

Estimating amount and timing of Late Palaeozoic uplift and erosion in the Rønne Graben, Bornholm, Denmark

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Late Palaeozoic uplift and erosion is evidenced by a discontinuous vitrinite reflectance profile of the Pernille-1 well situated in the Rønne Graben. Modelling vitrinite reflectance evolution by the methods of basin modelling, the unconformity is estimated to represent Late Carboniferous uplift and erosion of 3,300 m of Upper Silurian and Devonian sediments. Given a vitrinite reflectance value of 1.7% at the erosional surface, the maximum temperature obtained during deepest burial is 160-165°C, corresponding to a geothermal gradient of approximately 50°C/km. The sensitivity of the erosion estimate to the choice of model parameter values is quantified. For example, a ±10% uncertainty in the geothermal gradient equals an uncertainty of ±400 m in the erosion estimate.

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Introduction

The Rønne Graben off Bornholm (Fig. 1) is suggested to be a Carboniferous/Permian pull-apart basin developed in a releasing bend during dextral strike-slip movements along the Tornquist Zone (Vejbæk 1985; Liboriussen et al. 1987; Hamann 1994).

In the Rønne Graben, Lower Palaeozoic sediments deposited on a stable platform are succeeded by thick Silurian strata deposited during rapid subsidence in a foreland type basin to the German/Polish Caledonides. Carboniferous uplift and subsequent erosion were followed by accumulation of Permian and Mesozoic sediments in the graben, reflecting subsidence in connection with the initiation and development of the Tornquist Zone. Late Cretaceous/Early Tertiary transpressional movements resulted in inversion and reactivation of existing faults throughout the graben (Hamann 1994).

Evidence of a major Pre-Permian unconformity representing the Late Palaeozoic uplift and subsequent erosion is present as a truncation of seismic reflections throughout the Rønne Graben and in the discontinuous (segmented) trend of vitrinite reflectance (R_0) and spore colour profiles of the Pernille-1 well (Robertson Group 1989).

The fact that discontinuous (segmented and curvilinear) vitrinite reflectance profiles can be indicative of

changes in the geological environment during deposition, such as changes in sedimentation rates, changes in geothermal gradients, or the presence of an unconformity, has been noted by many authors (e.g. Middleton 1982; Katz et al. 1988). The irreversible nature of vitrinite reflectance evolution with increasing temperature implies that a segmented profile is indicative of a period of uplift and erosion. By applying quantitative models of vitrinite reflectance evolution, the segmented profile can then in principle be used to estimate the magnitude of this event.

Graphic methods, based on the assumption that the logarithm of R_0 usually shows a linear depth trend and that the reflectance of immature vitrinite is approximately 0.2%, are widely used to estimate erosion. Using the method of Dow (1977) on the vitrinite reflectance profile of the Pernille-1 well results in an initial erosion estimate of about 1,500 m. However, in this case the result of this method is subject to large uncertainties due to the limited depth range of the reflectance data.

In this study, vitrinite reflectance evolution is modelled as a function of subsidence and thermal history, and the aim is to give an estimate of the amount and timing of the Late Palaeozoic uplift/erosion by testing possible subsidence and thermal histories against vitrinite reflectance data from the Pernille-1 well of the Rønne Graben (Fig. 1).

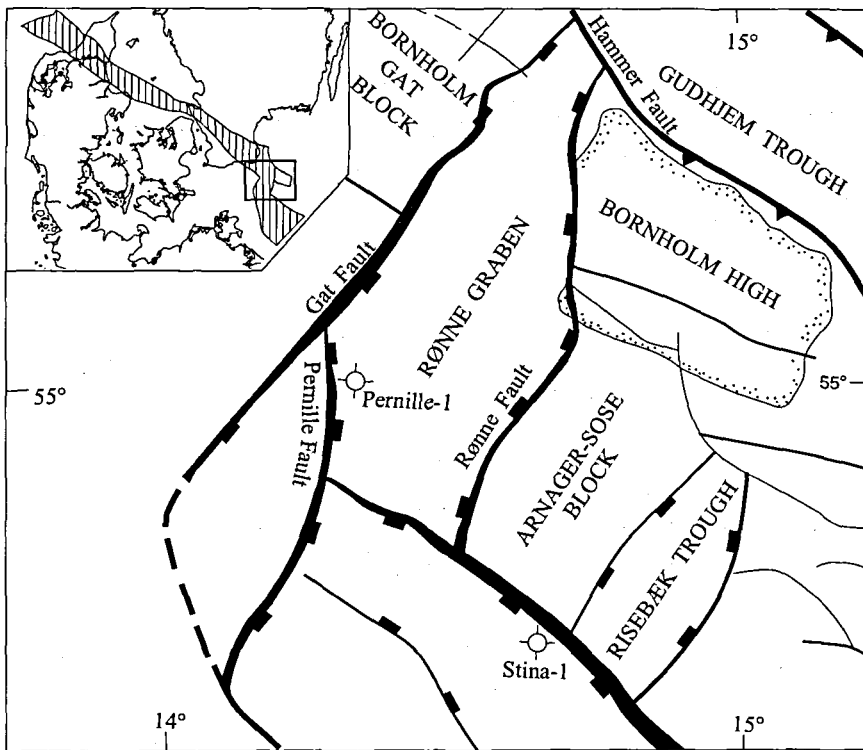


Fig. 1. General framework of the Tornquist Zone (upper left corner) and structural outline of the Rønne Graben and the adjacent area, including location of the Pernille-1 and Stina-1 wells. (Modified from Michelsen & Nielsen (1993) and Hamann (1994)).

Methods and data

The use of discontinuous vitrinite reflectance profiles to estimate the amount and timing of erosion calls for a reconstruction of the subsidence history, the thermal history, and the vitrinite reflectance evolution.

Reconstruction of the subsidence history of the Pernille-1 well requires lithostratigraphic subdivision of the sedimentary column into periods of sedimentation, non-deposition, and erosion. This subdivision (Fig. 2) is based on the interpretation of well logs and the biostratigraphy of the Robertson Group (1989). The total thickness of Silurian and Ordovician sediments is estimated from the depth to seismic basement. The thickness of Cambrian sediments is estimated to equal that of the sequence onshore Bornholm and is included in the "basement" (Table 1).

The modelling method applied in this study assumes exponential depth-dependent compaction (Steckler & Watts 1978), i.e. a porosity-depth relationship of the form:

$$\phi(z) = (\phi_0 - \phi_\infty) \exp(-z/L) + \phi_\infty$$

where z is the depth, and ϕ_∞ is the porosity at infinite depth. The compaction parameters of surface porosity ϕ_0 and porosity decay length L of the individual lithologies (Table 1) are estimated from the present-day porosity profiles derived from bulk density logs. Porosity at infinite depth ϕ_∞ is chosen to be constant with a value of 0.03 for sediments and 0.00 for basement and crystalline crust. Assuming that the present-day stratigraphic thickness is a consequence of cumulative compaction through time, the evolution of the sedimentary column is found by successive decompaction/compaction of each layer (Steckler & Watts 1978).

The thermal history of the sedimentary column is calculated by solving the one-dimensional transient heat equation for the compaction-corrected sedimentation history. The heat equation reads (Carslaw & Jaeger 1959):

The heat equation reads (Carslaw & Jaeger 1959):

$$\frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) - \rho c \frac{\partial T}{\partial t} = -A;$$

$$T(z=0, t) = T_s(t);$$

$$\lambda \frac{\partial T}{\partial z} (z=D, t) = Q_b(t);$$

where z is the depth below the sediment surface, λ is the thermal conductivity, T is the temperature, ρc is the heat capacity per unit volume, t is time, A is the radiogenic heat production, T_s is the surface temperature, and Q_b is the background heat flow at depth D . The transient heat equation is solved by a finite element method (Nielsen 1993).

The matrix thermal parameters (Table 1) are estimated

ted from mean values of different lithologies (Uldall & Balling 1989; Brigaud et al. 1990). Bulk thermal conductivity and heat production are calculated by applying the appropriate mixing laws, e.g. the geometrical mean law for thermal conductivity of mixtures. Throughout the modelling, constant values for matrix specific heat capacity of $850 \text{ Jkg}^{-1}\text{K}^{-1}$ for sediments and $900 \text{ Jkg}^{-1}\text{K}^{-1}$ for crustal material are applied.

The surface temperature through time is chosen to reflect the fact that the Baltic Shield and adjacent areas were previously closer to equator than today (Torsvik et al. 1992). A linear decrease from 15°C at 450 Ma over 10°C at 100 Ma to 0°C as present-day value was applied.

Background heat flow is one of the major unknown parameters, and available data does not allow for an unambiguous determination. In the method used in this study, the shape through time of the heat flow history curve is chosen a priori. Reconstruction of the thermal history is then performed by shifting the entire heat flow history by a constant value in order that the observed borehole temperatures are satisfied. The latter are corrected for drilling-induced temperature disturbances by the cylindrical source method of Nielsen et al. (1990).

Although vitrinite reflectance is one of the most widely used maturity indicators, the exact behavior of the macerals with increasing temperature and depth is not fully understood. Considerations as to the origin and quality of measured data (e.g. Tissot et al. 1987; Katz et al. 1988) and the properties of the chosen vitrinite reflectance model are therefore of importance. The measured reflectance data used in this study are average values from the Robertson Group (1989) and show an offset of approximately 0.8% at 3,150 m. However, true vitrinite is probably absent from the Silurian strata of the Pernille-1 well, and Robertson Group (1989) suggests that the vitrinite-like macerals observed is partly chitinozoan.

Several authors have suggested that vitrinite-like macerals, with precursors such as graptolites, chitinozoans and scolecodonts, can be used as maturation indices (e.g. Goodarzi et al. 1988; Bertrand et al. 1987; Buchardt & Lewan 1990). Bertrand et al. (1987) suggested that chitinozoan reflectivity is higher than that of vitrinite. Buchardt & Lewan (1990) showed that at high temperatures reflectance of vitrinite-like macerals of the Cambrian-Ordovician Alum Shale in southern Scandinavia responded to heating in a way similar to vitrinite with slightly lower R_0 values for reflectances above 1%. For the Silurian data of the Pernille-1 well the Robertson Group (1989) indicates a vitrinite reflectance equivalent of at least 1.3%–1.5% based on spore and kerogen colour.

Considering the uncertainties regarding the exact behavior and origin of the macerals, the modelling was performed assuming a R_0 value of 1.7% at the erosional surface, and with quantification of the possible error introduced by this assumption.

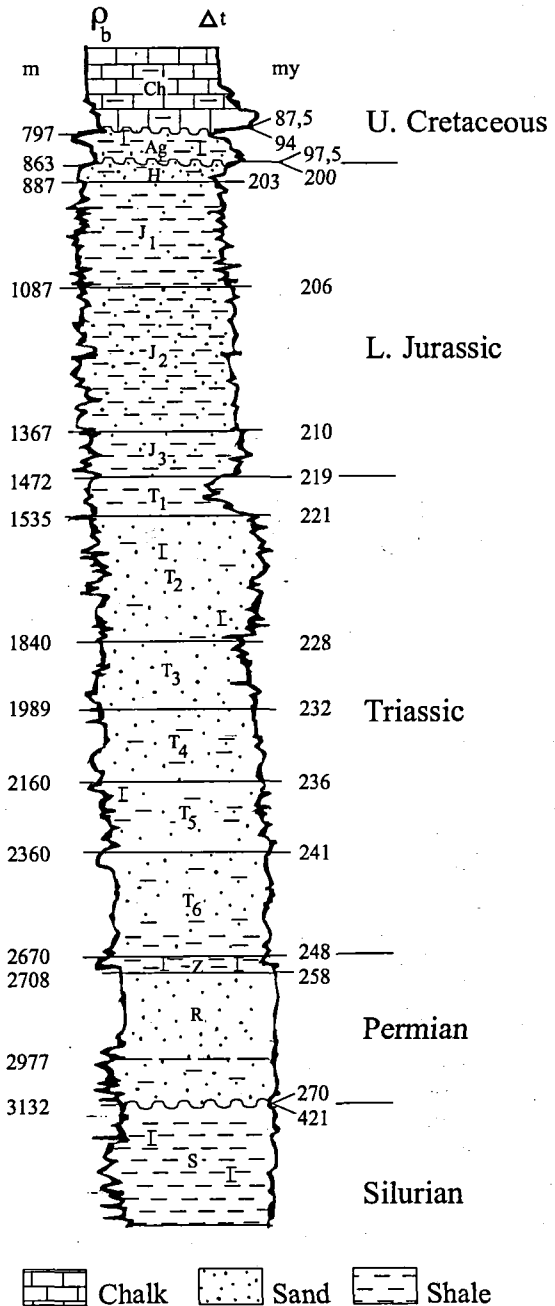


Fig. 2. Lithostratigraphic subdivision of the Pernille-1 well. Ch: undifferentiated chalk; Ag: Arnager Greensand Equivalent; H: Hasle Fm. Equivalent; J₁-J₃: Jurassic Group (Rønne Fm. Equivalent); T₁-T₆: Triassic Group; Z: Zechstein; R: Rotliegendes; S: Silurian. ρ_b is the bulk density log trace and Δt is the sonic log. Vertical scale is in two way time. (Modified from Robertson Group (1989)).

Table 1. Physical and thermal input parameters. ρ_m is the matrix bulk density, λ_m is the matrix thermal conductivity, A_m is the matrix radiogenic heat production, \emptyset_0 is the surface porosity, and L is the porosity decay constant.

Unit	Thickness (km)	ρ_m (kg/m ³)	λ_m (W/mC)	A_m (μ W/m ³)	\emptyset_0	L (km)
Chalk	0.797	2710	3.1	0.5	0.50	1.5
Arnager Gr.	0.066	2600	3.5	1.0	0.55	1.5
Hasle Fm.	0.024	2650	3.0	1.0	0.65	1.0
Jurassic 1	0.200	2650	3.0	1.0	0.41	2.0
Jurassic 2	0.280	2700	3.0	0.5	0.45	2.5
Jurassic 3	0.105	2700	3.0	1.0	0.57	2.0
Triassic 1	0.063	2680	3.1	1.0	0.64	1.0
Triassic 2	0.305	2680	2.8	0.7	0.44	2.0
Triassic 3	0.149	2700	2.8	1.0	0.44	2.5
Triassic 4	0.171	2650	3.0	1.0	0.51	1.5
Triassic 5	0.200	2650	3.1	0.5	0.52	1.5
Triassic 6	0.310	2680	3.1	1.0	0.53	1.5
Zechstein	0.038	2700	3.1	1.0	0.55	2.0
Rotliegende	0.424	2680	3.0	1.0	0.55	1.5
U. Silurian/Devonian	3.300	2680	2.3	1.0	0.50	3.0
Silurian	1.000	2690	2.8	1.5	0.59	1.5
Basement	1.000	2700	3.0	1.0	0.00	-
Average crust	30.000	2750	3.0	0.5	0.00	-
Subcrustal lithosph.	50.000	3000	3.0	0.0	0.00	-

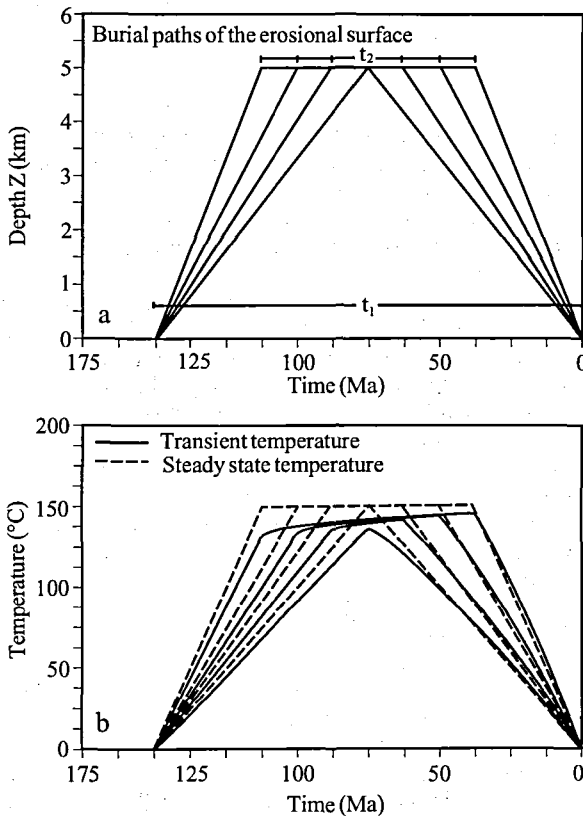


Fig. 3. a) Parameterization of the event causing the offset in vitrinite reflectance and b) corresponding transient and steady state temperature histories. Z is the depth of burial in km, t_1 is the total duration of the event causing the hiatus, and t_2 is the duration of deepest burial.

Based on the experiments of Thronsdon et al. (1993) and Morrow & Issler (1993), we choose to apply the vitrinite reflectance model of Sweeney & Burnham (1990). This model is based on the theory that the composition of vitrinite versus time and temperature - and therefore the reflectance - is controlled by the degassing of byproducts (H_2O , CO_2 , CH_4 and CH_n). This temperature and time dependent evolution is described by 20 parallel and independently weighted first-order kinetic reactions with Arrhenius rate constants. The degassing of the i^{th} vitrinite component is described by:

$$w_i(t) = w_{oi} \exp \left(- \int_0^t k_i(\tau) d\tau \right);$$

where w_{oi} is the normalized initial volatile content and $k_i = A \exp(-E_i/RT(t))$ is the Arrhenius reaction rate. A is the frequency factor, E_i is the i^{th} activation energy, R is the gas constant, and $T(t)$ is the absolute temperature. The transformation ratio F of the vitrinite is given by:

$$F = 1 - \sum_{i=1}^{20} w_i.$$

The vitrinite reflectance is then calculated according to:

$$R_0 = \exp(-1.6 + 3.7F) \%;$$

Ambiguities and parameter interdependencies in erosion estimation

Estimation of the amount of erosion by the method of basin modelling combined with indicators of thermal

maturation presents several difficulties related to the inherent ambiguities of the applied system. It is important to consider the extent to which the basic modelling parameters, i.e. heat flow, thermal conductivity, and amount and timing of the uplift and erosion, are constrained by the present-day data and how the effect of a change in one parameter can be neutralized or amplified by changes in other parameters.

Since R_0 responds to temperature and time, there is a trade-off in the resulting erosion estimate between temperature and duration of deepest burial, such that a short duration of burial can be compensated by higher temperatures, and vice versa. Furthermore, the temperature during deepest burial is mainly produced by the harmonic mean thermal conductivity, the background heat flow, and the depth of burial.

In the case of the Pernille-1 well, the post-erosional evolution affects only the upper part of the vitrinite reflectance profile, because the temperature never again approaches the temperature attained during the period of deepest burial (Fig. 7a). This means that the fundamental ambiguity of the method can be quantified by considering the values of a few key variables during the period of burial and subsequent erosion. For the lower part of the vitrinite reflectance profile, i.e. the pre-erosion period, these variables are the equilibrium geothermal gradient, the duration of the burial and erosional event, the duration of deepest burial, and the depth of deepest burial.

Figs. 3-4 summarize the fundamental ambiguities and inter-dependencies of the system for a R_0 value of 1.7% at the erosional surface, as in the Pernille-1 case.

Fig. 3a is a simple parameterization of the event causing the offset in the vitrinite reflectance profile. t_1 is the total time from the initiation of deposition to the end of the erosion. t_2 denotes the duration of a non-depositional period during deepest burial, and Z is the depth of the erosional surface as a function of time.

The R_0 value at the erosional surface is determined by its temperature history. Fig. 3b shows the transient temperature history of the erosional surface for a total duration of the event (t_1) of 150 Ma and for various values of t_2 . The thermal diffusivity of the homogeneous medium is $1 \cdot 10^{-6} \text{ m}^2/\text{s}$. Also shown are the steady state temperature histories which would result if the transient thermal effects of deposition and erosion were not considered. The equilibrium geothermal gradient Q/C is $30^\circ\text{C}/\text{km}$, resulting in an equilibrium temperature of 150°C during the time of deepest burial.

From Fig. 3b it is apparent that the transient temperatures are cooler than the equilibrium temperatures during the period of burial, that they never reach the equilibrium temperatures during the period of deepest burial, and that they exceed the equilibrium temperatures during the period of erosion. The last is of no consequence for vitrinite reflectance evolution, as cooling immediately halts the irreversible process of maturation. However, it is apparent that incorrect consideration of transient thermal effects due to sedimen-

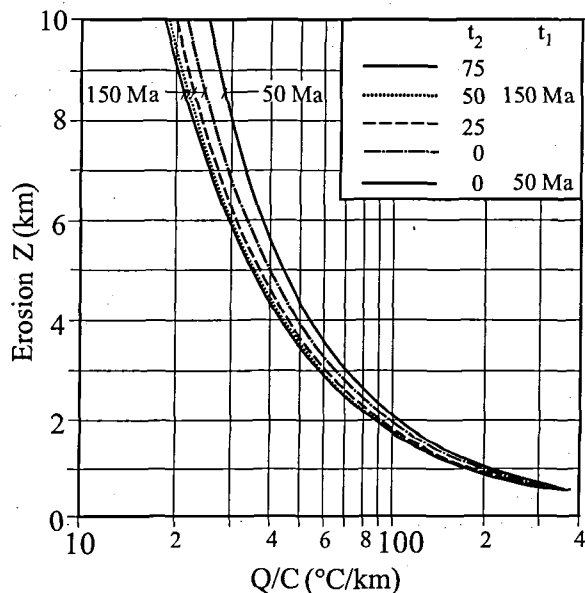


Fig. 4. Inter-dependency of the erosion estimate Z , the equilibrium geothermal gradient Q/C , the total duration of the event causing the hiatus t_1 , and the duration of deepest burial t_2 . Q is the heat flow and C is the harmonic mean thermal conductivity of the medium.

tation and erosion can increase temperatures, and thereby R_0 values, resulting in an underestimation of the amount of erosion.

The value of R_0 produced during the events in Fig. 3a depends mainly on the maximum temperature achieved. Since the corresponding temperature histories of Fig. 3b achieve different maximum temperatures, the resulting R_0 value of each event is also different. The fundamental ambiguity of erosion estimation now arises from the fact that for each of the burial histories of Fig. 3a it is possible to find another value of the temperature gradient Q/C so that the resulting temperature histories of Fig. 3b are modified to produce the same R_0 value at the erosional surface. Alternatively, for the same value of Q/C it is possible to find different values of the maximum depth of burial so that the resulting temperature histories produce the same R_0 value at the erosional surface.

Fig. 4 quantifies the inter-dependency of the basic parameters which results in a R_0 value of 1.7% at the erosional surface, as in the Pernille-1 case. The effect of changing the total duration of the event is shown with values of t_1 of 50 Ma and 150 Ma. For $t_1 = 150$ Ma the effect of changing the duration of the period of deepest burial is shown with values of 0, 25, 50, and 75 Ma.

The general hyperbolic relationship between the amount of erosion and the equilibrium geothermal gradient is due to the fact that a given R_0 value at the erosional surface during burial at depth Z mainly is a

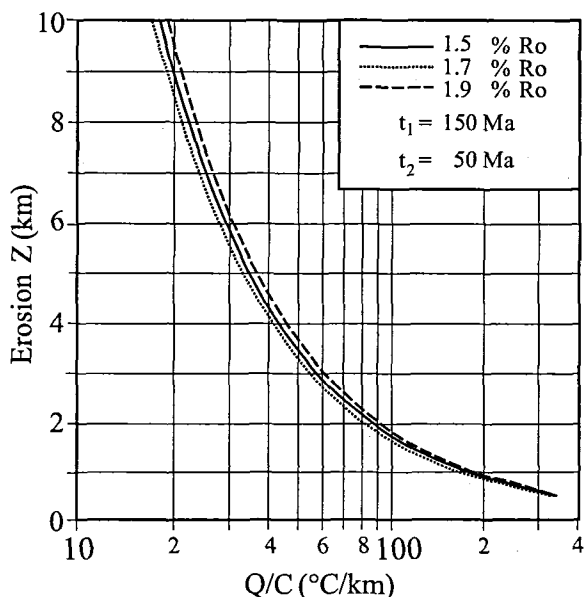


Fig. 5. Erosion estimate Z as a function of the equilibrium geothermal gradient Q/C for various vitrinite reflectance values at the erosional surface. Q is the heat flow and C is the harmonic mean thermal conductivity of the medium.

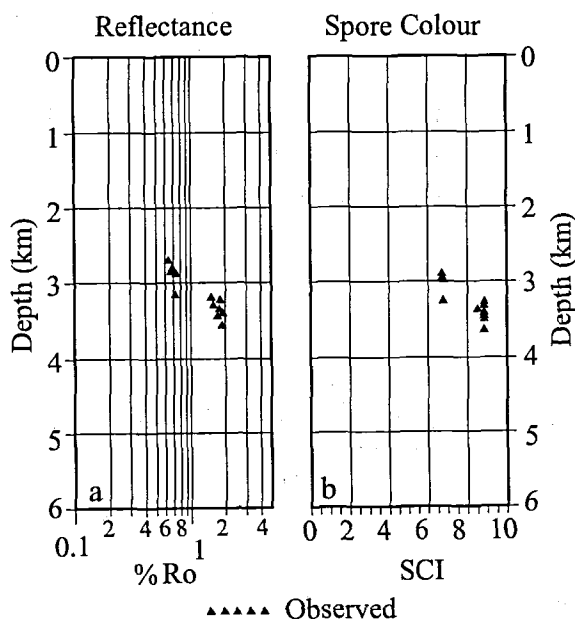


Fig. 6. Distribution of a) vitrinite reflectance ($\%R_0$) and b) spore colour (SCI) data with depth from the Pernille-1 well (Robertson Group 1989).

question of achieving a certain maximum temperature T_{R_0} characteristic of that R_0 value. Since the temperature T at depth Z is mainly given by $T = ZQ/C$ (Fourier's law), the hyperbolic relationship $Z = T_{R_0} / (Q/C)$ follows.

It is apparent from Fig. 4 that values of Q and C which keep the geothermal gradient Q/C constant result in the same erosion estimate.

Increasing values of the total duration of the event t_1 , and the duration of deepest burial t_2 results in decreasing erosional estimates, because the time available for temperature equilibration during deepest burial increases. The offset between the curves produced by changing the duration of deepest burial t_2 is due to the transient effects of sedimentation and erosion, and to a lesser extent to the delay in vitrinite reflectance evolution during heating. Finally, Fig. 4 shows that the erosion estimate is more sensitive to temperature than time.

The importance of considerations as to the origin and quality of the measured data and the properties of the chosen vitrinite reflectance model is quantified in Fig. 5. The erosion estimate Z as a function of the geothermal gradient Q/C is shown for R_0 values at the erosional surface of 1.9, 1.7, and 1.5%, representing a difference of $\pm 0.2\%$ in the data of the Pernille-1 case. This difference could represent the difference in reflectance between the vitrinite-like macerals of the Pernille-1 well and true vitrinite. The difference could also be caused by the measurement process, e.g. inadequate identification of the macerals or quality of the polish (e.g. Tissot et al. 1987), or could represent the effect of choosing a kinetically based vitrinite reflectance model as compared with other models, e.g. the more time sensitive TTI-based models (e.g. Issler 1984; Waples 1980).

Fig. 5 shows that an over- or underestimation of the R_0 value by $\pm 0.2\%$ at the erosional surface introduces an error in the erosion estimate of up to 500 metres, depending on the thermal regime of the system. For the more typical thermal regime, i.e. geothermal gradients greater than 30°C/km , the possible error amounts to 200-300 m.

Results and discussion

The Late Palaeozoic uplift and erosion in the Rønne Graben west of Bornholm is evident as discontinuous trends in both vitrinite reflectance and spore colour profiles (Figs 6a-6b). Spore colour data, however, are semiquantitative as compared with vitrinite reflectance and are therefore not used in the quantitative modelling of this study.

The modelling was performed by choosing the best possible parameters for the known part of the sedimentation history and letting the parameters during the Palaeozoic burial and uplift and erosion be the major unknowns.

Well Pernille -1

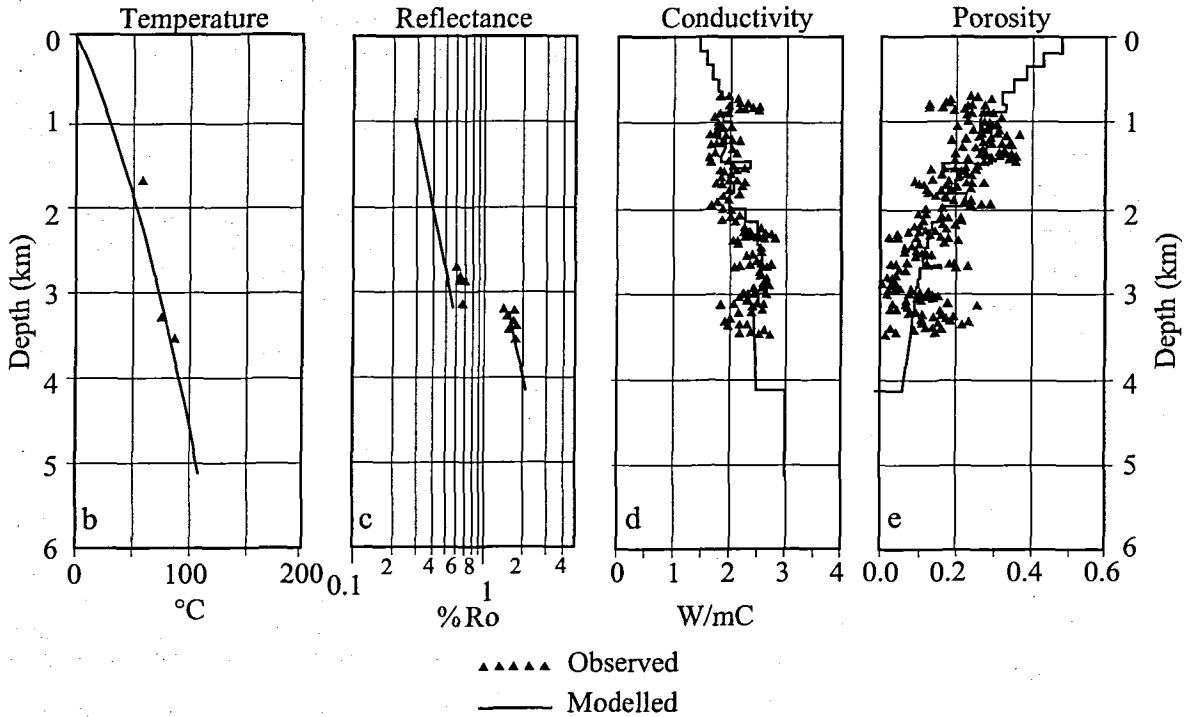
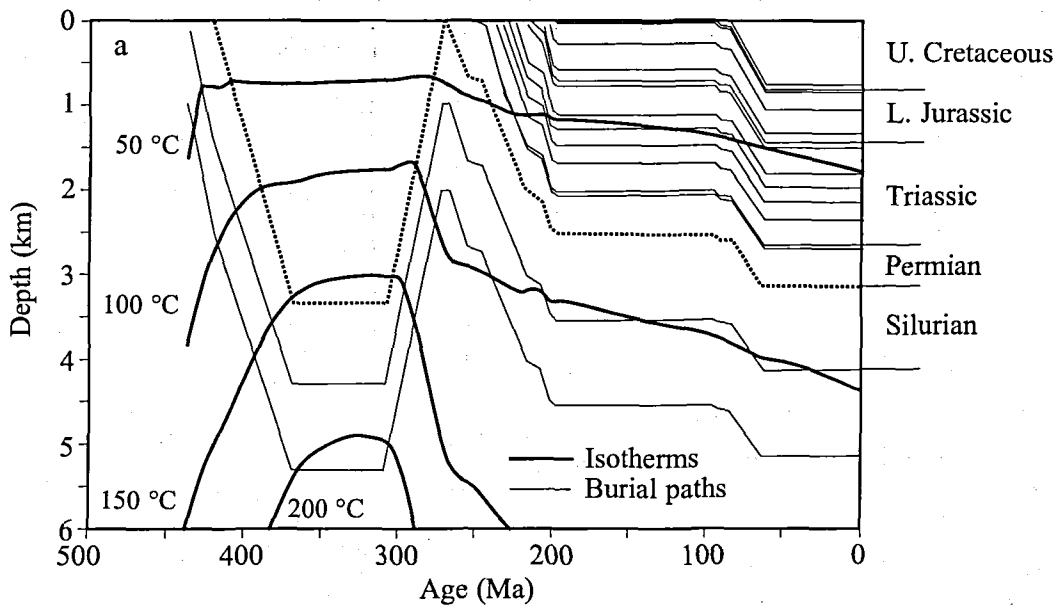


Fig. 7. Composite figure of a) a sedimentation diagram showing burial paths of each layer and temperature evolution as isotherms. The dotted line represents the erosional surface. b) temperature, c) vitrinite reflectance, d) thermal conductivity, and e) porosity versus depth are shown for observed (triangles) and modelled (solid line) values. Porosity is calculated as mean values of 10 m intervals causing the scattering of data.

Table 2. Sensitivity of the erosion estimate to the geothermal gradient.

Q/C (°C/km)	Erosion estimate (m)	-10 % in Q/C (m)	+10% in Q/C (m)
100	1,700	1,800	1,650
70	2,400	2,700	2,200
50	3,300	3,700	3,000
40	4,200	4,900	3,700
30	5,800	7,300	5,000

For the parameters chosen from the modelling procedure described above, 3,300 m of uplifted and eroded Upper Silurian and Devonian sediments provide the modelled curve with the best fit to the vitrinite reflectance profile of the Pernille-1 well. Fig. 7 is a graphic representation of the modelling results.

Fig. 7a shows the sedimentation diagram of the Pernille-1 well, including the temperature evolution presented as isotherms. The dotted line is the burial path of the erosional surface represented by the segmented vitrinite reflectance profile in this study. As can be seen, this erosional surface, i.e. the Silurian sediments, has experienced temperatures above 150°C during the period of deepest burial (370–310 Ma) as a result of rapid sedimentation of Devonian sediments with low thermal conductivity.

The agreement between the modelled present-day temperature profile and observed borehole temperatures in Fig. 7b is because the temperatures have been used to adjust the general level of the background heat flow.

Vitrinite reflectance versus depth (Fig. 7c) shows consistency with data in the pre-erosion part. The offset between modelled and measured R_0 above the unconformity could be an effect of the Late Cretaceous/Early Tertiary inversion and subsequent erosion, but has not been modelled, as this part of the temperature history is of little consequence for the evolution of the pre-erosion part of the vitrinite reflectance profile.

The thermal conductivity profile of Fig. 7d shows an over-all agreement between modelled values and those derived from well logs. Discrepancies in certain levels are seen to correspond with similar discrepancies in the porosity curve, as the porosity data were used for calculating the conductivity values.

Fig. 7e shows observed and modelled porosity versus depth. Discrepancies in certain levels are possibly caused by caving or fractures affecting the density log and thereby the derived porosity data. In these levels, average porosity values for the individual lithologies were used as input parameters in the modelling. Although the porosity profile data will reflect the deepest burial of the sedimentary column, the Late Palaeozoic erosion is not expected to be seen as the present-day depth nearly equals the depth of deepest burial.

The inter-dependency of the key modelling para-

meters illustrated in Fig. 4 means that the erosion estimate based on the vitrinite reflectance evolution can be changed in any one of three ways: 1) by changing the background heat flow, 2) by changing the thermal conductivity of the overburden, and 3) by changing the total duration of the event or the period of deepest burial.

1) Evidence of widespread Carboniferous/Permian volcanism in the Danish and Baltic areas (e.g. Pegrum 1984) suggests that the thermal regime of the lithosphere during this period was substantially warmer than at the present-day. Consequently, the shape of the background heat flow history curve was chosen to reflect this by increasing the Palaeozoic heat flow density by 25 mW/m² above the present-day value. The sensitivity of the erosion estimate to the choice of heat flow is quantified in Fig. 4. For example, our favoured erosion estimate of 3,300 m corresponds to a geothermal gradient of 50°C/km. A 10% change in Q induces a 10% change in the gradient Q/C, corresponding to gradients of 45°C/km (-10%) and 55°C/km (+10%). The associated erosion estimates are 3,700 m and 3,000 m (Table 2).

2) Devonian sediments are not found in the Danish area. However, the proximity of the Rønne Graben to the Fennoscandian Shield, and the generally high gamma-log readings and angular texture of the grains throughout the sedimentary column in the Pernille-1 well, indicates relatively immature sediments, i.e. a high content of feldspars with low thermal conductivity (Brigaud et al. 1990). An overburden with low conductivity and high sedimentation rate acts as an insulating layer, resulting in a rapidly increasing temperature of the underlying sedimentary column. This so-called blanketing effect (Nielsen & Balling 1990) is seen in Fig. 7a as an upward bend of the isotherms between 300 and 400 Ma. A matrix thermal conductivity of 2.3 W/mC for the missing sediments was chosen. The sensitivity of the erosion estimate to the thermal conductivity C of the eroded sediments is quantified in Fig. 4. A 10% change in C results in gradients of 45°C/km (+10%) and 55°C/km (-10%). The associated erosion estimates are 3,700 m and 3,000 m (Table 2).

3) The limits of seismic resolution and the uncertainty of the biostratigraphic data in the interval between 2,977 and 3,132 m mean that a number of scenarios are possible for the timing of the period of deposition, uplift, and erosion. The best result during modelling was achieved with Upper Silurian and Devonian sedimentation (421–370 Ma), a period of non-deposition (370–310 Ma), and Late Carboniferous/Early Permian uplift and erosion (310–270 Ma).

The modelled result of 3,300 metres of erosion shown in Fig. 7 must be tempered with the number of assumptions made and the limitations of the various models and data acquisition methods used, e.g. the possible introduction of errors by calculating the porosity from density log data and subsequently using this porosity

for calculation of thermal parameters, in both cases using estimated matrix values.

The one-dimensional modelling methods applied in this study mean that it is important to consider the validity of the modelling result in the rest of the Rønne Graben area. Lateral heat flow, for example, is not considered. The close setting of the Pernille-1 well to the Pernille Fault (Figs 1&8) could result in abnormal parameters of the sediments, caused by compressional stress during the Late Cretaceous/Early Tertiary inversion. These parameters could in turn affect the modelling result as well as cause a difference in lateral heat flow. Furthermore, the very complex structural framework of the Rønne Graben and adjacent areas means that the magnitude of uplift presented in this study might be local e.g. due to block rotations (Hamann 1994). Such deviation from the one-dimensionality is indicated by the porosity data from the Stina-1 well south-east of the Rønne Graben (Fig. 1), which shows a much deeper burial history.

There are no surface heat flow data from the Bornholm area available for calibration. However, interpolating values from the Danish (Balling 1992) and adjacent areas to the area around Bornholm indicates values of approximately 50–55 mW/m². This heat flow value, and values between 50–70 mW/m² observed in north eastern Germany, northern Poland, and southern Sweden (Hurtig et al. 1992), are consistent with the modelled present-day surface heat-flow density of 49 mW/m² obtained in this study. It is possible that thermal refraction effects, which must occur in narrow pull-apart basins (Pitman & Andrews 1985) if lateral conductivity contrasts exist, are responsible for the low value of the present-day heat flow. The modelled surface heat flow during the event causing the offset in vitrinite reflectance is 74 mW/m². Thus the very high geothermal gradient of approximately 50°C/km (maximum temperatures of 160–165°C) obtained during deepest burial is primarily due to the low conductive overburden rather than a high palaeo-heat-flow density.

The Late Palaeozoic evolution proposed in this study, i.e. only Upper Silurian and Devonian sedimentation and a single erosional phase, might be simplified. Occurrence of reworked Lower-Middle Carboniferous spores and pollen in Jurassic sediments onshore Bornholm indicates Carboniferous sedimentation in the Bornholm area (Nielsen & Koppelhus 1991). Furthermore, several erosional phases has been documented south of the Caledonian Deformation Front (Piske & Neumann 1993). However, the limited sensitivity of the vitrinite reflectance evolution to the duration of the burial event, as shown in Fig. 4, precludes an exact modelling of the sedimentation history.

The erosion estimate of 3,300 m is in agreement with other studies from the Rønne Graben. Hamann (1994) estimated a total Late Palaeozoic erosion of 1,000–5,000 metres in the Rønne Graben with approximately 4,000 metres close to the Pernille Fault from reconstructed

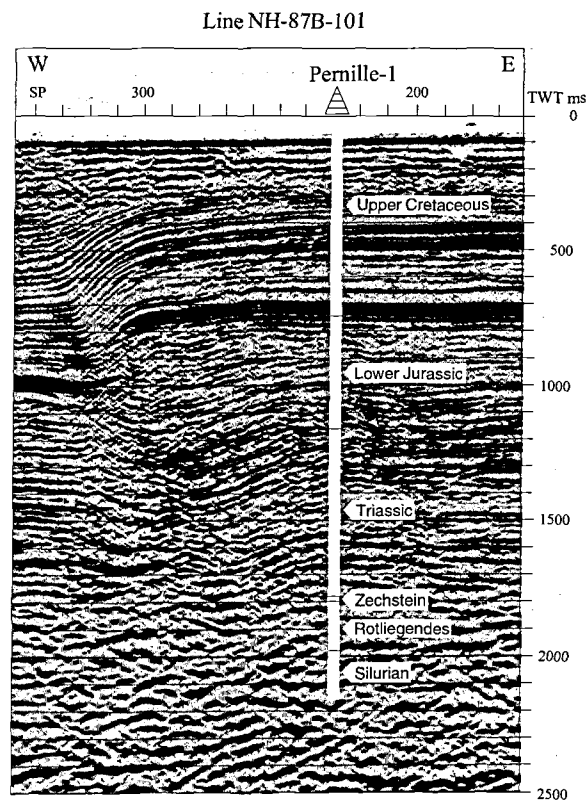


Fig. 8. Location of the Pernille-1 well on seismic line NH-87B-101. Note the disturbance of the seismic reflectors between SP 200–320.

original thicknesses of Palaeozoic sediments. Vejrbæk et al. (1994) used modelling of maturation history to estimate 2,700 metres of Late Carboniferous uplift and erosion. Buchardt & Nielsen (1985) estimated a minimum temperature at deepest burial of 90°C, corresponding to a minimum depth of 2,000 metres, for Silurian sediments onshore Bornholm, using the composition of carbon and oxygen isotopes.

Conclusion

Using basin modelling to simulate sedimentation history and vitrinite maturation, this study has shown that Late Carboniferous/Early Permian uplift and erosion of approximately 3,300 metres of Upper Silurian and Devonian sediments is needed to reproduce the offset in the vitrinite reflectance profile of the Pernille-1 well. This amount of erosion is consistent with results from other studies in the Rønne Graben area.

By quantification of the inter-dependency of the key variables, it is evident that the geothermal gradient, expressed as Q/C, is the most sensitive model parameter. The maximum temperature of 160–165°C obtained

in this case corresponds to a geothermal gradient of approximately 50°C/km. Using the fact that the sensitivity of the erosion estimate to the geothermal gradient depends on the value of Q/C , we find that a $\pm 10\%$ error in the geothermal gradient of this study yields erosion estimates between 3,000 and 3,700 m.

This study has also presented an example of basin modelling as a tool for providing useful complementary information for use with more traditional methods in assessing the structural history of sedimentary basins.

Dansk sammendrag

Med udgangspunkt i et diskontinuert vitrinit reflektans profil fra Pernille-1 boringen i Rønne Graven, Bornholm, er bassinmodellering anvendt til at estimere størrelsen af den sen palæozoiske hævnning og erosion. Modellering af boringens indsynknings-, temperatur- og vitrinit modningshistorie viser, at inkonformiteten repræsenterer 3.300 m Sen Karbon hævnning og erosion af øvre silure og devone sedimenter. Maximum temperaturer under dybeste begravelse er 160–165°C, svarende til en geotermal gradient på 50°C/km.

Følsomhedsanalyse af de vigtigste modelparametre anvendes til evaluering af nøjagtigheden af det modellerede resultat. Den geotermale gradient er den mest følsomme parameter og en $\pm 10\%$ usikkerhed på denne tilsvarende erosionsestimater på henholdsvis 3.000 og 3.700 m.

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