

## INTRODUCTION TO INCIDENT-LIGHT MICROSCOPY OF OIL AND GAS SOURCE ROCKS<sup>1</sup>

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### ABSTRACT

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Microscope investigation of oil and gas source rocks has experienced a rapid development during the last two decades. This is mainly due to the advent of improved fluorescence microscopes, the development of new sample preparation techniques and the availability of computers.

The new observations have led to the recognition of three main source rock types and six sub-types. This classification is similar to that proposed by Van Krevelen and by Tissot and Welte. However, it is not based on time-consuming elemental analyses, but can be achieved by simple and efficient incident-light microscopy.

Differences in optical behaviour of source rocks with increasing maturation can now be observed in much greater detail than in the past. With increasing levels of organic metamorphism the hydrogen-rich, insoluble organic matter (precursor of oil) in source rocks shows: 1) changes in fluorescence colour; 2) a decrease in fluorescence intensity; 3) plastic behaviour; 4) generation of mobile products and immobile residues.

These changes occur in bacterial organic matter at lower levels of maturation than in well preserved algal source rocks.

Keywords: Incident-light microscopy, oil source rock, gas source rock, ultraviolet light, tungsten light, polarised light, fluorescence, maceral, liptinite, vitrinite, intertinite, sporinite, cutinite, suberinite, alginite, resinite, structureless organic matter, laminated organic matter, exsudatinitite, liptodetrinite, vitrinite, vitrinite 1, vitrinite 2, fusinite, semi-fusinite, sclerotinite, micrinite, algal source rock, bacterial source rock, land plant derived source rocks, fractures expulsion.

### INTRODUCTION

The microscopic characterisation of organic matter in coal has developed very rapidly since STACH's (1935) recognition of its importance, not only in fundamental investigations but also in practical applications. Additional information was obtained when fluorescence microscopy was introduced by BERGER (1934) and SCHOCHARD (1943) in, respectively, hay-fever and brown coal studies. The importance of fluorescence microscopy was recognized by MAIER & WETZEL (1958), MAIER (1959) and WETZEL (1959), who detected fluorescing Hystrichosphaeridae in rocks by ultraviolet irradiation.

During the last 15 to 20 years, technical advances in incident-light microscopes for fluorescence investigations, in

vitrinite-reflectance microscopes, and in data-handling by computers, have resulted in greater use of these techniques in coal petrology and in oil and gas exploration (see references listed under VAN GIJZEL, MALAN, JACOB, OLLI, STACH, TEICHMÜLLER, LO & TING, OTTENJANN, PLOEM, ALPERN, TISSOT & WELTE, ROBERT, and DURAND).

Today, these new techniques are used to distinguish between different oil and gas source rocks. Fluorescence microscopy is especially suitable for determining the organic metamorphism and the expulsion stage of oil source rocks. Although fluorescence spectral analysis is useful for the determination of low-level organic metamorphism of source rocks, the routine method is still based on reflectance measurements of huminite and vitrinite (KÖTTER, 1960; TEICHMÜLLER, 1970, 1971, 1975, 1979; and BARTENSTEIN ET AL., 1971).

Source rocks are commonly classified on the basis of their chemical composition and the ratio of H/C to O/C, as exemplified by the three major types in the well-known Van

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Krevelen diagram (Fig. 1). Chemical analyses, however, are time-consuming and expensive. A classification that is based on recognition of the organic constituents of the source rocks using incident light microscopy is much faster and therefore considerably cheaper. In addition to a subdivision into the same major source-rock types as is derived from chemical analysis, incident-light microscopy also permits recognition of the main constituents (macerals) of that source rock in considerable detail, so that their environments of deposition can be inferred with some certainty.

Increasing maturation of the hydrogen-rich, insoluble organic matter (liptinites) in source rocks results in shifts in their fluorescence spectra, a decrease in their fluorescence intensities, plastic behaviour, the generation and expulsion of mobile products, and the formation of hydrogen-poor immobile residues (called micrinite by coal petrologists). With increasing coalification, vitritic coals (source rocks for gas) show a trend towards flat carbon-containing layers of increasing size and more parallel arrangement (BLAYDEN ET AL., 1944; SIEVER, 1952; YOUNG, 1954; and GRIFFIN, 1967).

The presence of an adequate amount of temperature-reactive insoluble organic matter is a prerequisite for the existence of a potential (immature) or an active (mature) source rock. The quantity of organic matter, its association, distribution, type and organic metamorphism are of importance in determining the presence of oil and gas source rocks, and in locating their recent and past zones of hydrocarbon generation and expulsion. Source rocks that have already generated their hydrocarbons are termed post-mature source rocks.

In this article we shall discuss the common macerals of oil and gas source rocks, and the microscope classification of source rocks, which is based upon them. The distribution of the macerals in the source rock and the changes that take place during maturation are also discussed.

## MACERALS

Acid insoluble organic constituents that are recognizable by means of microscopy are called macerals. Four main groups can be distinguished (STACH ET AL., 1975, 1982; TISSOT & WELTE, 1978; DURAND, 1980). A summary of the common macerals is given below (see also Fig. 2). For detailed descriptions, reference is made to the International Handbook on Coal Petrology (1971, 1975).

### Primary Macerals

*Liptinite (Exinite)* – This term covers a temperature-reactive, hydrogen-rich maceral group, including sporinite, cutinite, suberinite, alginite, resinite and structureless organic matter (Plate 1, see separate enclosures of this issue). Most liptinites are considered to be precursors of oil and gas.

*Sporinite* (Plate 1, Fig. 1) consists of spore and pollen

exines; a better term would be 'sporopollenite', but this term is not accepted internationally.

*Cutinite* (Plate 1, Fig 2) is derived from the outer layers of leaves, needles, shoots, stalks, thin stems and seeds.

*Suberinite* (Plate 1, Fig. 3) consists of corkified cell walls (bark) formed on the surface of roots, on stems and fruits.

*Alginite* (Plate 1, Fig. 4, 5, 6) originates from structural algal matter, such as Botryococcus, Tasmanites, Pediastrum and small spherical algae resembling Nostocopsis. Botryococcus (Plate 1, Fig. 4) is a colony-forming alga belonging to the Chlorophyceae (green algae) which occurs today in fresh water lakes (e.g. Gulf of Alkaool in Lake Balkbush and in central Europe) or in brackish to saline pools and lagoons (e.g. New South Wales, Australia; BLACKBURN, 1936). Tasmanites (Plate 1, Fig. 5) is considered to be a fossil Leiosphere (cyst) derived from a planktonic, marine, green alga, showing close affinity to the present day spherical alga Pachysphaera pelagica (CANE, 1968). Nostocopsis is a small, spherical single-cell alga (4-10 µm) belonging to the Schizophyceae and present, for example, in Liassic source rocks of the German Federal Republic (MADLER, 1968). Pediastrum is a colony-forming green alga (chlorococcales) occurring in fresh-water ponds.

*Resinite* (Plate 1, Fig. 7) is a resinous product of the metabolism of plants, common in the Tertiary coals of SE Asia.

*Brown fluorescent (when immature) structureless organic matter* (Plate 1, Fig. 8) occurs in specific oil source rocks, for example, in the Kimmeridgian oil source rocks of the North Sea. This organic matter is considered to be of bacterial origin (LIJMBACH, 1975).

*Blue/green/yellow fluorescent (when immature) non-structured organic matter* (Plate 1, Fig. 6), sometimes occurring in laminations, is considered to be of algal origin.

*Liptodetrinite* are small detrital fragments and degraded remains of liptinites that cannot be grouped with specific liptinitic macerals(s).

*Vitrinite* (Plate 2, Fig. 2-5) – This term covers a temperature-reactive maceral group (relatively hydrogen poor) derived from woody and cortical tissues. Two main types of vitrinite are distinguished, viz.:

*Vitrinite 1* (telocollinite Plate 2, Fig. 2), a relatively hydrogen-poor, non-fluorescing maceral, considered to be a gas precursor only. Telinite is a maceral of the vitrinite group with a clearly defined cell structure, while telocollinite is composed of collinite (solidified humic gels) completely covering the cell structure (telinite). It has a homogeneous appearance and no cell structures are recognizable. It is an important maceral because its chemical analysis and reflectance measurements are used as rank (coalification, diagenesis) scales (BUIKOOLOO-TOXOPEUS, 1983, in press). Oxidised vitrinite (Plate 2, Fig. 5) is not suitable for reflectance measurements because of the higher reflectances of the oxidised parts.

MACERAL GROUP

MACERALS

PRIMARY MACERALS

1. LIPTINITE  
(EXINITE)

TEMPERATURE REACTIVE MACERALS.  
RELATIVELY HYDROGEN-RICH.  
( precursors of oil and gas )

SPORINITE  
CUTINITE  
SUBERINITE  
ALGINITE  
RESINITE  
STRUCTURELESS  
ORGANIC MATTER

2. VITRINITE

TEMPERATURE-REACTIVE MACERALS.  
RELATIVELY HYDROGEN-POOR.  
( precursors of gas )

VITRINITE-1 :  
TELOCOLLINITE } COLLINITE  
                          } TELINITE  
  
VITRINITE-2 :  
DESMOCOLLINITE, ETC.

3. INERTINITE

NON-TEMPERATURE-REACTIVE  
(INERT)MACERALS.  
VERY POOR IN HYDROGEN  
( generates no commercial quantities  
of hydrocarbons )

FUSINITE  
SEMI-FUSINITE  
SCLEROTINITE  
OXY-MICRINITE

4.

SECONDARY MACERALS

EXSUDATINITE  
RANK MICRINITE

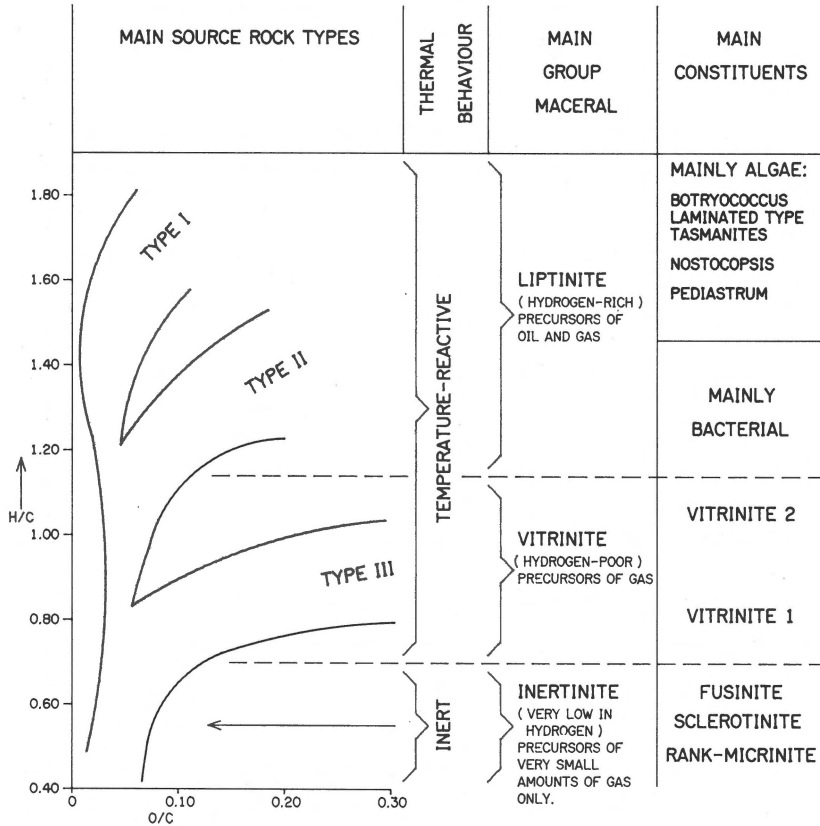


Fig. 1  
Main source rock types, their postulated macerals and thermal characteristics.

Fig. 2  
Microscope classification of organic matter in sediments.

*Vitrinite 2* (Desmocollinite etc. Plate 2, Fig. 4), a hydrogen-rich variety of vitrinite, is assumed to be a precursor of gas and oil. This group of vitrinite macerals shows weak fluorescence, in contrast to vitrinite 1, which is non-fluorescent. The hydrogen-rich character is caused by finely distributed (sub)-microscopic liptinites in the vitrinite, by syndimentary bacterial transformation of organic matter (for example, landplant matter), or by impregnation (BUIKSOOL-TOXOPEUS, 1983).

*Inertinite* (Plate 2, Fig. 6, 7, 8) – Covers a relatively hydrogen-poor inert to almost inert maceral group, which contains no precursors of commercial hydrocarbons. Several inertinites can be distinguished:

*Fusinite* (Plate 2, Fig. 6), a maceral, mainly found in fossil wood charcoal, showing a well-defined cellular structure.

*Semi-fusinite*, a maceral intermediate between vitrinite and fusinite, showing a well-defined cell structure.

*Sclerotinite* (Plate 2, Fig. 7), a maceral reported to be the resting stage of fungi.

*Oxy-micrinite*, a maceral consisting of very small spherical granules; it is considered to be the oxidation product of organic matter.

#### Secondary Macerals

*Exsudatinitite* (Plate 2, Fig. 1) is a secondary maceral (expulsion product) generated from liptinites.

*Rank micrinite* (Plate 2, Fig. 8), a maceral consisting of very small, reflecting, spherical granules; it is considered to be the inert final product (advanced maturation product) of liptinites.

### MICROSCOPE CLASSIFICATION OF SOURCE ROCKS

A chemical classification of source rocks on the basis of their H/C and O/C ratios was proposed by TISSOT & WELTE (1978; see also Fig. 1). It was, in essence, available in coal literature and was based on the changes in hydrogen and carbon percentages of hydrogen-poor and hydrogen-rich coals with increasing coalification (SEYLER, 1900; GROUT, 1907; RALSTON, 1915; WHITE, 1925; MOTT, 1942; FRANCIS, 1961; and VAN KREVELEN, 1961).

TISSOT & WELTE (1978) proposed naming the H/C-O/C ratio graph the 'Van Krevelen' diagram, because VAN KREVELEN was the first to use this plot to characterise coals and their paths of coalification. This diagram also provides a useful approach to classifying organic matter other than coal, and has found wide acceptance (FORSMAN, 1963; DURAND ET AL., 1972; TISSOT ET AL., 1974; TISSOT & WELTE, 1978; JONES & EDISON, 1978; and DURAND, 1980).

It should be emphasised, however, that the limits of the three source-rock zones, Types I to III, in the H/C-O/C

diagram (Fig. 1) is schematic.

The microscope classification is based on the different maceral associations encountered in source rocks of contrasting type (Fig. 1). The purpose of such a classification is:

- to distinguish various types of organic matter with regard to their ability to generate either oil and gas or gas only;
- to determine the changes in specific constituents with increasing diagenesis;
- to relate specific macerals or maceral associations to their depositional environments.

Three major source-rock types and six sub-types can be recognized by the interpretative characteristics outlined below; the three main types are characterised by their content of:

- Type 1: Algal source matter
- Type 2: Bacterial source matter
- Type 3: Landplant source matter

#### *Type 1: Algal source rocks* (Plate 3, Fig. 1, 2)

Algal source rocks can be subdivided into a *structured algal* source rock (Type 1A) and a *non-structured/laminated algal* source rock (Type 1B).

- *Structured algal source rocks* (Type 1A, Plate 3, Fig. 1) are characterised by recognizable structured algae such as Botryococci, Tasmanites and Nostocopsis. The colony-forming alga Botryococcus occurs in rocks ranging in age from Precambrian to Recent. The Australian torbanite (Permian) and the Missouri Decorah Formation (Ordovician) belong to type 1A. Many Tasmanites are present in the Tasmanite oil shale (Permian, Australia; Jurassic/Cretaceous, Alaska). This oil shale belongs to type 1A.
- *Laminated algal source rocks* (Type 1B, Plate 3, Fig. 2) are characterised by their blue/green/yellow fluorescent (when immature), laminated but otherwise structureless organic matter. The algal origin is assumed on the basis of the following microscopic evidence:
  - The bright fluorescence colours are similar to those of the recognizable, structured Botryococcus and Tasmanites algae in equivalent diagenetic ranges.
  - This organic matter is highly temperature-resistant, a characteristic of well-preserved algae such as Botryococcus and Tasmanites.

#### *Type 2: Bacterial source rocks* (Plate 3, Fig. 3)

Type 2 source rocks contain dull-yellow to brown fluorescent (when immature) structureless organic matter assumed to be the remains of the degraded bacteria that contributed to a large extent to this source matter (LIJMBACH, 1975). This source matter originated from algal, landplant and animal matter, for example, that was transformed, during and

immediately after sedimentation, by and into bacteria. The following microscopic observations are in agreement with chemical and sediment microbiological data.

- No internal structure (e.g. laminations) is visible during short-time ultraviolet exposure. After prolonged exposure a laminated structure may develop, which might indicate an algal origin.
- In clastic sediments, this source matter is generally associated with abundant framboidal pyrite, pointing to bacterial reworking (by sulphate reduction) of the digestible organic matter.
- The dull-yellow/brown fluorescent (when immature) organic matter generates expulsion products (exsudatinites) at lower diagenetic levels than the laminated, bright blue/green/yellow fluorescent structureless organic matter of assumed algal origin.

The fluorescence colour gradations from bright blue/green/yellow to dull-yellow/brown fluorescent organic matter of immature type 2 source rocks may be interpreted as different intensities of bacterial transformation and/or as oxidation of the original algal matter during or after sedimentation.

Source rock type 2 can be subdivided into two groups:

- *Type 2A source rocks* are characterised by the presence of dull-yellow/brown fluorescent (when immature) structureless organic matter associated with alginite (such as *Botryococcus* or *Tasmanites* algae) and sometimes with other minor macerals. An example of this source rock type occurs within the Scottish Oil Shale Group (Carboniferous-Visean) of the Scottish Midland Valley Graben.
- *Type 2B source rocks* are characterised by a major proportion of dull-yellow to brown fluorescent (when immature) structureless organic matter, sometimes associated with minor macerals such as reworked vitrinite and/or liptinites. The Kimmeridgian oil source rock of the North Sea belongs to this group.

It should be stressed that in the H/C-O/C diagram, sporopollenite and cutinite are reported to fall within the source rock 2 belt, while resinite plots between the belts of types 1 and 2 (ROBERT, 1979). These macerals are considered to be landplant-derived hydrogen-rich matter (superhydrous to perhydrous; MOTT, 1942), which, in concentrated form, fall outside the 'vitrific' coal belt (type 3). However, in general, they are associated with abundant vitrinite so that the combined H/C-O/C ratios plot either within the type 3 belt or just outside it.

*Type 3: Landplant-containing source rocks* (Plate 3, Fig. 4)

Vitrinite is a major component of this source-rock type. Liptinites, bacterial structureless organic matter, and inertinites may be present as additional macerals. This type can be subdivided into two major groups:

- *Type 3A source rocks* are the hydrogen-richer coals and

carbonaceous shales in which vitrinite 2 is the dominant maceral. Brown fluorescent (when immature) bacterial structureless organic matter, and typical landplant liptinites such as sporinite, suberinite, cutinite and resinite, are often important additional macerals (Plate 3, Fig. 4). Examples of this type are the suberinite-rich Acland coals of the Walloon coal measures, Middle Jurassic, Australia, and the resinite-rich coals of SE Asia.

- *Type 3B source rocks* are the typical humic (vitrific) coals and carbonaceous shales. The major constituent is vitrinite with or without minor macerals such as liptinites and inertinites. The vitrinite-rich Carboniferous coals of NW Europe and the USA belong to this source-rock type.

In the literature, an additional rock type has been proposed (TISSOT ET AL., 1974; JONES & EDISON, 1978; ROBERT, 1979) containing mainly primary inertinite; in general, these rocks are rare and can be regarded as subhydrous (very low hydrogen) rocks of type 3.

## MACERAL DISTRIBUTION

Microscope investigation of source rocks has indicated that there is an important relationship between the distribution of macerals and the amount of liquid hydrocarbon that can be expelled from a source rock. For this reason it is necessary to examine both the composition and distribution of the organic macerals in polished sections of potential source-rock formations.

### *Hydrocarbon source rocks*

*Good to excellent potential oil source rocks* are characterised by the presence of a three-dimensional network of organic matter, which in cross-section shows a dense (Plate 3, Fig. 7), layered and/or lens-like distribution (Plate 3, Fig. 6). Before the source rock reaches maturity, the full weight of the overburden is carried by the framework of sedimentary particles and it contained solid organic matter. In the zone of maturation, however, part of the organic matter becomes plastic or even fluid, and because its volume also expands, the full weight of the overburden may be carried by the fluid. The overburden pressure will be transmitted in all directions (Pascal's law) by the load-bearing plastic or liquid kerogen to the adjacent relatively competent mineral matter (limestone, dolomite, siltstone, shale, etc.) causing it to fracture perpendicular to the direction of least stress. The fluid escapes (expulsion) and the framework of sedimentary grains once again carries the full load of the overburden until such time as more fluid kerogen is produced (if any) and further expulsion takes place. Reference is made to MOMPEN (1978) and to DE GROOT (in press) for detailed information on oil migration from source rocks.

In summary, during fluidisation of the liptinites a phase

change of the load-bearing hydrogen-rich organic matter (liptinites) induces fractures in either the adjacent competent mineral matter or in the vitritic matter. The load-bearing character of the liptinites is therefore a prerequisite for the efficient expulsion of oil.

*Lean potential oil source rocks* are characterised by diffusely and intergranularly distributed organic matter (Plate 3, Fig. 5). In this case, the mineral matter carries most of the overburden and it seems that only marginal amounts of liquid hydrocarbons are expelled locally. Such rocks can be a good source for gas, however.

An excellent source rock for gas, such as a vitritic coal, will behave essentially as a solid throughout its maturation because of its relatively low hydrogen content. For this reason, only relatively small amounts of oil will be generated per unit weight of coal. The vitritic groundmass acts as a competent material and therefore will not flow. The liquefaction of liptinite (e.g. resinite, cutinite, suberinite and bacterial structureless organic matter) can cause fracturing of the vitritic groundmass.

Because the gas molecule is small, and the volume of gas produced from source rocks at higher levels of organic metamorphism is many times greater than that of oil, gas can be expelled from even lean source rocks.

## MACERAL DIAGENESIS

### *Oil source rocks*

In Shell's Rijswijk laboratories, investigations have been carried out both on samples heated in the laboratory and on a suite of natural oil-source-rock samples that had been subjected to progressively increasing diagenesis. These samples were analysed using incident-light microscopy (ultraviolet, tungsten and polarised tungsten light).

The microscopic changes in macerals were investigated in these samples. The observed changes in fluorescence colour were measured using fluorescence spectral analysis. For details on this technique, reference is made to TEICHMÜLLER & OTTENJAN (1977), JACOB (1974), LO & TING (1972), STACH ET AL. (1975, 1982), HAGEMAN & HOLLERBACH (1980), OTTENJAN (1980, 1981/1982) and VAN GIJZEL (1961 to 1981).

With increasing diagenesis, the following observations were made on well preserved liptinites:

- 1) The maxima of the fluorescence spectra of the liptinites shift, in general, from the blue to the red part of the spectrum.
- 2) The liptinites reacted in a plastic fashion and were associated with the formation of fractures in the adjacent competent mineral and vitritic matter.
- 3) Exsudatinites (expulsion products) and micrinite were generated.

- 4) Exsudatinites were expelled into adjacent pores and fractures.

It was also found that:

- a) bacterial organic matter (main maceral of type 2 source rocks) exhibits the changes mentioned above under 2, 3 and 4 at lower levels of organic metamorphism than observed in well preserved algae (e.g. Botryococcus, Tasmanites)
- b) algal source rocks exhibit widely different rates of change.

### *Gas source rocks*

Vitritic coal (source rock type 3), or vitritic particles in carbonaceous shales, will behave essentially as solids in the oil-generation zone. They are considered to generate and release mainly dry hydrocarbon gases because of their relatively low hydrogen content, which is allied to their poly-aromatic structure.

The diagenetic changes in vitrite can be observed by X-ray diffraction analysis (BLAYDEN ET AL., 1944; SIEVER, 1952; YOUNG, 1954; and GRIFFIN, 1967) and by means of vitrinite reflectance measurements. The progressive increase of vitrinite reflectance in sediments with an increasing degree of coalification was first observed by HOFFMANN & JENKER (1932). At present, this method is considered 'the most widely applied maturity scale' (TISSOT & WELTE, 1978; TEICHMÜLLER & TEICHMÜLLER, 1981; see also Fig. 3).

### *Recognition of post-mature source rocks*

Immature and mature source rocks can be detected by pyrolysis, combustion, extraction and microscope techniques. These techniques, with the exception of the microscope approach are, in general, not suitable for the recognition of post-mature source rocks.

While analysis of the percentage of organic carbon can be used to determine the quantity of organic matter in post-mature source rocks, it cannot distinguish between post-mature oil source rocks and post-mature gas source rocks. This distinction is possible only by the application of organic carbon percentage analysis in combination with incident tungsten light microscopy and X-ray diffraction analysis.

Post-mature oil source rocks (types 1 and 2) show increasing micrinitisation with increasing diagenesis. This inert, high-rank product consists of microscopically small spherical particles ('micrinite') up to at least a vitrinite reflectance level of 2.50-3.00%  $R_m$  oil.

Microscopically, the organic particles of post-mature gas source rocks are anisotropic under crossed nicols. According to X-ray diffraction analyses, they form flat carbon-containing layers of increasing size and more parallel plate arrangement (GRIFFIN, 1967).

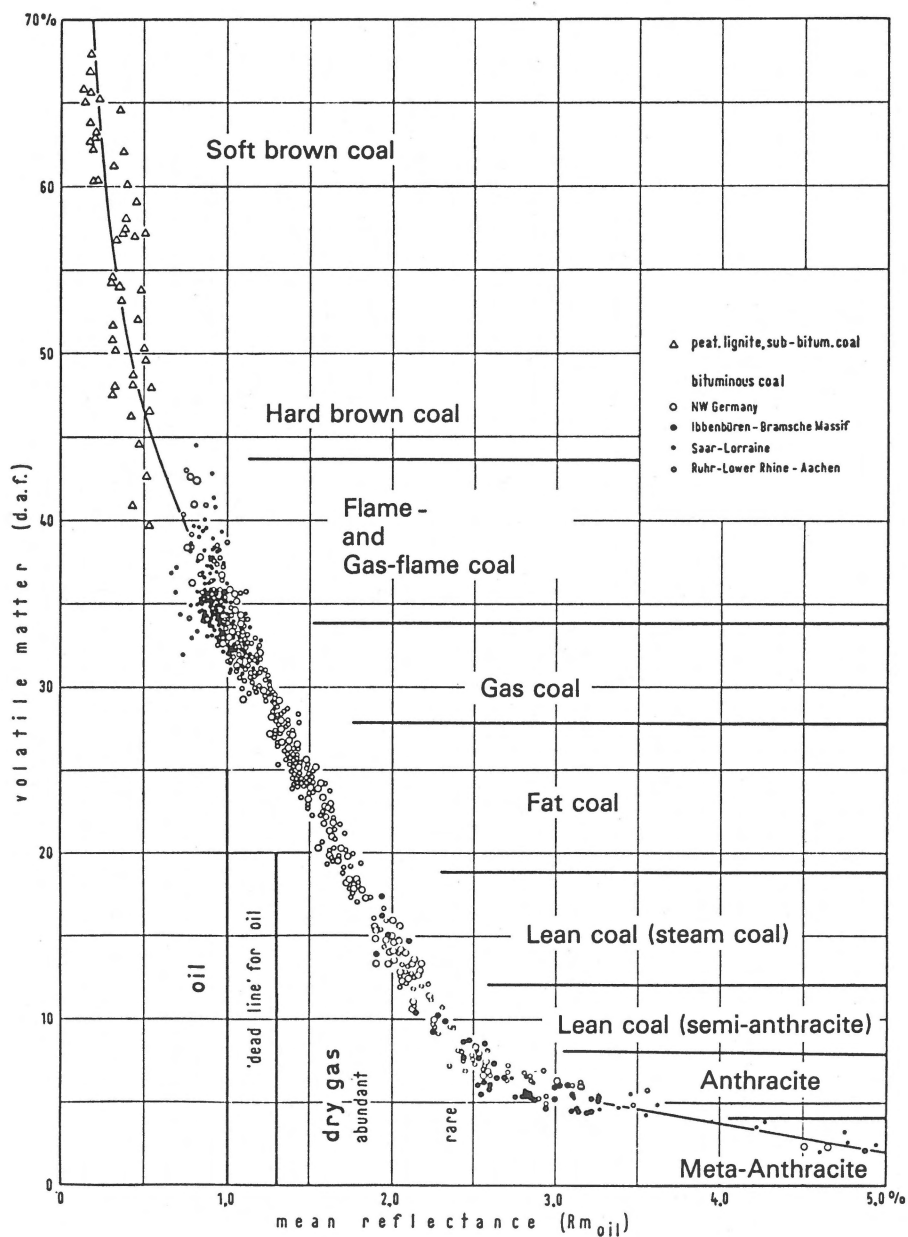


Fig. 3 Relationship between volatile matter, mean reflectivity of huminite/vitrinite for the different stages of coalification (brown coal to meta-anthracite) of German coal deposits and the occurrence of oil and natural gas (after BARTENSTEIN & TEICHMÜLLER, 1974).

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#### REFERENCES

- Alpern, B., 1976 Fluorescence et réflectance de la matière organique dispersée et évolution des sédiments - Bulletin du Centre de Recherches Pau-SNPA 10, 1: 201-220.
- Bartenstein, H., M. Teichmüller & R. Teichmüller, 1971 Die Umwandlung der kohligen Substanz im Dach des Bramscher Massivs - Fortschr. Geol. Rheinld. u. Westf. 18: 501-538.
- Bartenstein, H. & R. Teichmüller, 1974 Inkohlungsuntersuchungen, ein Schlüssel zur Prospektierung von Paläozoischen Kohlenwasserstoff-Lagerstätten - Forsch. Geol. Rheinld. u. Westf. 24: 129-160.

- Berger, F., 1934 Das Verhalten der Heufieber erregender Pollen im filtrierten ultra-violetten Licht – *Beitr. Biol. Pflanz.* 22: 1-12.
- Blackburn, K. B., 1936 Botryococcus and algal coals. A reinvestigation of the alga Botryococcus Braunii Kützing – *Trans. Roy. Soc. Edinb.* 58: 841-854.
- Blayden, H. E., J. Gibson & H. L. Riley, 1944 An X-ray study of the structure of coals, cokes and chars. In: *Ultra-fine structure of coal and cokes – Conf. proc., British Coal Utilisation Res. Assoc., London:* 176-231.
- Bostick, N. H., 1970 Thermal alteration of clastic organic particles (phytocoals) as an indicator of contact and burial metamorphism in sedimentary rocks – Ph.D. Dissertation, Stanford Univ.
- Bostick, N. H. & J. N. Foster, 1975 Comparison of vitrinite reflectance in coal seams and in kerogen of sandstones, shales and limestones in the same part of a sedimentary section. In: B. Alpern, (ed.): *Pétrographie de la Matière organique des Sédiments, relations avec la paléo-température et le potentiel pétrolier – Centre national de La Recherche Scientifique, Paris:* 13-25.
- Buiskool Toxopeus, J. M. A., 1983 (in press) Selection criteria for the use of vitrinite reflectance as a maturity tool – *Geol. Soc. London. Spec. Publication.*
- Cane, R. F., 1968 The constitution of Tasmanites – Joint Symposium on oil shale, tar sand and related material – American Chemical Society, San Francisco: 93-97.
- Castano, J. R. & D. M. Sparks, 1974 Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals – *Geol. Soc. America, Special Paper* 153: 31-52.
- De Groot, K. & C. C. M. Gutjahr (in press) Expulsion of oil from source rocks – Paper delivered on 2 December 1981 at a meeting 'Migration of Fluids' organised by the Geological Society of London, Burlington House, Piccadilly, London.
- De Vries, H. A. W., P. J. Habets & C. Bokhoven, 1968 Das Reflexionsvermögen von Steinkohle. I. Beschreibung der Kohlenanschlißherstellung der Reflexionsmessapparatur und der Eichung der Apparatur – *Brennst. Chemie* 49 (1): 15-21.
- 1968 Das Reflexionsvermögen von Steinkohle. II. Die Reflexionsanisotropie – *Brennst. Chemie* 49 (2): 47-52.
- 1968 Das Reflexionsvermögen von Steinkohle. III. Der Einfluss der Temperatur – *Brennst. Chemie* 49 (4): 105-110.
- Durand, B., J. Espitalié, G. Nicaise & A. Combaz, 1972 Étude de la matière organique insoluble (Kérogène) des argiles du Toarcien du bassin de Paris – *Revue de l'Institut Français du Pétrole.* 27 (6): 865-884.
- Durand, B., 1980 Kerogen, insoluble organic matter from sedimentary rocks – Editions Technip, Paris, 513 pp.
- Forsman, J. P., 1963 Geochemistry of kerogen. In: I. A. Breger (ed.): *Organic Geochemistry – Macmillan, New York:* 148-182.
- Francis, W., 1961 Coal, its formation and composition (Second edition) – Edward Arnold Publishers, London: 806 pp.
- Griffin, G. M. 1967 X-ray diffraction techniques, applicable to studies of diagenesis and low rank metamorphism in humic sediments – *Jl. Sediment Petrol.* 37 (4): 1006-1011.
- Grout, F. F., 1907 The composition of coal – *Economic Geol. No. 3* (2): 225-241.
- Gutjahr, C. C. M. 1966 Carbonization measurements of pollen-grains and spores and their application – *Leidse Geol. Meded.* 38: 1-30.
- Hagemann, H. H. & A. Hollerbach, 1980 Spektralfluorimetrische Analysen von Sediment-Extrakten – *Erdöl und Kohle-Erdgas-Petrochemie*, 33 (12): 577.
- Heidenreich, R. D., W. M. Hess & L. L. Ban, 1968 A test object and criteria for high resolution electron microscopy – *Journ. of Applied Cryst.* 1: 1-19.
- Hood, A., C. C. M. Gutjahr & R. L. Heacock, 1975 Organic metamorphism and the generation of petroleum – *Am. Assoc. Petrol. Geol. Bull.* 59 (6): 986-996.
- Huntjes, F. J. & D. W. van Krevelen, 1954 Chemical structure and properties of coal II-reflectance – *Quart. J. Fuel Sci.*, 33 (1): 88-103.
- Hutton, A. C., A. J. Kantsler, A. C. Cook & D. M. McKirdy, 1980 Organic matter in oil shales – *J. Austral. Petrol. Explor. Assoc.* 20: 44-68.
- International Committee for Coal Petrology 1971 International handbook of coal petrology (2nd ed.) – Centre National de la Recherche Scientifique, Paris.
- 1971 International handbook of coal petrology. Suppl. (2nd ed.) – Centre National de la Recherche Scientifique, Paris.
- 1975 International handbook of coal petrology. 2nd. Suppl. (2nd ed.) – Centre National de la Recherche Scientifique, Paris.
- Jacob, H., 1964 Neue Erkenntnisse auf dem Gebiet der Luminezenz-Mikroskopie fossiler Brennstoffe – *Fortschr. Geol. Rheinld. u. Westd.* 12: 569-588.
- 1969 Luminezenz-Mikroskopie der organopetrographischen Bestandteile von Sedimentsgesteinen – *Leitz Mitt. Wiss. Techn.* 4: 250-254.
- 1974 Fluoreszenz-Mikroskopie und -Photometrie der organischen Substanz von Sedimenten und Böden. In: H. Freund (ed.): *Handbuch der Mikroskopie in der Technik*, 4 (2) – Frankfurt/M.: 369-391.
- 1980 Die Anwendung der Mikrophotometrie in der organischen Petrologie – *Leitz – Mitt. Wiss. u. Techn.* 7 (7): 209-216.
- Jones, R. W. & T. S. Edison, 1978 Microscopic observations of kerogen related to geochemical parameters with emphasis on thermal maturation. In: D. F. Oltz (ed.): *A symposium in geochemistry: low temperature metamorphism of kerogen and clay minerals.*
- Kötter, K., 1960 Die mikroskopische Reflexionsmessung mit dem Photomultiplier und ihre Anwendung auf die Kohlenuntersuchung – *Brennst. Chem.* 41 (9): 263-272.
- Lijmbach, G. W. M., 1975 On the origin of petroleum – *Proc. 9th World Petroleum Congress, 1975, Tokyo, SPI:* 357-369.
- Lo, H. B. & F. T. C. Ting, 1972 Fluorescence microscopy for coal Petrography – *Abstract, Geol. Soc. America*, 5 (7): 715.
- Madler, K., 1968 Die figurierten organischen Bestandteile der Posidonienschiefer – *Beiheft zum Geol. Jahrbuch*, 58: 287-406.
- Malan, Ö., 1962 Die Entwicklung der optischen Methoden zur Beurteilung von Braunkohlen – *Freiberger Forsch. H.A.* 253: 5-20.
- Maier, D. & W. Wetzel, 1958 Fluoreszenz-Mikroskopie geologischer und paläontologischer Objekte – *Zeiss Mitteilungen* 1 (4): 127-131.
- 1959 Planktonuntersuchungen in tertiären und quartären marinen Sedimenten – *N. Jb. Geol. Paläont. Abh.* 107 (3): 298-299.
- McCartney, J. T. & L. J. E. Hofer, 1955 Microreflectivity analysis of coal – *Anal. Chemie*, 27 (8): 1320-1325.
- Momper, J. A., 1978 Oil migration limitations suggested by geological and geochemical considerations. In: *AAPG Continuing Education Course Notes Series 8, Physical and chemical constraints on petroleum migration.*
- Mott, R. A., 1942 The origin and composition of coals – *Fuel*, XXI (6): 129-135.
- Murchison, D. G., 1964 Reflectance techniques in coal petrology and their possible application in ore mineralogy – *Trans. Inst. Mining Metal* 73: 479-502.
- Oberlin, A., G. Terriere, B. Durand & C. Clinard, 1972 Contribution de la microscopie et de la microdiffraction électronique à l'étude de la matière organique insoluble des sédiments – *Adv. in Org. Geochem.* 1971, Pergamon Press, Oxford: 577-589.
- Olli, I. A. 1964 The use of luminescence microscopy in determining the epigenetic and syngenetic bituminosity of rocks – *Geol. i.*

- Geofiz. Akad. Nauk. SSR, Sibirsk, No. 12: 119-123.
- Ottenjann, K., M. Teichmüller & M. Wolf, 1973 Spectral fluorescence measurements of sporinites in reflected light and their applicability for coalification studies (Colloque International). In: B. Alpern (ed.): *Pétrographie de la matière organique des sédiments* – Centre national de la Recherche Scientifique, Paris, 49-65.
- Ottenjann, K., M. Teichmüller & M. Wolf 1974 Spectral fluorescence measurements on sporinites with incident light excitation, a microscopic method for determining the rank of low-rank coals – *Fortschr. Geol. Rheinld. u. Westf.* 24: 1-36.
- Ottenjann, K., 1980 Spectrale Fluoreszenz-Mikrophotometrie von Kohlen und Ölschiefern – *Leitz Mitt. Wiss. Techn.* 7 (8): 262-273.
- 1981/82 Verbesserungen bei der mikroskopphotometrischen Fluoreszenz-Messung und Kohlenmaceralen – *Zeiss-Inform. Oberkochen* 26 (93): 40-46.
- Pickhardt, W. & K. Robock, 1965 Weiterentwicklung einer Apparatur zur photoelektrischen Messung der Reflexion und der Adsorption – *Brennst. Chemie* 46 (2): 3-7.
- Ploem, J. S., J. A. de Sterke, J. Bonnet & H. Wasmund, 1974 A microspectrofluorometer with epi-illumination operated under computer control – *Jl. Histochemistry Cytochemistry* 22 (7): 668-677.
- Ralston, O. C., 1915 Graphic studies of ultimate analysis of coal – US Bureau of Mines Tech. Paper No. 93: 1-41.
- Robert, P. 1979 Classification des matières en fluorescence application aux Roches-meres Pétrolières – *Bulletin du Centre de Recherches Explor.-Prod. Elf-Aquitaine* 3, Pau, France: 223-263.
- Schohardt, H., 1943 Grundlagen und neuere Erkenntnisse der angewandten Braunkohlenpetrographie – Halle/Saale (Knapp): 208 pp.
- Seyler, C. A., 1900 The chemical classification of coal – *Proc. South Wales Inst. Inst. Eng.* 22: 112-120.
- Siever, R., 1952 X-ray diffraction study of rank increase in coal. In: *On the origin and constitution of coal – 2nd Conf. Proc. Nova Scotia. Dept. of Mines, 18-20 June 1952, Nova Scotia Research Foundation: 341-362.*
- Stach, E., 1935 *Lehrbuch der Kohlenpetrographie* – Gebrüder Borntraeger, Berlin: 293 pp.
- 1969 Fortschritte der Auflicht-Fluoreszenz Mikroskopie in der Kohlenpetrographie – *Frieberger Forsch. H.C.* 242: 35-56.
- Stach, E., M. Th. Mackowsky, M. Teichmüller, G. H. Taylor, D. Chandra & R. Teichmüller, 1975 *Coal Petrology* – Gebrüder Borntraeger, Berlin, Stuttgart: 428 pp.
- 1982 *Coal Petrology* (revised edition) – Gebrüder Borntraeger, Berlin, Stuttgart: 535 pp.
- Teichmüller, M., 1970 Bestimmung des Inkohlungsgrades von kohligem Einschüssen in Sedimenten des Oberrheingraben sein Hilfsmittel bei der Klärung geothermischer Fragen. In: J. H. Illies & S. T. Müller (eds.): *Graben Problems – Internat. Upper Mantle Project, Sci. Rep.* 27: 24-142.
- Teichmüller, M., 1971 Anwendung Kohlenpetrographischer Methoden bei der Erdöl- und Erdgas Prospektion – *Erdöl u. Kohle* 24: 69-76.
- Teichmüller, M., 1974 Über neue maceralen der Liptinit-Gruppe und die Entstehung von Micrinit – *Fortschr. Geol. Rheinld. u. Westf.* 24: 37-64.
- Teichmüller, M., 1974 Origin and alteration of bituminous substances in coals as related to the origin and transformation of Petroleum – *Fortschr. Geol. Rheinld. u. Westf.* 24: 65-112.
- Teichmüller, M. & M. Wolf, 1977 Application of fluorescence microscopy in coal petrology and oil exploration – *Jl. Microscopy*, 109: 49-73.
- Teichmüller, M. & K. Ottenjann, 1977 Liptinite und lipoide Stoffe in einem Erdölmuttergestein – *Erdöl und Kohle-Erdgas-Petrochemie*, 30 (9): 387-398.
- Teichmüller, M., 1979 Die Diagenese der kohligem Substanzen in den Gesteinen des Tertiärs und Mesozoikums des mittleren Oberrhein-Grabens – *Fortschr. Geol. Rheinld. u. Westf.* 27: 19-49.
- Teichmüller, M. & R. Teichmüller, 1979 Zur geothermischen Geschichte des Oberrhein-Grabens – *Fortschr. Geol. Rheinld. u. Westf.* 27: 109-120.
- Teichmüller, M. 1981 Braunkohlenmikroskopie -Entwicklung und Stand der Methoden – *Forsch. Geol. Rheinld. u. Westf.* 29: 449-468.
- Teichmüller, M. & B. Durand, 1983 Fluorescence microscopical rank studies on liptinites and vitrinites in peat and coals, and comparison with results of the rock-eval pyrolysis – *Intern. Jl. Coal Geology* 2: 197-230.
- Tissot, B., B. Durand, J. Espitalié & A. Combaz, 1974 Influence of nature and diagenesis of organic matter in the formation of petroleum – *Am. Assoc. Petrol. Geol. Bull.* 58: 499-506.
- Tissot, B. P. & D. H. Welte, 1978 *Petroleum formation and occurrence* – Springer-Verlag, Berlin, Heidelberg, New York: 538 pp.
- Van Gijssel, P., 1961 Autofluorescence and age of some fossil pollen and spores – *Proc. Kon. Ned. Akad. Wetensch. B Ser.* 64, No. 1: 56-63.
- 1966 Notes on autofluorescence of some Cenozoic pollen and spores from The Netherlands – *Mededel. Geol. Sticht. N Ser.* 16: 25-32.
- 1966 Die Fluoreszenz-Photometrie von Mikrofossilien mit dem Zweistrahl-Mikroskopphotometer nach Berek – *Leitz Mitt. Wiss. Techn.* 3 (7): 206-214.
- 1967 Palynology and fluorescence microscopy – *Rev. Palaeobotan. Palynol.* 2: 49-79.
- 1967 Autofluorescence of fossil pollen and spores with special reference to age determination and coalification – *Leidse Geol. Meded.* 39: 263-317.
- 1973 Polychromatic UV-fluorescence photometry of fresh and fossil plant substances with special reference to the location of dispersed organic material in rocks (Colloque international). In: B. Alpern (ed.): *Pétrographie de la matière organique de sédiments* – Centre National de la Recherche Scientifique, Paris: 67-91.
- 1976 Procedures for the correction of fluorescence spectra and the evaluation of fluorescence data by means of computer-operated microspectrophotometry with incident UV-illumination – Report presented at the ICCP meeting, University of New Castle-upon-Tyne, England: 1-10.
- 1981 Applications of the Geomicrophotometry of kerogen, solid hydrocarbons and crude oils to petroleum exploration. In: J. Brook (ed.): *Organic maturation studies and fossil fuel exploration* – Academic Press Inc., London: 351-377.
- Van Krevelen, D. W. 1961 *Coal* – Elsevier Publ. Comp. (Amsterdam, London, New York, Princeton): 514 pp.
- Wetzel, W., 1959 Das Lumineszenzmikroskopische Verhalten von Sedimenten – *N. Jb. Geol. u. Paläont. Abh.* 107 (3): 261-277.
- White, D., 1925 Progressive regional carbonization of coals – *Trans. of the American Institute of Mining and Metallurgical Engineers* 71: 282-288.
- Young, R. S., 1954 Preliminary X-ray investigation of solid hydrocarbons – *Am. Assoc. Petrol. Geol. Bull.* 38: 2017-2020.