Reflectance of dispersed vitrinite in Palaeozoic rocks with and without cleavage: Implications for burial and thermal history modeling in the Devonian of Rursee area, northern Rhenish Massif, Germany

Ralf Littke, Janos L. Urai, Anna K. Uffmann⁎, Fotios Risvanis 1

RWTH Aachen University, Energy and Mineral Resources (EMR), Lochnerstr. 4–20, 52056 Aachen, Germany

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Vitrinite reflectance is used as coalification parameter in coals and as maturity and palaeotemperature indicator in sedimentary rocks. In high grade diagenetic rocks, i.e. rocks at the boundary between diagenesis and metamorphism, vitrinites become increasingly anisotropic. Therefore, it has been suggested to study maximum/minimum reflectance instead of mean reflectance for rocks which reached this stage. In the present study, vitrinite reflectance data from a folded sequence of the northern Rhenish Massif (Germany) are combined with microtectonic study of thin sections in samples in which both bedding and cleavage are present. We show that vitrinites in different microtectonic domains (cleavage domains and microlithons) show significant differences in both maximum vitrinite reflectance and vitrinite reflectance anisotropy. This behaviour is due to a strong partitioning of deformation in cleavage domains as compared to microlithons, so that vitrinite reflectance is controlled by the thermal and deformation history. Accordingly, estimation of maximum palaeotemperatures during burial should be based on vitrinite reflectance measurements in microlithons unaffected by deformation after maximum burial. Based on this finding, burial and temperature history of the Rursee area in the eastern Rhenish Massif is reconstructed. Numerical simulations indicate a maximum burial at the Siegen/Ems boundary of about 5000 m and a maximum burial temperature of about 220 °C.

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1. Introduction

Sedimentary basins can be regarded as large-scale reactors in which a great number of important reactions take place such as the generation of natural gas and oil, the conversion of peat into coal and anthracite and the conversion of thermally unstable minerals into more stable ones. All these reactions are irreversible and depend largely on temperature and time and in particular on maximum palaeotemperatures reached during burial (Hedberg, 1974; Levine, 1993; Tissot et al., 1974). Thus, the reconstruction of burial temperatures that affected sedimentary rocks is one of the key tasks of geological sciences.

Accordingly an increasing number of temperature-sensitive parameters have been developed over the last decades, providing insight into thermal histories of sedimentary rocks (e.g. Leischner et al., 1993; Peters et al., 2005). Clearly, one of the most widely used parameters is vitrinite reflectance (Mukhopadhyay and Dow, 1994). Vitrinites are derived from small pieces of higher land plants such as wood and are ubiquitous in sedimentary rocks of Devonian and younger age (Taylor et al., 1998). In very young, near-surface sediments, vitrinite reflectance is as low as 0.2%. With increasing burial and temperature, reflectance increases monotonously to values of greater than 4%, when the transition zone between high-grade diagenesis and very-low grade metamorphism is reached (Taylor et al., 1998). Accordingly, vitrinite reflectance is a parameter, which provides palaeo-temperature information for rocks at the stage of high-grade diagenesis/anchimetamorphism. However, it has been noted that vitrinite reflectance anisotropy or “rotational reflectance of dispersed vitrinite” provides superior information about thermal maturity and the relative timing between thermal and kinematic events in fold belts at the transition between diagenesis and metamorphism (Houseknecht and Weesner, 1997; Levine and Davis, 1989a,b).

At high reflectance values, vitrinites become increasingly anisotropic due to condensation and ordering of aromatic layers (Béhar and Vandenbrouke, 1987; Schenk et al., 1990). Therefore in high-grade diagenetic rocks, maximum reflectance ($VR_{\text{max}}$) is commonly measured as temperature-sensitive parameter instead of random
reflectance VR\textsubscript{r}. Some studies in fold belts revealed that the VR\textsubscript{max} axis is oriented parallel to the fold axis (Hower and Davis, 1981; Levine and Davis, 1984, 1989a) and that the optical ellipsoid was transformed from uniaxial to biaxial depending on the stress field during coalification. Furthermore, laboratory experiments at high differential stress and high temperatures demonstrate reorientation of optical axes and increase in anisotropy (Bustin et al., 1986). These data indicate that tectonic stress played a crucial role in the process of ordering of aromatic layers in vitrinite during progression of vitrinite reflectance. On the other hand field data and experiments indicate that reflectance increase is slowed down if high confining pressures or fluid overpressures act (Carr, 1999; Huck and Patteisky, 1964).

In this context it is our primary objective to provide data on maximum and minimum reflectance (bireflectance) for different lithologies in study areas which have reached the “anthracite” stage or “anchimetamorphic” stage (high grade diagenesis and earliest metamorphism; note: term “anthracite” stage is commonly referred to coals and “anchimetamorphic” stage is commonly referred to illite crystallinity). Whereas most detailed studies on vitrinite reflectance anisotropy dealt with coals, where vitrinites are abundant and often large, we concentrated here on dispersed vitrinite particles in clastic sedimentary rocks. Often, only these rocks are available as archives for former plant particles, because coals/anthracites are comparatively rare, especially in pre-Carboniferous rocks. The results may give hints on sampling in future studies of sedimentary rocks at the “anthracite” stage. Our second objective is to reconstruct the burial and thermal history for the study area using vitrinite reflectance as calibration data. This study area is situated at the northern margin of the western Rhenish Massif, Germany, close to the borders towards Belgium and The Netherlands.

### 2. Tectonic and stratigraphic setting

The study area is situated in the Rhenish Massif (“Rheinisches Schiefergebirge”), Germany, 60 km southwest of Cologne in the northern part of the Eifel fold belt (Fig. 1). Stratigraphically, the Rhenish Massif consists mainly of Devonian rocks cropping out at the surface. Pre-Devonian rocks are restricted to the cores of a few large anticlines whereas Carboniferous rocks occur along the northern transition zone between Rhenish Massif and the so-called Sub-Variscan foreland basin (Ruhr Basin, Wurm and Inde Syncline). This foreland basin contains the largest hard coal resources of Western Europe.

Lithologically, sedimentary rocks predominate which are partly in the zone of low grade metamorphism, especially in the southern parts of the Rhenish Massif. The majority of Lower Devonian and older rocks are clastic sediments and the same holds true for Upper Carboniferous (Pennsylvanian) rocks. In contrast shallow marine carbonates are more common in the upper Mid-Devonian, Upper Devonian and Lower Carboniferous sequences.

The Rhenish Massif was tectonically deformed during the Variscan orogeny (330–300 Ma). K/Ar ages decrease northward from 329 to 305 million years (Ahrendt et al., 1978) indicating a slow northward propagation of the fold belt. Orogenic shortening was greater than 50% in many areas leading to the development of numerous folds and overthrusts (Oncken et al., 2000; von Winterfeld, 1994). Deformation occurred at a time when rocks were close to their maximum burial and temperature as indicated by pre- or syntectonic coalification (Littke et al., 1994; Nöth et al., 2001).

In the area around the artificial lake Rur (“Rursee”), Lower Devonian clastic sediments crop out (Rurberger and Heimbacher Formation).

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**Fig. 1.** Map of Rhenish Massif in western-central Europe and location of study area in the Venn Anticline at Rursee.
These rocks consist of rather uniform, interlayered shale-siltstone-greywacke sequences with a total thickness of at least 2000 m. Stratigraphically, they belong to the Siegenian and Emsian. Greywackes are usually fine- to medium grained (0.1–0.5 mm average grain size). Quartz grains and rock fragments predominate and clay minerals are abundant whereas feldspars are absent. Siltstones are of similar composition but smaller grain size. Shales contain more than 75% clay minerals and are characterized by well visible tectonic cleavage at variable angle to bedding. The Lower Devonian rocks exposed at the Rursee water reservoir are Siegenian Upper Rurberger beds and Emsian Klerfer and Heimbacher beds to the NE. They are located on the SE-flank of the NE-plunging major Venn anticline which was formed during Variscan deformation (330–300 Ma). Both units expose shales, siltstones and greywackes deposited in the subsiding Devonian Eifel Basin.

The area has been intensively studied, and overview of the structural evolution is given in Van Noten et al. (2008; see also Hilgers et al., 2004; Holland et al., 2006; Kenis et al., 2005; Trautwein-Bruns et al., 2010; Urai et al., 2001). The rocks contain two types of veins which are pre- to early-Variscan age. The first generation of veins is subperpendicular to bedding, clearly predating Variscan deformation and associated to a regional high pressure cell. The second generation of veins is bedding-parallel and is related to bedding-parallel shear in the early stages of Variscan deformation. Folding and the evolution of axial plane cleavage are after this second generation of veins (Van Noten et al., 2008). In several of the small outcrops of the area, the axial plane cleavage is discontinuous (Passchier and Trouw, 2005). Cleavage domains and microtectons occur in clay-rich lithologies, whereas there is no cleavage in directly adjacent quartz-rich rocks. It is one of our goals to describe differences between these microtectons and the cleavage domains with respect to vitrinite reflectance and vitrinite anisotropy.

Several maturation studies have been published on the northern Rhenish Massif (e.g. Büker et al., 1995; Kalkreuth, 1979; Karg, 1998; Nöth et al., 2001; Oncken, 1982; Paproth and Wolf, 1973; Wellens, 1997; Wolf and Braun, 1994). Some of these studies are based on measurements of maximum reflectance, whereas others used random reflectance measurements. Recently, a new vitrinite reflectance map of this area (Drozdewski et al., 2009) was compiled for the top Pennsylvanian, taking into account all available vitrinite reflectance data and converting VR_{max} values into VR values whenever necessary using standard algorithms (Taylor et al., 1998; Ting, 1991 and references therein). In most cases, there was a good fit between data measured by different authors; however, in some high maturity areas, where the low grade metamorphic stage has almost been reached and cleavage is visible, VR_{max} values converted into VR values indicate higher maturity than directly measured VR values.

In this paper, we present data on vitrinite reflectance anisotropy from different microtectonic domains, i.e. cleavage domains and directly adjacent microtectons. These rocks were taken from outcrops around Rursee situated in Devonian strata in which cleavage is visible indicating that the transition zone between high grade diagenesis and earliest metamorphism has been reached (Fig. 2).

3. Samples and methods

More than 100 samples from more than 80 outcrops were sampled for vitrinite reflectance analysis. These rocks consist of interlayered greywacke, siltstone, and shale. Most samples contain enough vitrinite grains (>50) for microscopic analysis. For detailed studies on microstructure and vitrinite reflectance anisotropy 16 rocks were selected. Special care was taken to avoid samples with strong weathering. The dip direction and angle of dip of the bedding, cleavage, and δ-lineation (this is the intersection lineation between bedding and cleavage) were measured in the field.

The rocks were cut both perpendicular and parallel to cleavage and bedding. From these rock pieces, polished blocks and polished thin sections were prepared. Transmitted light microscopy was used to identify the microtectonic domains and reflected light microscopy for vitrinite reflectance measurements in these domains. This analysis which combines transmitted light and reflected light microscopy and the techniques of microtectonics and organic petrology, allowed to simultaneously measure vitrinite reflectance and determine the microtectonic position in one sample.

Analytical methods for organic petrology closely follow the guidelines published in Taylor et al. (1998) but vary in some points. Polished sections were prepared from pieces of core which have a size of approximately 1–6 cm². The rock samples were embedded in a mixture of epoxy resin (Araldite® XW396) and hardener (Araldite® XW397) at the rate of 10:3 and hardened in an oven (37 °C) for approximately 12 h. Then the samples were ground and polished using an automated Struers Tegra Pol 21, with a Tegra Force 5 head.
polishing system. It is a two stage process under wet conditions: at first the samples were ground sequentially using two different carborundum papers and H_2O as lubricant. The first paper is a Diamante MD Piano 120 plate (Struers GmbH), the second is a SiC paper 1200 (grain size 15 μm, Struers GmbH). After each grinding stage samples were washed with H_2O to remove debris and prevent swelling. The next step was polishing the sample block to obtain a clean, uniformly flat and scratch-free surface. Three polishing laps covered with short-nap cloth (MD Plan (Struers GmbH), MD Dac (Struers GmbH) and Billard OP-U (Buehler) were loaded subsequently with suspensions of decreasing grain size and used in the following sequence; 9 μm (DP-Plan), 1 μm (DP-Nap) and 0.5 μm (Feinpol OP-U). Each step lasted 2 to 4 min, depending on the kind of rock, but should be kept to a minimum to avoid the development of a relief. Water was used as a lubricant during polishing. After each polishing step the sample was washed with water to remove debris. Finally, the block was hand-buffed to remove fine smears and checked under a microscope for polishing quality and particle relief.

Vitrinite reflectance analysis was performed on the individual samples at a magnification of 500× in a dark-room using a Zeiss Axios Imager microscope for incident light equipped with a tungsten-halogen lamp (12 V, 100 W), a 50×/0.85 Epiplan-NEOFLUAR oil immersion objective and a 546 nm filter. Zeiss immersion oil (n_o = 1.518; 23 °C) and mineral standards of known reflectance were used for calibration; namely Klein and Becker® leuco-saphire (0.592%), yttrium–aluminum–garnet (YAG; 0.889%), gandolinium–gallium–garnet (GGG; 1.721%) and cubic zirconium (3.125%). The standards are kept in dust free boxes at constant temperature and humidity. In this study the GGG and the cubic zirconium standards were used. Initially vitrinite reflectance measurements (VR_r) at random orientation of grains were made (i.e., no rotation of the microscope stage) in non-polarized light. In order to reach sufficient accuracy of vitrinite measurements, at least 50 points were measured on each sample whenever possible. Data are processed using the DISKUS Fossil software (Technisches Büro Carl H. Hilgers).

To obtain rotational reflectance data, polarised incident light was used and the microscope table was rotated by hand in 10° steps. For all measurements in sections perpendicular to cleavage, in the 0° position the axis of cleavage (which is usually well visible in the samples in transmitted light) runs parallel to the vertical axis of the microscopic image. From this position, the microscopic stage was rotated in 10° intervals. Besides the reflectance data, the position of the long axis of each particle relative to foliation was recorded.

Numerical 1D modeling of burial and temperature history was performed for a pseudo-well at the eastern margin of Rursee according to the methods described by Nöth et al. (2001). The method of 1D modeling using PetroMod software and in particular calibration of the models has been described in Petmecky et al. (1999) and Nelskamp et al. (2008).

4. Results and discussion

4.1. Sample quality and maturity pattern

Care was taken to obtain non-weathered samples in order to avoid any influence of weathering on vitrinite reflectance. Typical features of weathered vitrinite are discussed in Taylor et al. (1998: 529; see references therein), but are not observed in our sample set. An even
more sensitive parameter on degree of weathering is pyrite oxidation (Littke et al., 1991). Good pyrite preservation as observed in our samples indicates that organic matter is not weathered significantly.

Mean random vitrinite reflectance (VR_r) data were obtained for more than 100 samples of about 80 locations around Rursee covering an area of about 30 km². Although there is some scatter in the data, an overall tendency of decreasing maturity from west to east is visible (Fig. 3). As the axis of the large Venn anticline and of adjacent structures dip towards northeast (Figs. 1, 2 and 3), younger strata are found at the eastern flank of the anticline towards the east. This data indicates an increase in maturity with stratigraphic age. Highest values reach more than 5.5% VR_r and minimum values are at 2.5% VR_r (Fig. 3) Thus the data are in accordance with VR_max data published earlier on the same area by Wellens (1997). The scatter in the VR_data is partly due to an intense folding and faulting of the strata leading to many smallscale anticlines and synclines. Another reason for the scatter is the difference in microstructural domains, which will be discussed in detail below.

4.2. Influence of lithology and cleavage

In the study area, coarse grained sedimentary rocks are usually greywackes, rich in rock fragments, quartz, and chert, whereas fine-grained rocks are shales/claystones and siltstones. Mostly both rock types are interlayered on a centimetre to meter scale in the study area. Cleavage is developed only in fine-grained rocks having vitrinite reflectance values (VR_r) greater than 2.5–3%. In some cases, there are significant differences in reflectance in the same outcrop although any influence from magmatic dikes or sills can be excluded (for examples see Figs. 4 and 5b).

Interestingly, we found in the same samples strong discrepancies between VR_r and VR bi (bireflectance: difference between R_max and R_min during stage rotation) of individual particles, especially in fine-grained rocks. Thin section microscopy clearly revealed that within the same layer these rocks are strongly heterogeneous on a millimetre-centimetre scale, divided into cleavage domains and microlithons (Passchier and Trouw, 2005). An example is shown in Fig. 4.

Vitrinites in both domains are shown in Fig. 5a and b. Two micrographs from the same outcrop are represented in reflected light, one of a microlithon and the other of a cleavage domain, cut...
perpendicular to bedding and cleavage foliation. It can be seen that the shape of the vitrinite particles and anisotropy differs greatly. The sample from the microlithon shows a difference between minimum and maximum reflectance of 1.7%, whereas that from the cleavage domain is 5.7%. Also, the maximum reflectance differs greatly and is at 4.7 and 7.6%, respectively. This difference cannot be attributed to the general temperature history, but must be related to the difference in deformation.

The same analysis was performed systematically for a total of 48 particles from microlithons and 73 particles from cleavage domains of different outcrops from the Rursee area. Results are plotted in Fig. 6. The mean bireflectance for vitrinites from microlithons is about 2% with maximum values not exceeding 3.6% and minimum values of only 0.2%. In contrast, samples from cleavage domains have a mean bireflectance of about 5% with maximum values greater than 12% and minimum values of 2% (Fig. 6).

In microlithons, vitrinite particles with a low length/width ratio predominate. In contrast, in cleavage domains, minerals and vitrinite particles are aligned parallel to cleavage foliation, i.e. generally there is only a small angle between the direction of foliation and the long axis of the particles (Fig. 7) which varies between 0 and 48° and is usually less than 20°.

4.3. Vitrinite particles of different elongation

In order to assess systematic difference in vitrinite shape between particles in cleavage domains and in microlithons, the aspect ratio (length/width: L/W) of the particles was measured; results are shown in Fig. 8. In the microlithons, the L/W ratio is on average at about 2, reaching maximum values of about 5. In cleavage domains, the mean value is about 4, and there are several particles characterized by
values greater than 10. However, both groups of particles also contain equiaxed particles, and the minimum of both populations is 1.

The clear and systematic difference in the properties (both shape and optical) of particles from microlithons and cleavage domains is evident. Because the cleavage is a feature which is not present in the rocks during deposition but forms much later during tectonic deformation this difference is clearly related to the formation of cleavage. To illustrate this further, birefringence was plotted against L/W ratio (Fig. 9). The results reveal clear differences between cleavage domains and microlithons with respect to both properties, indicating that not only birefringence but also shape (L/W ratio) is affected by cleavage.

Keeping in mind that the formation of the cleavage domains is a tectonic process which occurred at the time of maximum burial or shortly after that time, the model which simply explains all these observations considers the development of slightly deformed (during compaction) and anisotropic (maximum temperature) vitrinites, followed by deformation partitioned in the cleavage domains where pressure solution processes lead to an enrichment of insoluble particles and plastic deformation of insoluble but weak vitrinites in these zones (Passchier and Urai, 1988). While the aspect ratio and anisotropy on average is clearly higher, there are also vitrinites in the cleavage domains, which have a low aspect ratio and anisotropy. A basic explanation of this phenomenon is shown in Fig. 11. Here, the first picture shows a set of vitrinite particles after compaction, with a weak preferred orientation parallel to bedding, in that part of the rock which later will become a cleavage domain. The anisotropy which is also variable is not shown. The second picture shows the same, but after a homogeneous strain shown by the deformed circle, as can be the case in a cleavage domain. Although the strain of all particles is the same (as shown by the small deformed circles in each), their aspect ratio and orientation is quite variable (Ramsay and Huber, 1987). Using the same argumentation, and keeping in mind the weakly crystalline structure of the deforming vitrinites, it is also quite conceivable that deformation of a particle with the principle shortening direction parallel to the direction of largest reflectance can lead to a reduction of reflectance anisotropy. Here, more work is needed to understand this process further.

4.4. Interpretation of microstructures

It is clear from the data presented that vitrinites in the cleavage domains are more strongly deformed. During formation of the cleavage, pressure solution processes lead to an enrichment of insoluble particles and plastic deformation of insoluble but weak vitrinites in these zones (Passchier and Urai, 1988). While the aspect ratio and anisotropy on average is clearly higher, there are also vitrinites in the cleavage domains, which have a low aspect ratio and anisotropy. A basic explanation of this phenomenon is shown in Fig. 11. Here, the first picture shows a set of vitrinite particles after compaction, with a weak preferred orientation parallel to bedding, in that part of the rock which later will become a cleavage domain. The anisotropy which is also variable is not shown. The second picture shows the same, but after a homogeneous strain shown by the deformed circle, as can be the case in a cleavage domain. Although the strain of all particles is the same (as shown by the small deformed circles in each), their aspect ratio and orientation is quite variable (Ramsay and Huber, 1987). Using the same argumentation, and keeping in mind the weakly crystalline structure of the deforming vitrinites, it is also quite conceivable that deformation of a particle with the principle shortening direction parallel to the direction of largest reflectance can lead to a reduction of reflectance anisotropy. Here, more work is needed to understand this process further.

4.5. Burial and temperature history

It was one objective of this study to reconstruct and possibly quantify burial and temperature history of the northwestern Rhenish Massif, i.e. the Rursee study area. In order to assess the maximum temperatures reached by the rocks at Rursee, numerical 1D basin
models were calibrated by vitrinite reflectance values. For calibration, the EasyS%Ro algorithm of Sweeney and Burnham (1990) was used. In this approach, V_R, i.e. the mean random reflectance, is calculated from temperature history. For comparison with real data, we used VR, data measured on the coarse grained samples (sandstones/greywackes) without cleavage following standard procedures. This model is valid for the eastern margin of Rursee, where lowest vitrinite reflectance values were recorded (2.5–3.0% V_R).

The input data applied for the model are summarized in Table 1. Sediment–Water–Interface–Temperature (SWIT) evolution through time was estimated from the palaeogeographical position of the area. In addition, for calculation of palaeo-surface temperatures, palaeo water depths were adopted from Büker et al. (1996). Heat flow through time was affected during Lower Devonian times by extension of the lithosphere, which led to high subsidence rates along with high heat flow (Littke et al., 2000). For the area around Rursee, a V_R-value of 1.8 was calculated based on structural modeling (Littke et al., 2000). This factor can be converted into a heat flow during maximum extension of 90 to 100 mW/m² following the approach of Bodri and Bodri (1985). A decline of crustal extension and heat flow through time was assumed for the following Devonian/Carboniferous period. This is reflected by a decreasing sedimentation rate. Lithologies and thicknesses for the different eroded stratigraphic intervals listed in Table 1 were taken from the well-known stratigraphic record of surrounding areas, where the complete sequence of Devonian and Carboniferous rocks is preserved (von Winterfeld, 1994). The post-Permian sedimentation and erosion history was very roughly adopted from knowledge on surrounding areas (i.e. Büker et al., 1996) and from fission track data published by Glasmacher et al. (1998) and Karg et al. (2005). Based on the lithologies, petrophysical properties were assigned as described in Nelskamp et al. (2008). Post-Permian sedimentation and erosion history did not affect maturation, because temperatures remained much below those reached in the Late Carboniferous. Our model includes the assumption of rapid cooling between 120 and 80 Ma as suggested by both Glasmacher et al. (1998) for an area further to the west and Karg et al. (2005) for an area further to the east. Late Cretaceous (Campanian/Maastrichtian) sedi-

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Devonian and Carboniferous rocks with a total thickness of 4700 m. Within the Siegen/Ems boundary layer temperatures of about 220 °C were achieved during maximum burial (5100 m at about 300 Ma; Fig. 12a, b) leading to vitrinite reflectance (VR) values of 2.9% as measured in the coarse grained greywackes without any cleavage. This leads to a good fit between measured and calculated vitrinite reflectance.

Our model was based on calibration with measured vitrinite reflectance data from rocks without cleavage. If we would have calibrated the model with data from rocks showing cleavage, a total thickness of 6800 m of eroded Palaeozoic rocks (instead of 4700 m) would have to be assumed in order to calibrate the model. Furthermore, the calculated temperature during maximum burial would be at 290 °C (instead of 220 °C). This comparison shows that the selection of rocks without cleavage is essential for calibration of burial and temperature history models.

5. Conclusions

At high levels of diagenesis and during earliest stages of metamorphism, deformation influences vitrinite reflectance. Our data indicate differences between cleavage domains and microlithons with respect to vitrinite reflectance and bireflectance. Even vitrinites from different microtectonic domains (cleavage domains and microlithons) from the same sample can show significant differences in both maximum vitrinite reflectance and vitrinite reflectance anisotropy.

This difference is due to a strong partitioning of deformation into cleavage domains as compared to microlithons, so that in these microstructural domains the observed reflectance of the vitrinites is caused by a combination of burial temperatures and deformation.

Accordingly, calculation of maximum palaeotemperatures during burial should be based on vitrinite reflectance measurements in rocks without cleavage, or - if this is not possible - on vitrinites in microlithons which are less affected by deformation than those in cleavage domains. This requires a combination of transmitted and reflected light microscopy.

In addition, differences between reflectance in microlithons and cleavage domains may provide important information on deformation in rocks that have reached the stage of late diagenesis or earliest metamorphism.

A numerical model on burial and temperature history was developed for the Siegenian/Emsian boundary layer at Rursee. According to this model, maximum temperature of about 220 °C was reached at about 5 km burial depth during the Late Carboniferous leading to mean vitrinite reflectance values of about 2.9%. Deformation occurred during or directly after maximum burial and greatly affected vitrinite reflectance in cleavage domains.

![Fig. 12. a: Burial and temperature history for sedimentary rocks from outcrops around Rursee. The model was calibrated by VR, data from greywackes.](image)

![Fig. 12. b: Maturity evolution through time for Siegen/Ems boundary strata at Rursee based on the model shown in Fig. 12a.](image)
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References


