Karweil (1973), Koch (1970), Kuyl & Patijn (1961), Paproth & Wolf (1973), Patteisky & M. Teichmueller (1960, 1962), Robert (1971, 1973), M. Teichmueller (1971), M. Teichmueller & R. Teichmueller (1971a) and Wolf (1969, 1972).

The diagram of Fig. 1 shows that the vitrinite rank runs parallel to the maturation of liquid hyrdocarbons at least for mean reflectivity values of up to about 1.35% ('iso-aromatization grade'). If the order parameters are known, the time-factor can be derived from Fig. 1. Such a procedure permits the time-calibration of Fig. 7, which is used for the determination of maximum temperatures from mean vitrinite reflectivities. Data from published approaches to a calibration of the coalification-rank thermometer have been plotted on double-log paper for the purpose of presenting a graphic analysis. It appears that the calibration values of Wassojewitch et al. (1969) are located on two straight lines with differing slopes. The point of intersection is situated at about 31% volatiles, i.e. approx .1.2% R_m. Apparently, this point is equivalent to the coalification break of Stach (1953) and Patteisky & M. Teichmueller (1962) which has been defined as the border-line between weak and strong coalification as well as between gas-rich and gas-poor coal. Differing slopes indicate differing reaction-velocities. The 'deadline for oil' seems to coincide with this coalification break.

Since the calibration values published by other authors do not show the coalification break, two additional approaches will be discussed (Figs. 8 & 9).

(1) Density values for coal of varying coalification ranks have already been compiled by Fülöp (1967). They were supplemented with data published by Ruhrkohle (1969) and with the precise density value of clean graphite (Correns 1949), and plotted in such a manner as to indicate the relationship between subsidence and alteration. In Fig. 8 the coalification break is defined by the blurred density minimum. A distinct differentiation, however, can be found only beyond the anthracite stage. Thus, from the diagram it can be concluded that the Formation Density Log can be used, if at all, for direct coalification logging below the liquid window only.

(2) A more successful approach to the problem was made by Stahl (1973, see also Boigk et al. 1971) in the Laboratory for Isotope Studies of the Federal Geological Survey of Germany in Hanover. It is based on the

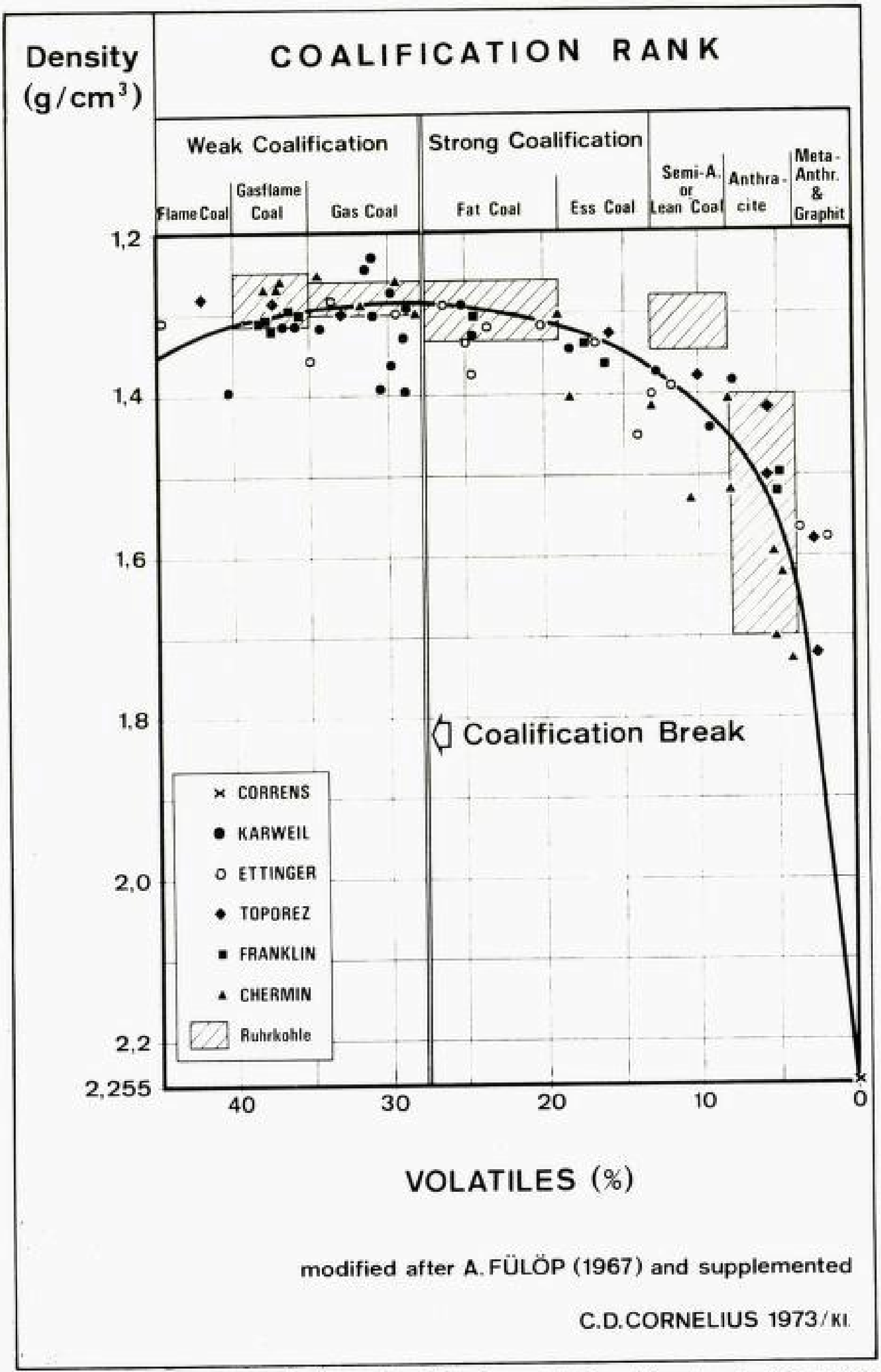

Fig. 8. Coal density versus volatiles and coalification rank, from laboratory studies, mainly after Fülöp (1967).

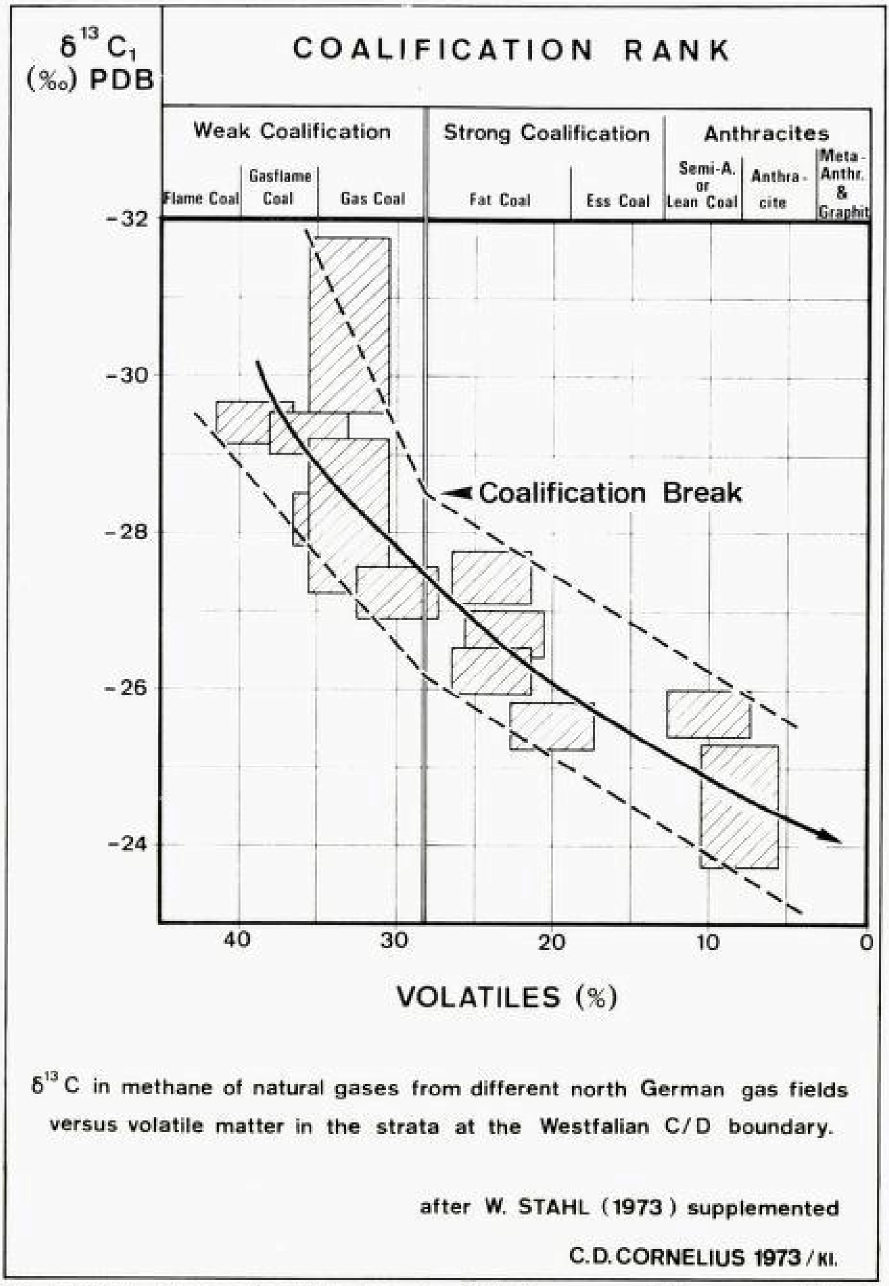

Fig. 9. Carbon isotope ratios of methane from NW German gas fields versus volatiles in coal seams near Westphalian C/D boundary, mainly after Stahl (1973).

correlation of volatiles percentages with carbon-isotope ratios of methane (Fig. 9). The δ^{13}C-ratio increases proportionally to the coalification rank, i.e. the gas becomes the heavier, isotopically, the more the coal is altered. This trend slows down in the range of intensified coalification (Fig. 9) thus confirming the results of Fig. 7. Although Stahl assumes a continuous change of the isotope ratio, a possible break is indicated in Fig. 9, again coinciding with Stach's (1953) coalification break. (Silverman's (1971) correlation of carbon-isotope ratios with the boiling-temperatures of the various constituents of crude oil proves other discontinuities but could not be evaluated for our purposes because of abolition of the time-factor.)

Accordingly, the validity of the rule of the coalification break and, at the same time, the Russian calibration appears to be approved. The author would like to make the following additional remarks:

a) Bostik's (1973) maximum-temperatures, assumed for North West German coals with evidently longer maturation times than those of the Russian samples, appear to be based on reaction rates which are too low (because they are based on Karweil's frequency factor for reactions in a solid state). However, he already had doubts about the reliability of maximum temperatures derived from vitrinite reflectivities of less than 0.6%. Demaison (1973) made the same mistake for shorter coalification times.

b) The shortest coalification times were found by Ting (1973). His samples from the Upper Miocene of Texas represent a maturation stage from before the coalification break and indicate still greater reaction velocities than the Russian samples, possibly because of better permeabilities. Ting's uppermost value was obtained in the laboratory.

c) Karweil's maximum temperatures from the contact-metamorphic aureole of the acidic laccolith of Uchte within the Lower–Saxony tectogene (see Bartenstein et al. 1971) have been calculated with shorter reaction-times after the coalification break than those on which Wassojewitsch's calibration values appear to be based. Faster reactions seem to be possible over batholiths because the related tensional faults allow thermal convection (chapter 3.2). A similar case was already suggested by Teichmueller & Teichmueller (1966) for the laccolith of Erkelenz at the SE corner of the Oostzaan High (Fig. 6), where exposure times of 5 m.y. (and more) were calculated. In the case of Uchte no time factors were published. If, however, the temperature values of 190° and 290°C from Fig. 7 are checked by transferring the respective R_m-values of 1.4% and 2.48% into Fig. 1, time-values of 45–40 m.y. will be obtained which are irrelevant to batholiths. From an earliest possible intrusion age of 100 m.y. — during the Austrian orogenic phase — and from the fact that the laccolith of Uchte was already cooled at the early Upper Campanian, 75 m.y. ago, the conclusion can be drawn that the thermal event was effective for less than 25 m.y. If, finally, the calculation is based on a temperature of about 800°C for anatexis and consequently a straight line parallel to the line integrating the Russian values is drawn in Fig. 7, maximum temperatures of 300°C and 400°C, respectively, result from the above-mentioned R_m-percentages. Hence, there is good proof that the heat event associated with the intrusion of this laccolith was short-lived.

Once more, these case histories from the broader North Sea region prove the significance of the determination of the time factor. If it cannot be obtained from the reconstruction of the burial history, other methods of maximum temperature determination are to be applied. Although the experiences with such methods are limited so far, the following observations may be summarized.

I. The vitrinite-thermometer of Fig. 7 will be supplemented by humanite–reflectivity measurements and by fluorescencse spectra of sporinites for weak coalification ranks (Ottenjann et al. 1973).

II. Methods of colorimetric and transparency investigations of sporinites have been introduced by Correia and by Staplin, both in 1969. These are optical methods like the vitrinite reflectivity method. Although their data are less accurate, they can be evaluated by computer processing. To the author's knowledge, time-corrections can be made only after calibration by vitrinite reflectivities. Apparently, scientists are oblivious to the fact that this method was already proposed by Kirchheimer as early as in 1934. He calibrated the palynomorphs' conservation stages with experimental temperature values which were too high, again because of a neglecting of the time factor.

III. Mineral temperatures determined from authigenic minerals are very useful as, for instance, the temperatures of more than 300°C (Bartenstein et al. 1971, Stadler & R. Teichmueller 1971) indicated by pyrophyllite from Oxfordian sediments above the Bramsche Massif (Figs. 6, 12 & 13); especially if they can be time-corrected according to equation (1). The zeolite-zones in the sense of Winkler's (1967) mineral facies concept can be used as a thermometer (Kisch 1969, 1973) only if they are calibrated by vitrinite reflectivities (Castano 1973a) or after a reconstruction of the burial history of Kisch's samples, which has yet to be undertaken.

IV. Temperatures from hydrothermal mineral veins are thought to be very reliable for the study of crude oil formation (Florowskaja & Pikowskij 1973). However, in our opinion they are of minor importance because they are limited to 2-dimensional anomalies. Certainly, the veins indicate thermal convection, but generally they produce only narrow zones of thermal contact metamorphism. This could be proved from ESR-measurements along basaltic dykes of the Lower Rhine valley carried out by Fauth from the Ruhrkohle Research Center in Essen. Since they affect the adjacent rock only over short distances, they produce atypical mineral temperatures which, referring to the concept of Fig. 2, appear to be too high. An exception may be made for mercury because of its mobility which, indeed, is quite similar to that of the hydrocarbon gases, as suggested by Dikenstejn et al. (1973, see also Tunn 1973) from an investigation of the Rotliegend gas reservoirs of the southern North Sea. This may also be conclusive for inert gases like nitrogen and helium (Müller et al. 1973). On the other hand, the mineralization of the ore veins within the Lower Saxony gas field Rehden (Fabian et al. 1957, for location see Fig. 12) most probably started already at temperatures above 170°C, which have been calculated from the adjacent fat coal seams.

V. For these reasons, the organic inclusions of hydrothermal minerals as described by Mueller (1964, 1973) from Derbyshire/England and elsewhere, are considered to be overtempered compared to their environment and — contrary to his suggestions — their temperatures are not conclusive for the formation temperatures of any oil accumulation; not even for the smallest British oil fields.

VI. Statistical comparisons of maximum-temperatures determined from various methods are, so far, insignificant because the methods and their respective data are incompatible unless they were calibrated by vitrinite reflectivities. Comparative studies of mineral facies, illite crystallinity and coalification ranks remain promising for the future (Frey & Niggli 1971).

5. The geothermal history of the North Sea region (Figs. 10-13)

After the determination of a sufficient number of maximum temperatures from a well, a paleo-thermogram (Fig. 10) can be drafted following the procedure explained in Fig. 3. In some cases, uniform paleo-interval temperatures can be observed which show no gradient. Such interval temperatures may be explained by homogeneous lithologies and their uniform heat conductivity characteristics (equation 4). Jones et al. (1972) discovered in onshore and offshore Northumberland and Durham that Carboniferous coal measures show no thermal paleo-gradient where they are overlain by heat-insulating shales, but distinct gradients where they are overlain by heat-conducting sandstones. Differing observations were published by Patteisky & M. Teichmueller (1962). In summary, the interdependency of vitrinite reflectivity and lithology is not completely understood.

The paleo-thermograms of Fig. 10 differ from each other and from the actuo-thermogram by their slopes. Six cases are possible; all have been confirmed by studies in the broader North Sea region and elsewhere:

(1) Case P — present temperatures = maximum temperatures: in continuously down-warped basins, e.g., U.S. Gulf Coast and main parts of the Central North Sea basin and Graben.

(2–5) Cases L, M and B — maximum temperatures > present temperatures: uplifting after reaching the maximum paleo-gradient(s) at the margins and elevated areas of the North Sea Graben.

(2) Case L — paleo-gradient < actuo-gradient, temperature difference to be recognized in the upper parts of sections only; in lower parts cit. (1), e.g., Oklahoma (Pusey 1973).

(3) Paleo-gradient = actuo-gradient: appears to be possible along basin flanks, possibly realized in S. Texas (Pusey 1973).

(4) Case M — paleo-gradient > actuo-gradient: the most common case outside the central graben zone (examples to be discussed below).

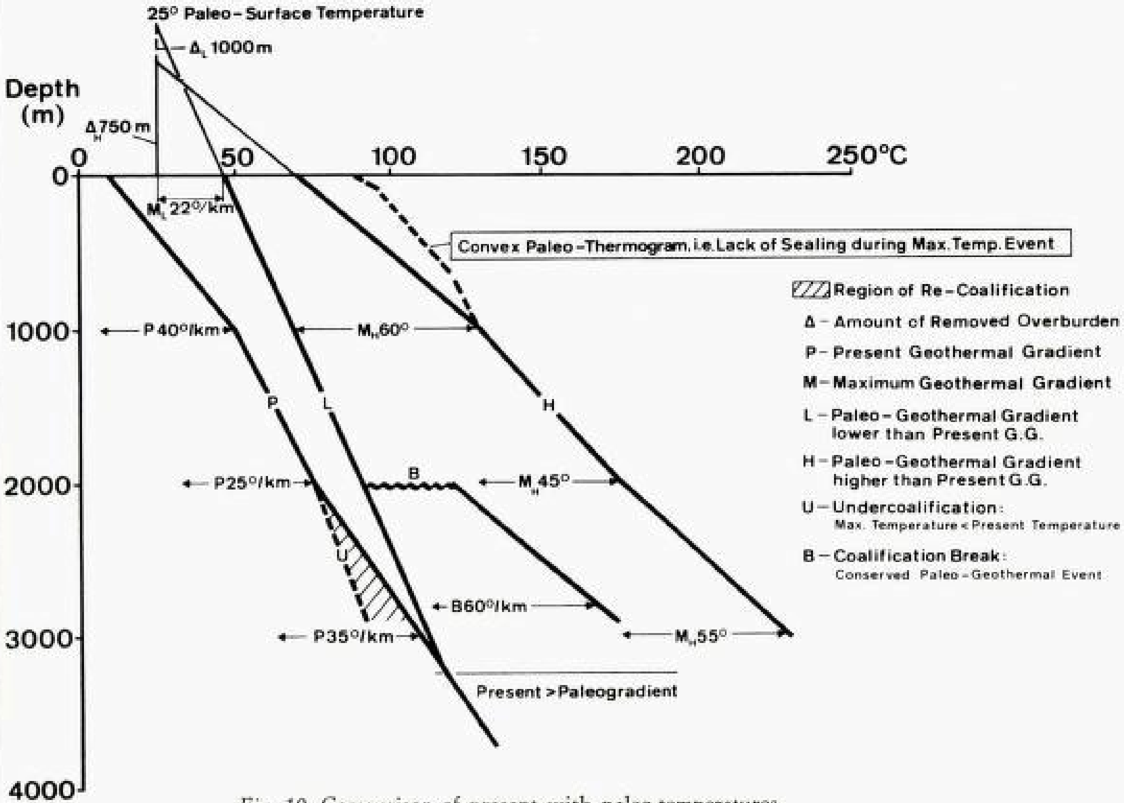

Fig. 10. Comparison of present with paleo-temperatures.

(5) Case B — earlier paleo-gradient > later paleo-gradient: combination of case L in the upper part of the sections and of case M in the deeper parts, i.e. a paleo-thermal event encountered in the well; examples cit. (4).

(6) Case U — maximum temperature < actuo-temperature, i.e. the present temperature prevailed for a shorter effective time than the maximum temperature, so that the final maturation rank was not yet reached: 're-coalification' at Groningen (Patijn 1964), called 'main-coalification' by Hedemann (1967); another example is the current formation of gas in Bunter reservoirs east of Yorkshire (Fig. 11).

Other compilators may, of course, consider (3) as a subcase of (2); or (5) as a subcase of (4), and (6) as a subcase of (1). For cases (2–5) the paleo-heat flow can be calculated according to equation (4). If good approximations to both the heat conductivity of the eroded section and the paleo-surface temperature at the time of a paleo-thermal event can be achieved, the amount of removed overburden can be graphically determined from Fig. 10. Consequently the time of the paleo-thermal event can be determined from the paleo-thermogram.

Some representative paleo-thermal events of the North Sea region will be

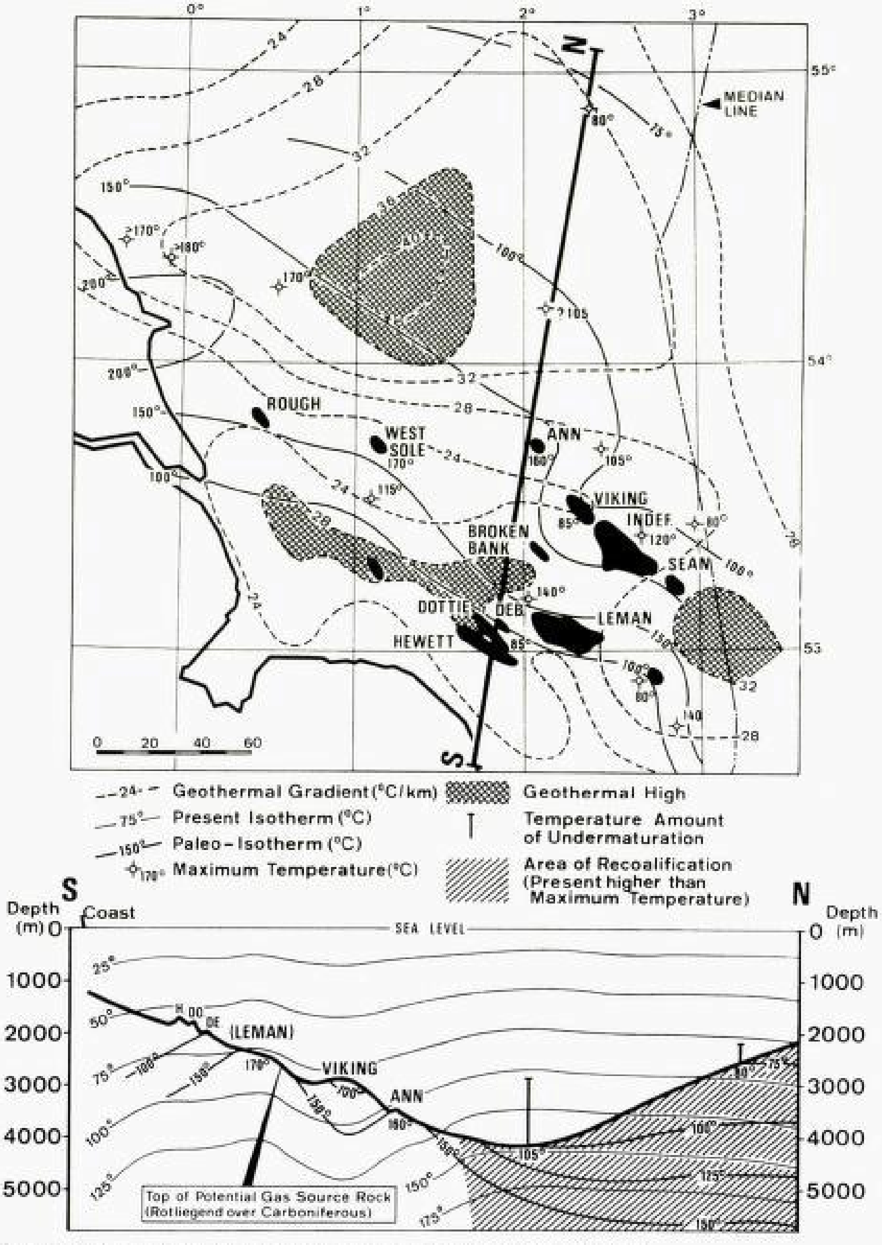

Fig. 11. Present and paleo-temperatures, East Anglian gas province.

discussed in chronological order to give an outline of the thermal history of this region.

a) The Palaeozoic history of the North Sea region was interpreted by McKerrow & Ziegler (1972). More details on its evolution during the early Palaeozoic era have been provided by Dewey (1971), Gunn (1973) and Hallam (1973), especially for the Midland Valley graben. The paleo-gradients for this era can be determined by mineral temperatures only. Following the hypothesis that the Grambian orogeny was associated with subduction of the Proto–Atlantic crust under the eastern margin of the Canadian Shield, a paleo-thermal gradient of about 50°C/km could be presumed from comparison with the recent Andean thermal realm. For the Early Caledonian (Wurm 1973) or Taconian orogeny — with axial strikes of around 100° in the Stavanger area — which might be the result of collision of Gondwanaland with the Baltic Shield, the author assumes a gradient of more than 30°C/km based on the shallowness of folding. The main Caledonian orogen, which is thought to be the result of a subsequent collision of the Baltic and the Canadian Shields, displays mineral temperature gradients between 17.5° and 25°C/km, i.e. of an intermediate range in comparison with the 'hot' Hercynian mountains and the 'cool' Alps (Zwart 1967).

b) The Caledonian molasse, i.e. the Old Red sediments of the Orcadian basin, requires an investigation by the experts in organic metamorphism. However, the number of maximum temperature data is not yet sufficient to prove an estimated paleo-gradient of about 35°C/km.

c) The status of investigations in the Hercynian area is much better than in the Orcadian. Based on the studies of Wolf (1969, 1972) and Paproth & Wolf (1973) as well as Weber (1972), even pre-orogenic gradients of about 60°C/km could be estimated for parts of the Rhenish geosyncline. During the orogeny, heat waves migrated through the geosyncline starting from the Bohemian Massif and directed towards the Ruhr District (Krebs & Wachendorf 1973), which produced heat domes characterized by gradients up to 250°C/km (Zwart 1967, see also Hall 1973). But gradients of 150°C/km could be established even for the synclines calculated from coalification ranks published by Paproth & Wolf 1973).

d) Even better data are available from the Hercynian molasse, the Upper Carboniferous coal measures of the mining districts. Kuyl & Patijn (1961) determined a paleo-gradient of 50°C/km from South Limburg. The same value was derived from Thiadens' (1963) coalification ranks for the Oostzaan High (Fig. 6). North-east of this, Corle 1 revealed a paleo-gradient of less than 40°C/km, whereas Zeddam 1 yielded only 22°C/km. The high paleo-gradients are restricted to NW–SE striking highs which most probably formed not earlier than the Mesozoic. Patijn's (1964) re-coalification in the area around Groningen becomes clear by the assumption that the low gradients are the original ones. R. Teichmueller (1973) estimated the paleo-gradient of the Ruhr District to be as high as 70°C/km. This gradient must have been developed during subsidence providing that the coal measures show almost uniform coalification ranks through anticlines and synclines. For instance, coal seam 'Sonnenschein' is characterized by the level of the coalification break (Fig. 7) almost throughout (Patteisky & M. Teichmueller 1962).

e) Pb–Zn ore mineralization of Asturian age, i.e. post-molassian open faults in the Ruhr District (Pilger 1956) indicates gradients of around 100°C/km. According to the definition given under chapter 4. IV such mineralization is brought about by two-dimensional convection which has no effect on the coalification rank of intersected coal beds.

f) During the Mesozoic era, the Eurasian Plate drifted over the northern hemisphere as demonstrated by Dietz & Holden (1970) and other workers. Following Turcotte & Oxburgh's (1973) membrane-theory, we may assume that the formation of the Viking Graben began during the Lower Jurassic at a paleo-latitude of 45°N. The graben extended progressively southward, but discontinuously, without acquiring a thermal identity — as defined in Fig. 6. (The Upper Rhine Valley Graben opened at the same latitude during the Early Tertiary.)

g) In the southern North Sea, the central graben is bounded by NW–SE striking structures (Fig. 6). From these, the East Anglian gas province is geothermically well studied (Fig. 11). In addition to the present temperatures the maximum temperatures have been calculated based on Robert's (1971) coalification ranks. The Rotliegend gas reservoirs are restricted to a zone of maximum temperatures from 100°C up to 170°C at the top of Carboniferous source rocks. The maturation studies are not sufficient for precise calculation of paleo-gradients but from a temperature profile a gradient around 65°C/km may be conjectured. This gradient should have been reached when the Carboniferous of the Leman field was covered by approximately 1850 m of sediment.

   Referring to Kent & Walmsey's (1970) information on Leman and other gas fields, the paleo-thermal event was tentatively dated as early Middle Jurassic. Should this assumption be correct, the positive heat anomaly below the East Anglian Basin, i.e. the Sole Pit trough, would have built up simultaneously with the opening of the Bay of Biscay and the possible onset of sea-floor spreading in the southern North Atlantic.

   Situated to the south-east is the Oostzaan High (Fig. 6) and, at its south-eastern corner, the above-mentioned laccolith of Erkelenz near Aachen. This was dated late-Hercynian by Teichmueller & Teichmueller (1971b), but was considered to be of Permian or Cretaceous age in earlier papers (Patteisky & M. Teichmueller 1962). If one supposes that the author's as well as Burek's (1973) recent concept of heat waves originating not only from sites of orogenic activity but also from sites of sea-floor spreading is correct, post-Hercynian dating of the Erkelenz laccolith finds new support in as much as it might have a close genetic connection to the opening of the North Atlantic Ocean. The north-eastward overhang of the laccolith seems to indicate centrifical movements in connection with the Biscay spreading.

h) The laccolith of Bramsche (Fig. 13) also reveals a northward overhang. The strike of the main axis of this pluton is parallel to the axial trend of the Austrian orogeny (Fig. 13). The best age estimate for the intrusion is

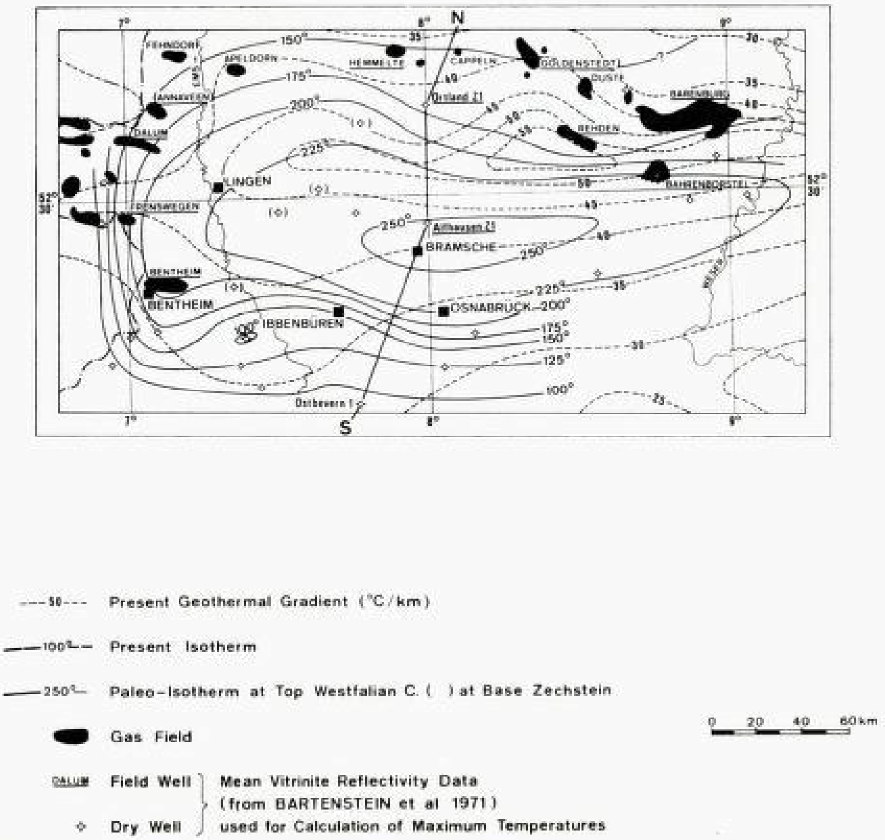

Fig. 12. Bramsche massif, map of present and paleo-isotherms.

Middle Cretaceous. Fig. 13 includes the actual gradients of Fig. 6 with maximum temperature data deducted from vitrinite iso-reflections given by Bartenstein et al. (1971). The related isotherms were fitted into a cross-section prepared by the same authors (Fig. 13). Both diagrams demonstrate that the paleo-temperature high, with gradients up to 65°C/km, was located on top of the Bramsche Massif, whereas the actuo-temperature high with gradients up to 55°C/km is situated some 55 kms further north within the Lower Saxony Basin, just south of the gas province. The situation could be interpreted by northward heat migration which lasted for 100 m.y., but related thermograms do not allow such a conclusion. Because of this a coalification break of type B (Fig. 10) at the base of the Upper Campanian substage refers to the already mentioned upwarping of the Lower Saxony Tectogene (Boigk 1968) which, therefore, should preferably be called an aulacogen — during the sub-Hercynian Phase. The possibly contemporaneous intrusion of the Uchte laccolith has been discussed in chapter 4 c.

i) During the final stage of the Laramide Phase, i.e. during the late Paleocene, the well-studied spreading of the North Atlantic shifted into the Reykjanes Ridge axis. Contemporaneously the Lofoten Islands charnockites were

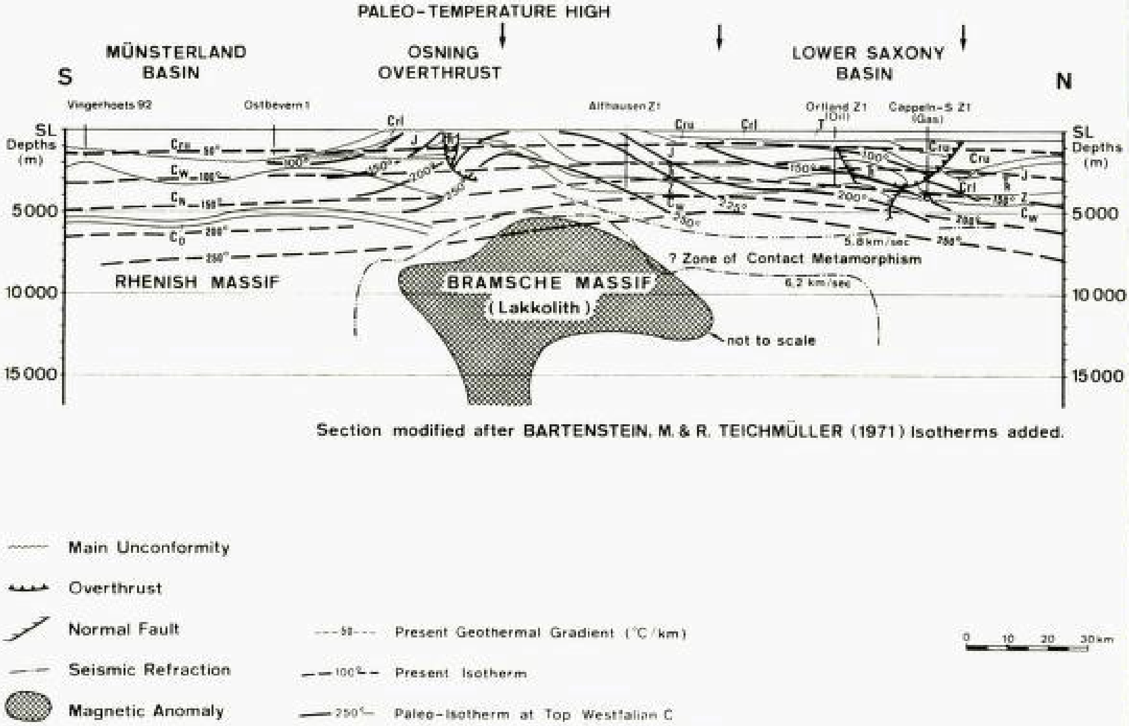

Fig. 13. Section through the Bramsche massif; present and paleo-temperatures.

emplaced along faults parallel to the ridge axis, thus subdividing the northern part of the Nordland Basin. The assumption that a paleo-gradient of 50 °C/km originated from that event was based on coal-petrographic studies from Andøya, although ESR-temperatures as well as hydrothermal quartz temperatures would indicate higher gradients. The ESR-measurements, however, have probably been disturbed by the resinite-compounds of the Upper Jurassic coal and the veins are to be interpreted as untypical, 2-dimensional, local heat anomalies (see chapter 4, IV).

In summary, the main results of our investigations are that the examined paleo-thermal events indicate a time-space relationship to the compressional phases of the various orogenies or to the spreading-phases along mid-oceanic ridges. Some overturns which have been determined are directed about north and, therefore, are explained as a result of tangential forces produced by the a.m. tectonic events. The paleo-thermal events cannot only be studied optionally within the coal-bearing belt of the Carboniferous but they also appear to be restricted to that zone. One reason for this restriction may be a thinning of the northern margin of the Hercynian crust characterized by high paleo-thermal gradients which provided for repeated thermal upwelling. It seems natural that the North Sea Graben finds its southern end in this zone. Many additional detailed investigations will be necessary before the thermal history of the North Sea region can be completely understood.

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