DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/63

Thermal modelling of the Lower Palaeozoic shales on Zealand and Scania

Niels H. Schovsbo, Anders Mathiesen & Arne Thorshøj Nielsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF ENERGY, UTILITIES AND CLIMATE

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/63

Thermal modelling of the Lower Palaeozoic shales on Zealand and Scania

Niels H. Schovsbo, Anders Mathiesen & Arne Thorshøj Nielsen

Released 31.10.2018

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF ENERGY,UTILITIES AND CLIMATE

G E U S

Table of Contents

1. Introduction

The aim of this report is to evaluate the shale gas prospectivity on Zealand, Denmark, by presenting an update of the thermal maturity model for the Palaeozoic interval for the area. The discussion in this report focusses on the heat flow model and the assessment of the magnitude of Late Palaeozoic uplift and erosion which is one of the key uncertainties for gas retention in the shale (Pool et al. 2012, Gautier et al. 2013, Schovsbo et al. 2014).

The report is based on a series of 1D profiles of petroleum system modelling of the thermal maturities within the Lower Palaeozoic shales that has been measured in key wells within the Zealand-Kattegat-Scania area (Figure 1). The wells included are the Slagelse-1, drilled on southern Zealand, the Terne-1, drilled offshore in the Kattegat area, and the Lövestad A3-1, drilled in Scania, southern Sweden. The Lövestad A3-1 well was drilled by Shell in 2010 as one of several exploration wells for shale gas in Scania (Pool et al. 2012).

The vitrinite data from the Terne-1 and Slagelse-1 wells are from Schovsbo (2011a, b) whereas the data from the Lövestad A3-1 well were measured as part of the Sommerodde GeoCenter research programme in 2015. All modelled profiles are compared to a GEUS in-house heat flow and burial history model for the Alum Shale Formation developed for the Terne-1 well in 2013. In this model two heat flux models are used to elucidate different maximum burial scenarios. Uplifts are constrained by regional palaeogeographical reconstructions and present day thickness of the Palaeozoic strata.

To model the burial histories for the Terne-1, Slagelse-1 and Lövestad A3-1 wells the 1D PetroMod basin modelling software v2014.1 was used. PetroMod is a petroleum system modelling tool (IES, Integrated Exploration Systems GmbH, Aachen, Germany) that integrates a wide range of geological, geophysical, geochemical and petrophysical data and forms a framework for testing various hypotheses about the origin and evolution of a given model layer integrating processes and the geological development. A conceptual stratigraphical model that describes the definition and history is made. Based on this conceptual model, which includes all available well data on the geological evolution, a discrete numerical model is made. Discretisation was performed by defining layer events based on lithological break-down of the drilled section for the selected wells. Only standard lithologies integrated in the IES software were used to ensure comparable 1D models.

PetroMod is a forward model, starting at the time of deposition and calculating towards present-day (0 Ma). For each new model layer the previous model layer is compacted until the present-day is reached. The modelled present-day results are compared with measured data and re-run until a match is reached. This iterative modelling process is repeated until a satisfactory match is obtained between modelled and present-day measured data. Thus from the geological model inputs (thickness and ages of sediments, lithology, estimated magnitude and timing of erosion and estimated heat-flow history) the modelled parameters (temperature, porosity etc.) are calculated as a function of time at the specific well location.

The result of the reflectance measurements from the Lövestad A3-1 well are presented in Appendix A.

The input parameter to the conceptual basin model including heat flow models, the sea-level and sea water temperatures and burial events are presented in Appendix B.

2. Regional geological setting

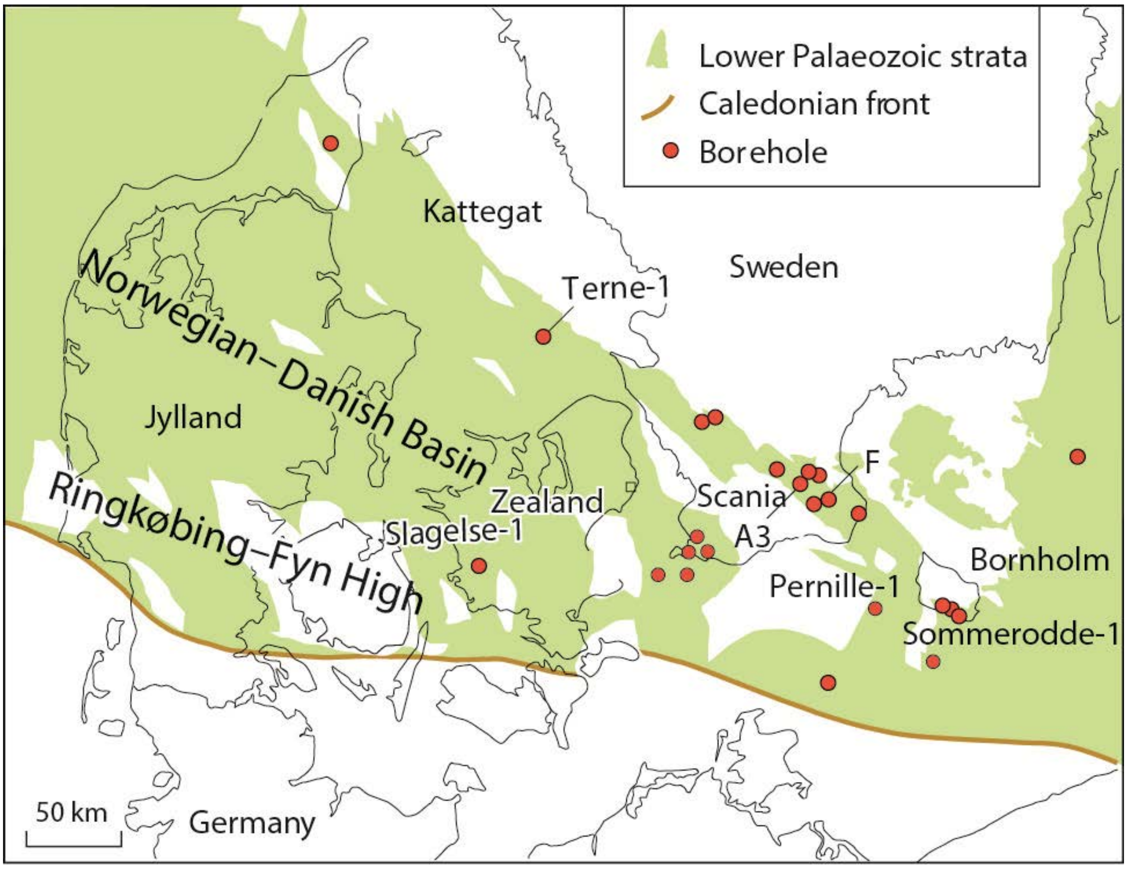


Figure 1. Locality map of wells and areas referred to in this report. Green shading indicates the presence of Palaeozoic strata (from Nielsen & Schovsbo 2011). Abbreviations: A3: Lövestad A3-1; F: Fågeltofta-2.

Lithostratigraphy of the Palaeozoic in Denmark and Scania
The Lower Palaeozoic litho- and chronostratigraphic frame is shown in Figure 2 and below is presented a brief overview of the most important petroleum system elements in the different formations.

The Lower Cambrian sand- and siltstones in Denmark and in southern Sweden (Scania) comprise the Nexø, Hardeberga, Læså and Gislöv Formations. For a recent review of these units, see Nielsen & Schovsbo (2006).

<u>The Nexø Fm</u> predominantly consists of reddish coloured sub-arkosic sandstone. The formation is a potential reservoir unit.

<u>The Hardeberga Fm</u> comprises well-sorted strongly cemented quartzite fine-grained sandstone. The formation includes subordinate silt- and mudstone beds. Albeit strongly cemented the formation is a potential reservoir unit.

<u>The Læså Fm</u> is dominated by greenish grey siltstone with variable glauconite content. Phosphorite nodules occur at several levels and sandstone beds are common especially in the upper part of the formation. The thin top member, the Rispebjerg Member, is a regionally

distributed sandstone bed that records a major regressive event. The formation is not considered a potential reservoir unit.

The Alum Shale Fm consists of dark organic rich mudstone with abundant disseminated pyrite. It was deposited from the Mid Cambrian to the Early Ordovician (Tremadocian). In Denmark and Scania the formation contains a low proportion of diagenetic carbonate beds. The formation is considered a source rock for oil and gas and is the target for shale gas exploration in Denmark and Sweden (Pool et al. 2012; Schovsbo et al. 2014). The formation average is 9 % TOC but holds up to 20 % TOC in the Furongian part (Figure 3).

Ordovician shales and limestone formations above the Alum Shale comprise the Bjørkåsholmen Fm, Tøyen Shale, Komstad Limestone, Almelund Shale, Dicellograptus Shale (here used as collective term for the Sularp, Skagen, Mossen and Fjäcka shales) and the Lindegård Fm (Figure 2).

The Tøyen Shale in southern Sweden is a greenish-grey mudstone with occasional siltstone beds. Dark organic rich intervals occur in the upper part of the formation in the Oslo area. The formation is organic lean.

The Komstad Limestone is a thin-bedded cold water bioclastic carbonate. The unit contains variable amounts of clay, phosphorite and glauconite. It is known from Bornholm and southern Sweden (Scania), but thins out westwards and is likely not present in the subsurface of Denmark.. It is a potential reservoir unit.

The Almelund Shale is a black to dark-grey shale with rare carbonate inter-beds. The unit is a potential source rock and holds on average 1.5% TOC. It is not considered to have shale gas potential due to its relatively low TOC content.

The Dicellograptus Shale is a grey to dark grey mudstone. The lower part contains numerous bentonite beds including the up to one metre thick ‘Kinnekulle’ Bentonite; this bentonite rich interval is included in the Sularp Shale in southern Sweden. The Kinnekulle Bentonite represents the most significant volcanic eruption in the entire Phanerozoic. The topmost 5-8 m of the Dicellograptus Shale constitutes a TOC rich interval with up to 4 % TOC (Figure 3). This unit is considered a source rock to conventional hydrocarbon fields but are not considered to have a shale gas potential in Denmark due to its limited thickness.

The Lindegård Fm is a bioturbated green-grey mud- to siltstone. Thin sandstone beds with conglomeratic horizons locally occur in the upper part.

The Silurian is represented by the Rastrites and Cyrtograptus shales on Bornholm and the Nøvling and Rønde fms in the Danish area (Michelsen & Nielsen 1991). They are equivalent to the Colonus Shale and Öved-Ramsåsa Group of Scania (Figure 2).

The Rastrites Shale comprises black to dark-grey silty mudstones. Current generated sedimentary structures and calcite cemented sandy beds occur in some intervals. TOC rich intervals occur notably near the base of the formation and in the *convolutus* graptolite Zone (Figure 3). The latter interval contains up to 4 % TOC (Figure 3). It is considered a source rock for conventional hydrocarbon fields but are not considered to have a shale gas potential in Denmark due to its limited thickness.

The Cyrtograptus Shale comprises grey silty mudstone. The unit is not considered a reservoir rock or a source rock.

The Rønde Fm consists of interbedded shale and sandstone and the Nøvling Fm consists of volcanics and locally Late Palaeozoic sills, interbedded with shale and sandstones. These units may include reservoirs.

Silurian formations in Scania comprise the Rastrites, Cyrtograptus and Colonus shales and the Öved-Ramsåsa Group. The latter includes shallow water limestones and red-coloured fine-grained sandstones. The latter units are considered as potential reservoir units.

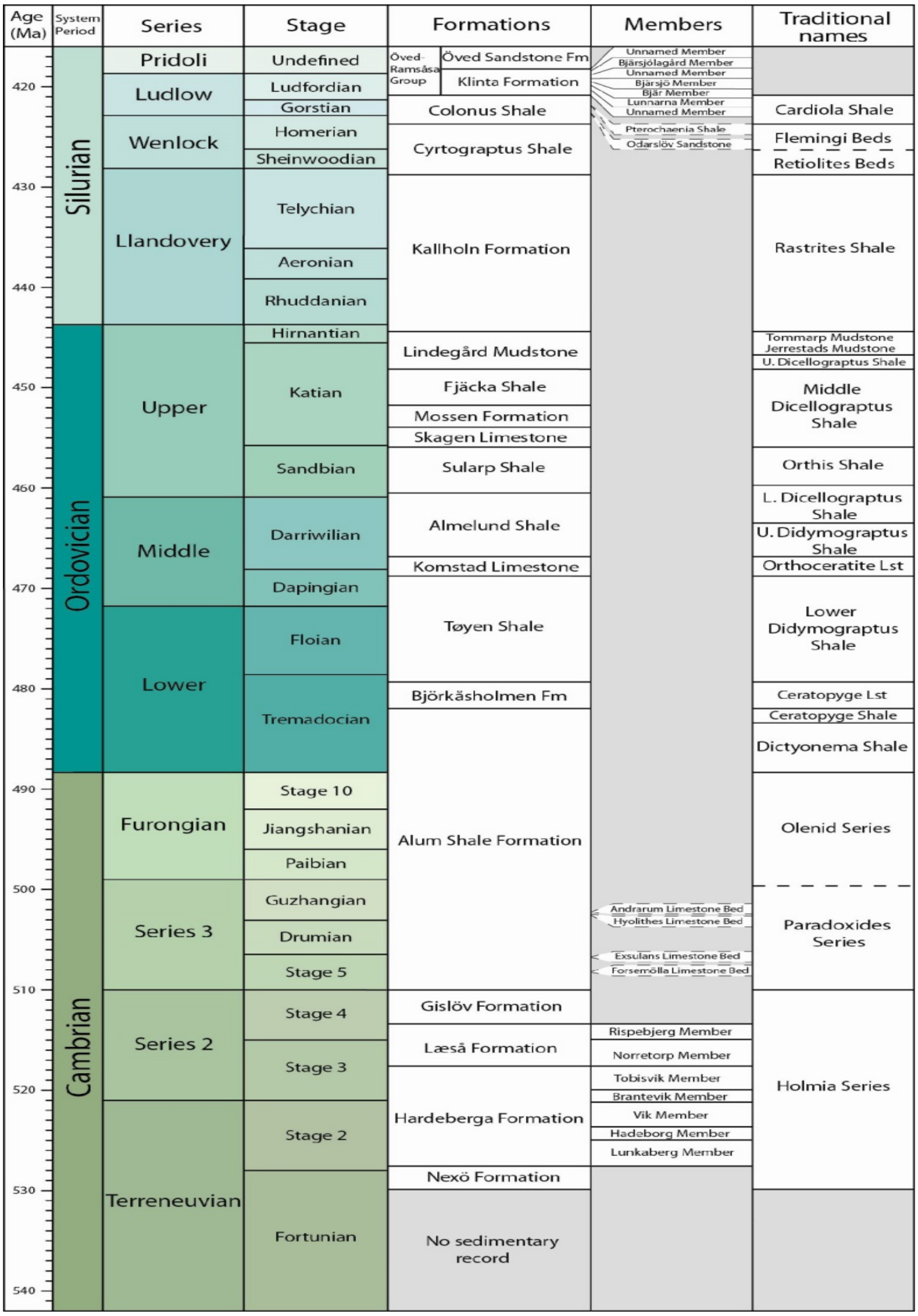


Figure 2. Lithostratigraphy and chronostratigraphy for the Lower Palaeozoic. After Eriksson (2012).

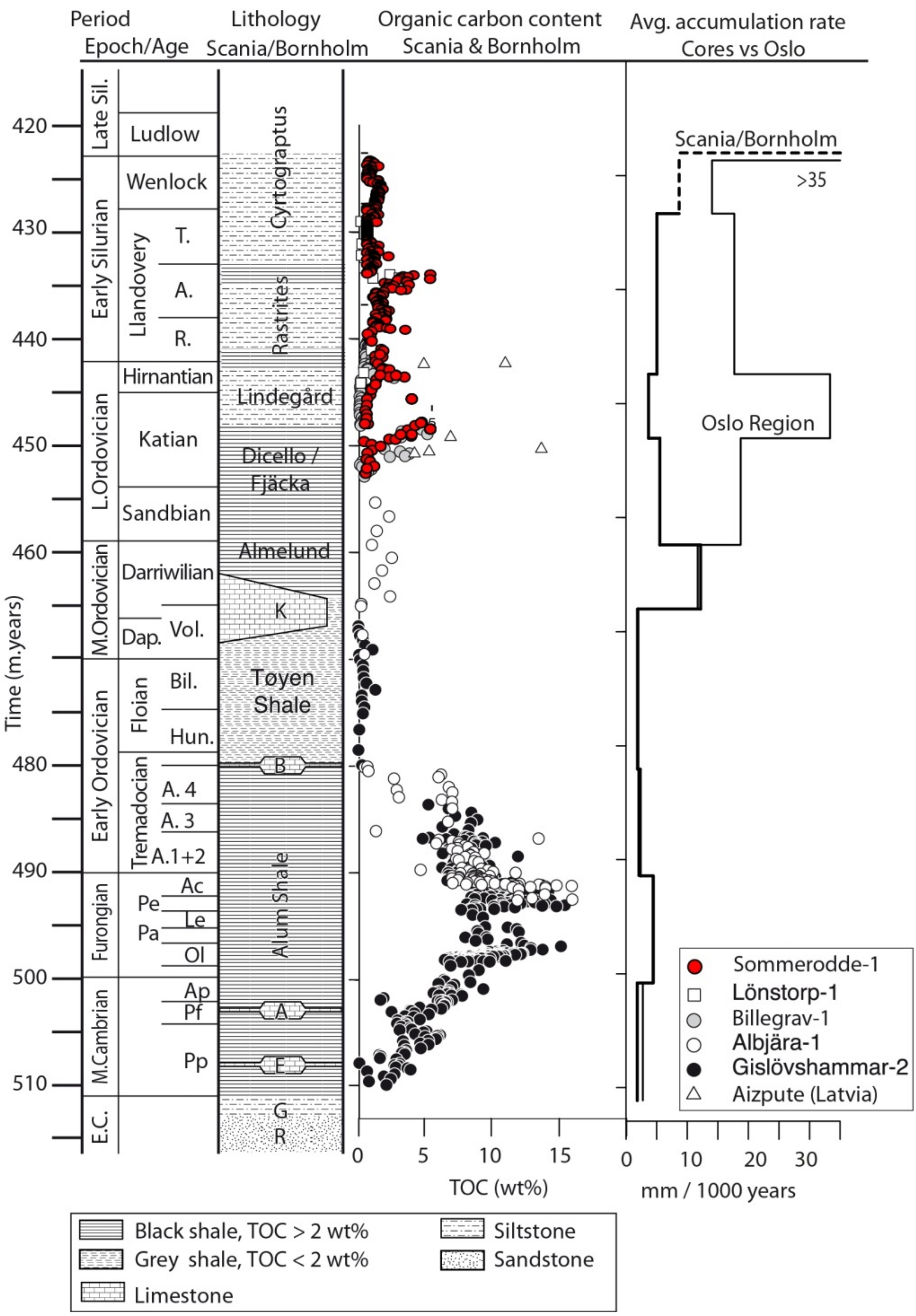


Figure 3. The Lower Palaeozoic source rock intervals. Updated from Schovsbo (2003).

2.1. Thermal maturity of the Alum Shale

The Alum Shale was deposited prior to the evolution of vascular land plants and the shale therefore does not contain terrestrial vitrinite particles *sensu stricto*. Nevertheless, the Alum Shale contains vitrinite-like particles supposedly of marine origin and according to Buchardt & Lewan (1990) these particles behave in a similar manner as true vitrinite particles with respect to thermal maturity. Consequently, reflectance of vitrinite-like particles has been widely used as a thermal maturity proxy for the shale (Thomsen et al. 1987; Vejbæk et al. 1994; Buchardt & Lewan 1990; Buchardt et al. 1997; Petersen et al. 2013).

Recently Petersen et al. (2013) re-evaluated the vitrinite-like particles in the Alum Shale and suggested that they may represent graptolite fragments. They also showed that the vitrinite-like and the graptolite material matured in a similar manner but slightly faster than true vitrinite material and hence a correction factor between reflectance of vitrinite-like + graptolite particles and equivalent vitrinite reflectance was introduced (Figure 4).

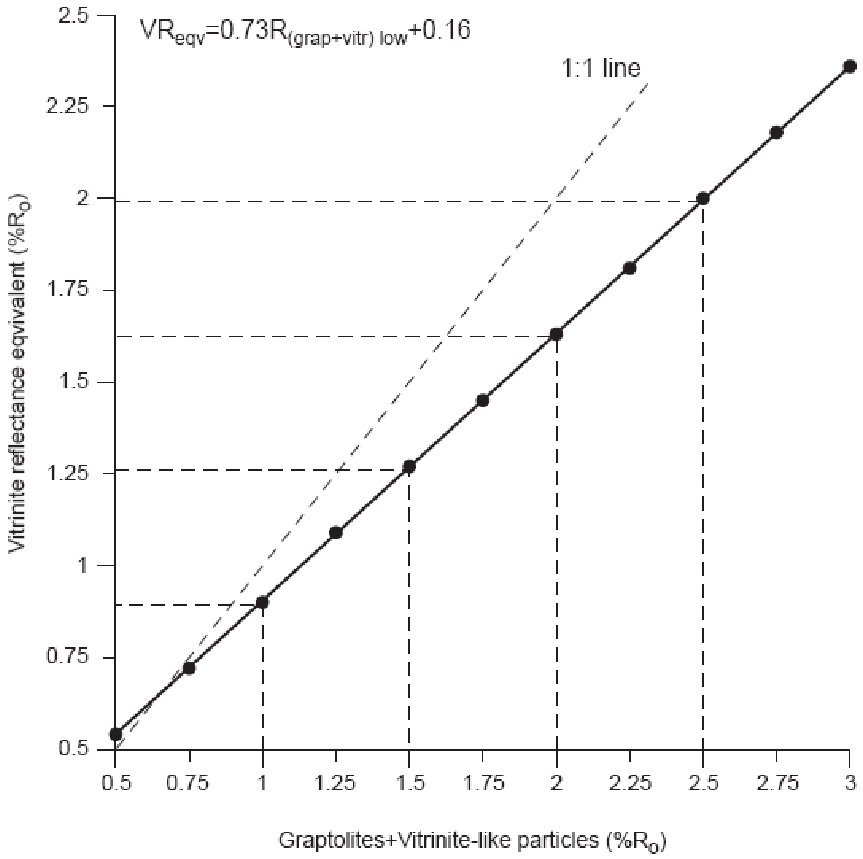


Figure 4. Correlation between vitrinite-like and graptolite reflectance to vitrinite reflectance equivalent. From Petersen et al. (2013).

Thermal maturity of the Alum Shale on Zealand

Buchardt et al. (1997) showed that the thermal maturation of the Alum Shale in southern Scandinavia increases rapidly towards the Caledonian Front (Figures 5 and 6). According to Buchardt et al. (1997) this pattern reflected that there is a relationship between the extent of the Caledonian nappes (translated into sedimentary thicknesses and thus maximum burial depths) and the present day distance from the front at any given location (Figure 5). In the relationship, however, the Terne-1 well plotted with a higher thermal maturity than expected and was considered as an outlier (Buchardt et al. 1997).

Schovsbo (2011a) showed that the vitrinite reflectance value used by Buchardt et al. (1997) was incorrect and that the Terne-1 well had a much higher thermal maturation than originally recognized.

As a consequence of this re-evaluation of the Terne-1 maturity, the maturity map presented by Buchardt et al. (1997) has been modified to account for the higher maturity of the Terne-1 well (Figure 6). According to this new interpretation the anomalously high thermal maturity seen in the Terne-1 well reflects its position within the Tornquist Zone. The area is expected to have experienced an additional burial component not predicted from its position relative to the Caledonian Front.

According to the redrawn maturity map in Figure 6 this high maturity is not expected to influence Zealand where the maturity is assumed to reflect the distance from the Caledonian Front (i.e. as predicted from Figure 5) and thus decrease from 2.3% in the southern part to about 1.9% vitrinite reflectance in the northern parts.

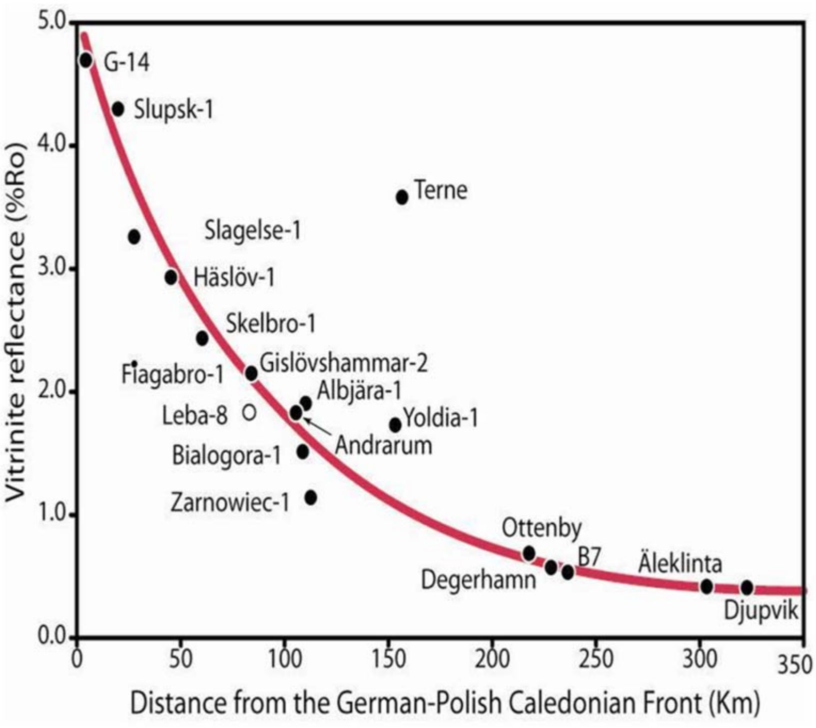


Figure 5. The relationship between reflectance of vitrinite like particles (graptolites) and the distance from the German-Polish Caledonian Front. Modified from Buchardt et al. (1997). The Terne-1 well is plotted with the re-evaluated Ro of 3.6%.

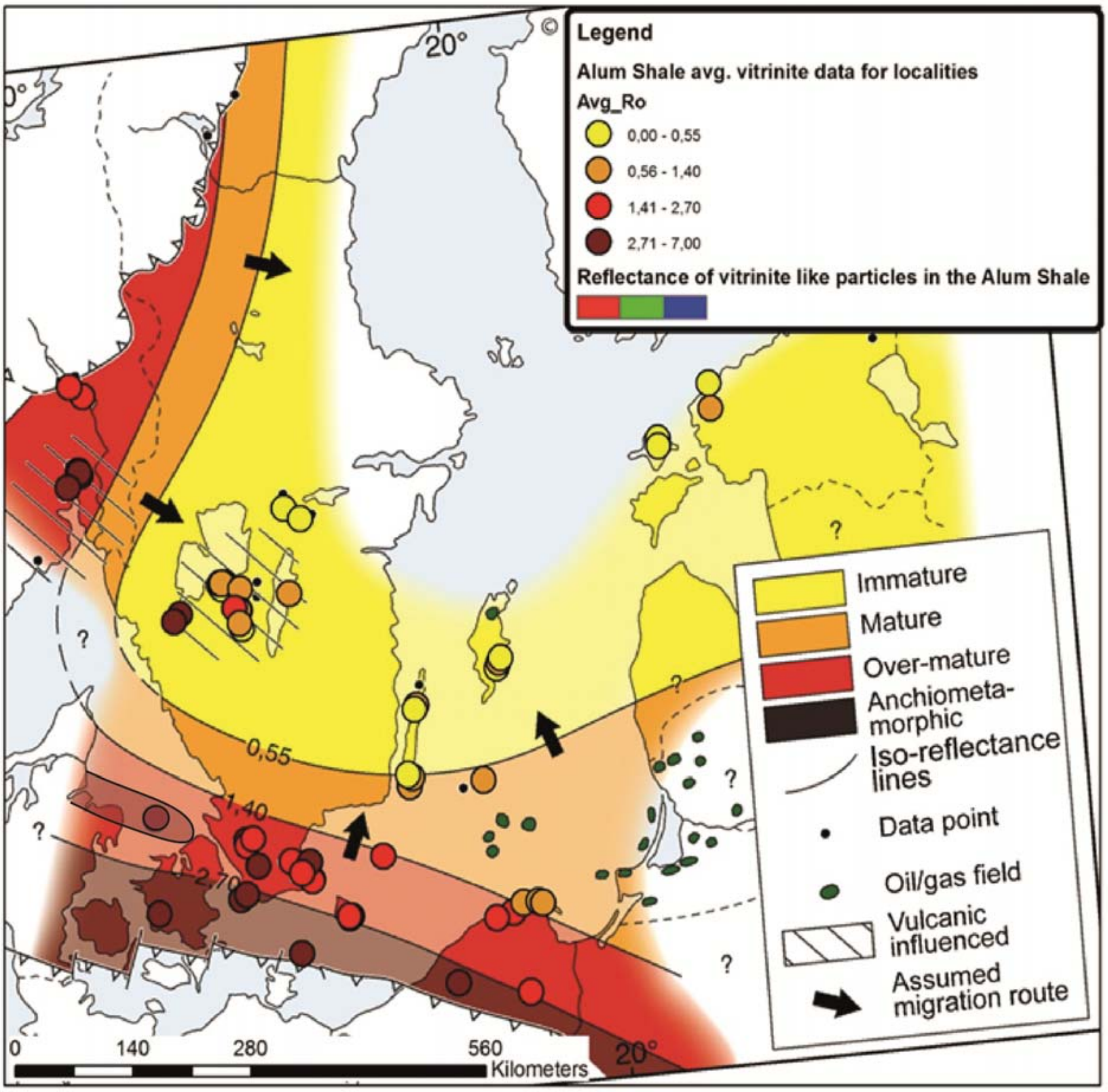


Figure 6. Updated maturity map of the Alum Shale Formation based on reflectance of vitrinite-like particles and graptolites (based on Schovsbo et al. 2012 from a map published by Buchardt et al. 1997). The map represents the thermal maturity of the Alum Shale at the time of maximum burial depth during the Caledonian Orogeny. Subsequent deep burial in the Danish-Norwegian basin may have raised the maturity of the Alum Shale in parts of mid Jutland; however, these modifications are not included in the map.

3. Profiles of graptolite reflectance versus depths

Terne-1 well

The Terne-1 well has been extensively studied by the Source Rock Laboratory at GEUS and a total of 60 samples - including 40 samples from the Palaeozoic interval - were measured in the 1990'ies. The original raw data were reprocessed by Schovsbo (2011a) and the corresponding reflectance evaluated based on the individual frequency distribution diagrams in order to ensure a comparable data quality.

For the Alum Shale in the Terne-1 well the average graptolite reflectance is 3.6% Ro based on 12 samples. The average graptolite reflectance values for the Ordovician and Silurian shales are 3.4 to 2.5% Ro, respectively. The Triassic and Jurassic have average vitrinite (*sensu stricto*) Ro values of 0.44% and 0.32%, respectively.

The reflection values exhibit a general increasing trend with depth (Figure 7). Reflectance values >5% are observed in two intervals in the Silurian. The samples with elevated %Ro were picked close to Late Palaeozoic sills and the elevated maturity is therefore interpreted to reflect local heating in Late Carboniferous time. It appears that the effect of the heating decreases rapidly away from the sills. At a distance of two times the thickness of the sill the effect on the reflectance appears to be minor (Figure 7).

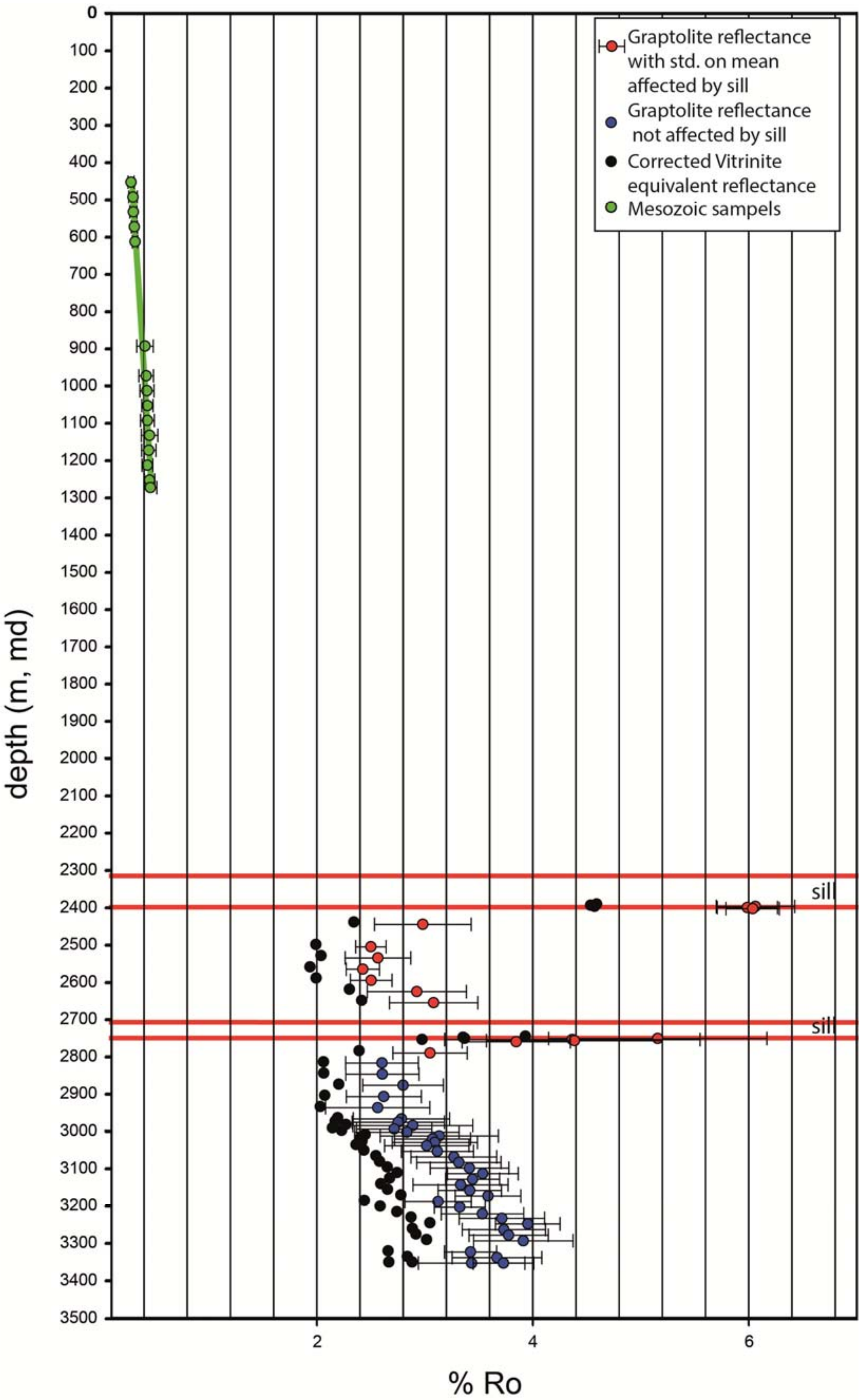


Figure 7. Reflectance measurements versus depth in the Terne-1 well (from Schovsbo 2011a). The correction between graptolite reflectance and equivalent vitrinite reflectance are made according to Petersen et al. (2013).

Slagelse-1 well
The Slagelse-1 well was studied by the Source Rock Laboratory at GEUS during the 1980'ies. The original raw data has been reprocessed by Schovsbo (2011b) and reflectance evaluated based on the individual frequency distribution diagrams in order to ensure the data quality. Samples for measurements were picked in both of the cored intervals and from cuttings as well, but since cuttings in this well are dominated by cavings only samples from the cores are considered to be relevant.

For the Alum Shale in the Slagelse-1 well the average graptolite reflectance is 3.0% Ro and the average graptolite reflectance for the Silurian shale samples is 2.7% Ro.

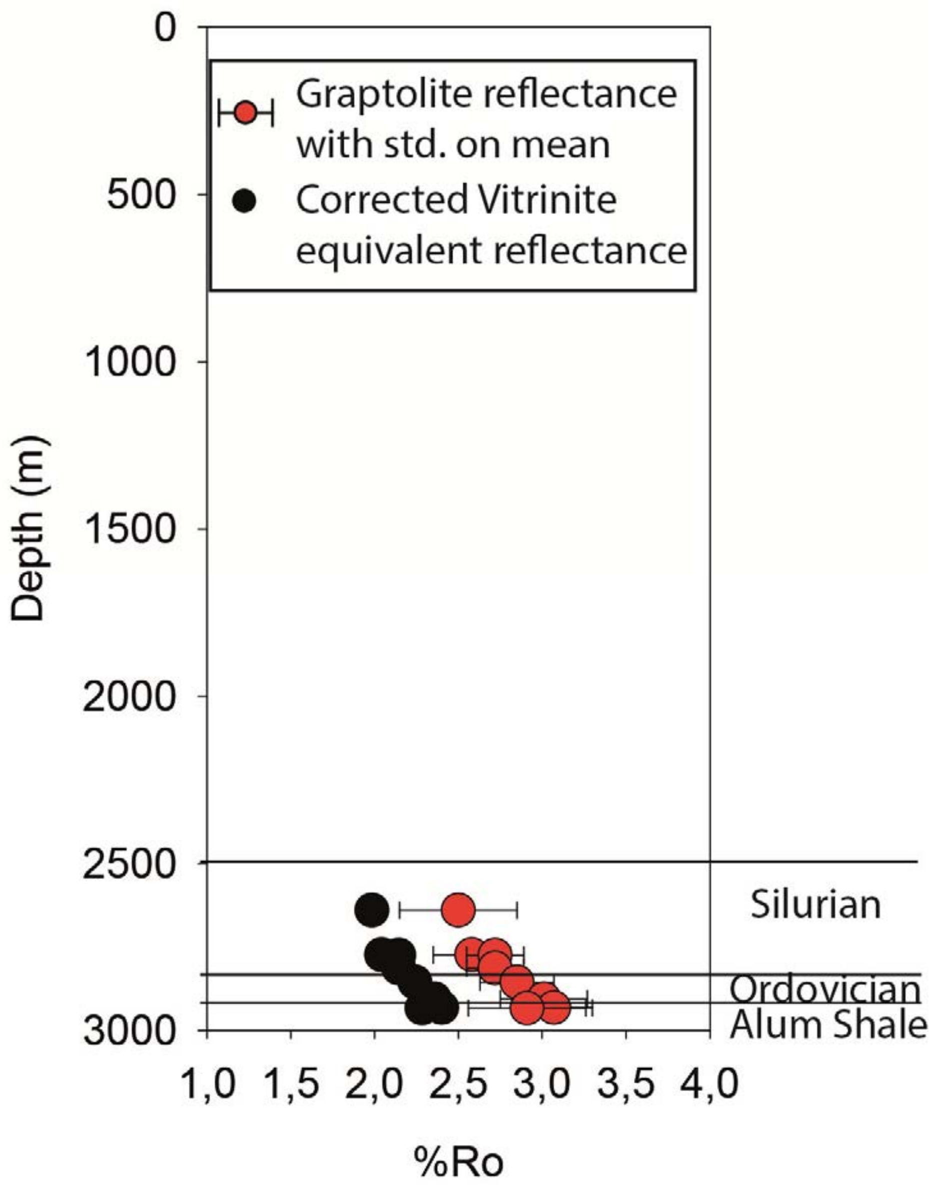


Figure 8. Graptolite reflectance measurements (selected population) versus depth in the Slagelse-1 well. The correction between graptolite reflectance and equivalent vitrinite reflectance are made according to Petersen et al. (2013). Modified from Schovsbo (2011b).

Lövestad A3-1 well

The Lövestad A3-1 well was studied by the Source Rock Laboratory at GEUS in 2015 as part of the Sommerodde GeoCenter research project. Cutting samples for each 20 m was made available by Shell in the section above the cored Alum Shale. Geochemical screening was done on the cuttings including hand held XRF, TOC and Rock Eval. Based on these results 15 samples were selected which reflect the lithological rock types present in the interval and which provide a depth profile.

Since no Alum Shale samples were made available by Shell, representative samples from the Fågeltofta-2 drilled 8 km east of Lövestad A3-1 well were used instead.

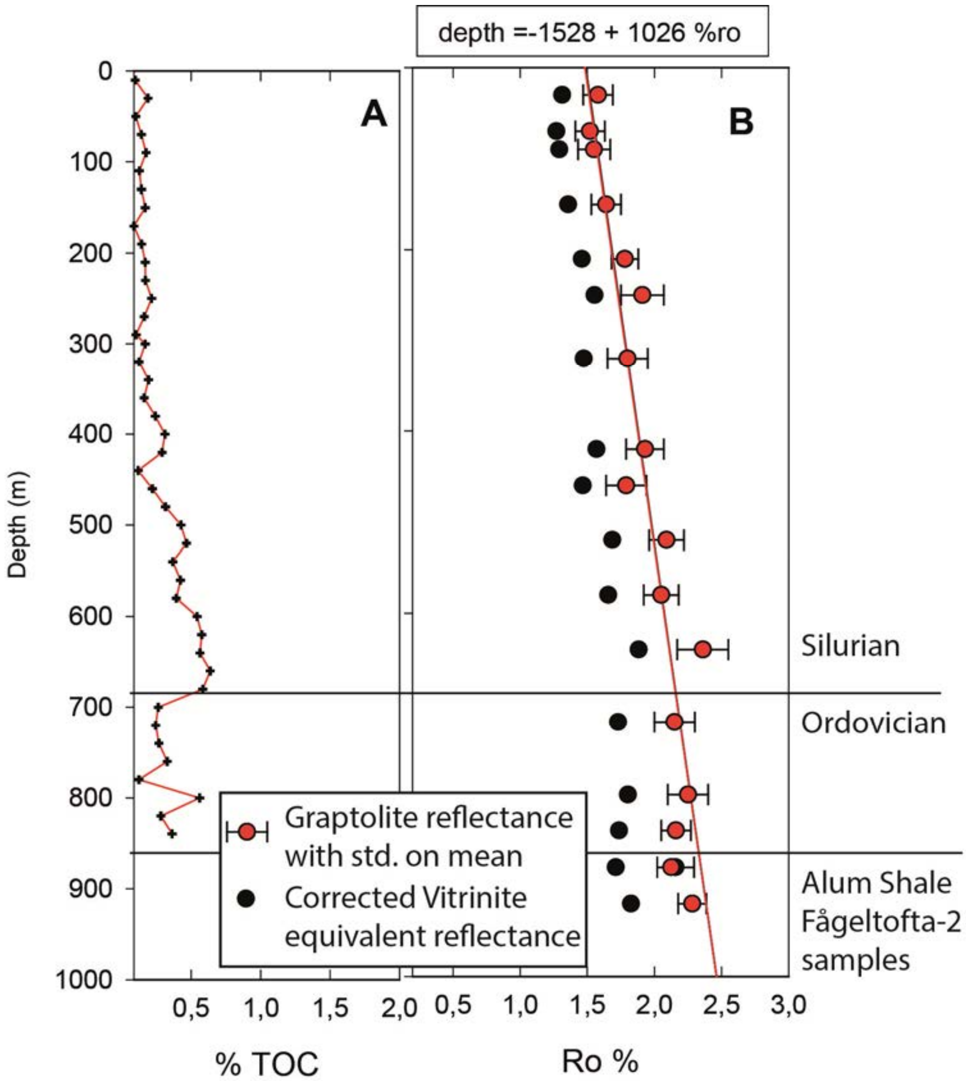


Figure 9. Profile established on cuttings of A) the organic carbon content and B) graptolite reflectance in the Lövestad A3-1 well. Note that for the Alum Shale interval the reflectance values for the Fågeltofta-2 well drilled 8 km east of the Lövestad A3-1 well are used. The correction between graptolite reflectance and equivalent vitrinite reflectance are made according to Petersen et al. (2013).

4. 1D Thermal maturation modelling

Burial model

It is generally assumed that the present day maturation pattern of the Alum Shale reflects deep burial during the Caledonian Orogeny (Buchardt et al. 1986, 1997; Thomsen et al. 1987; Jensenius 1987; Vejbæk et al. 1994; Jensen & Nielsen 1995; Mogensen & Korstgård 2003). Peak burial is assumed to have occurred in the late Silurian to Devonian time as rapid subsidence and high clastic input led to deposition of several kilometres of sediments in a Caledonian foreland basin in southern Scandinavia. The onset of the Late Palaeozoic uplift is poorly dated and only sporadic indications of reworked Carboniferous occur, notably in the Jurassic (e.g. Guy-Ohlson et al. 1987), but commencement of uplift must have started much earlier. The tectonic mode changed in late Carboniferous time into a rift phase and it is generally assumed that the uplift phase was terminated by this time (Figure 10).

The burial history of the Mesozoic and onwards have been dealt with by several authors (Michelsen & Nielsen 1991, Mogensen & Korstgård 2003, Japsen & Bidstrup 1999). There is general agreement that the maximum depth of burial was reached in the Cretaceous. Subsequent inversion resulted in an uplift of about 0.5-1.5 km (Japsen & Bidstrup 1999).

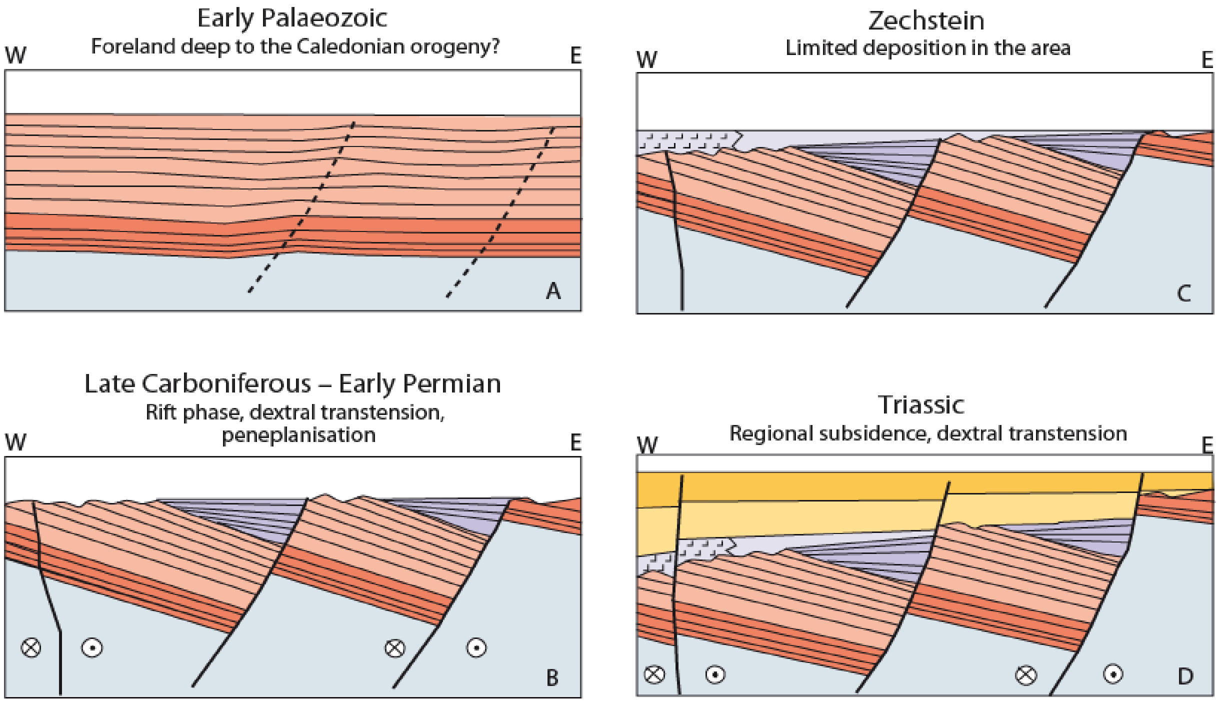


Figure 10. Conceptual geological development during the Palaeozoic to early Mesozoic in the Danish Basin. From Mogensen & Korstgård (2003).

Heat flow model

Two different heat flow models are used for sensitivity testing of the modelled maximum burial depth (Figure 11).

The high heat flow model assumes an increase in heat flow during the Caledonian collision phase from about 60 mW/m^2 to 80 mW/m^2. The increase in heat flow assumes that the Baltic crust behaved as a thick crust in the sense of Bodri & Bodri (1985). Accordingly, the 20 mW/m^2 increase in heat flow reflects a thickening of the crust by some 18 ± 4 km during the orogenic phase.

The low heat flow model assumes that the deep burial phase in the late Silurian to mid Carboniferous was not associated with an increase in heat flow. In this interval a heat flow of 45 increasing to 55 mW/m^2 is assumed, which is slightly below average crustal heat flow of 60 mW/m^2. A slight increase in heat flow to values above the crustal average is assumed in the Late carboniferous throughout the Devonian (Figure 11). The increase in heat flow is expected because of the mid Carboniferous extension phase and thereby crustal thinning processes. However, this rise in heat flow has no effect on the thermal maturation since it post-dated the uplift phases. This model is regarded as a conservative “base case” for the evaluation of the heat flow development.

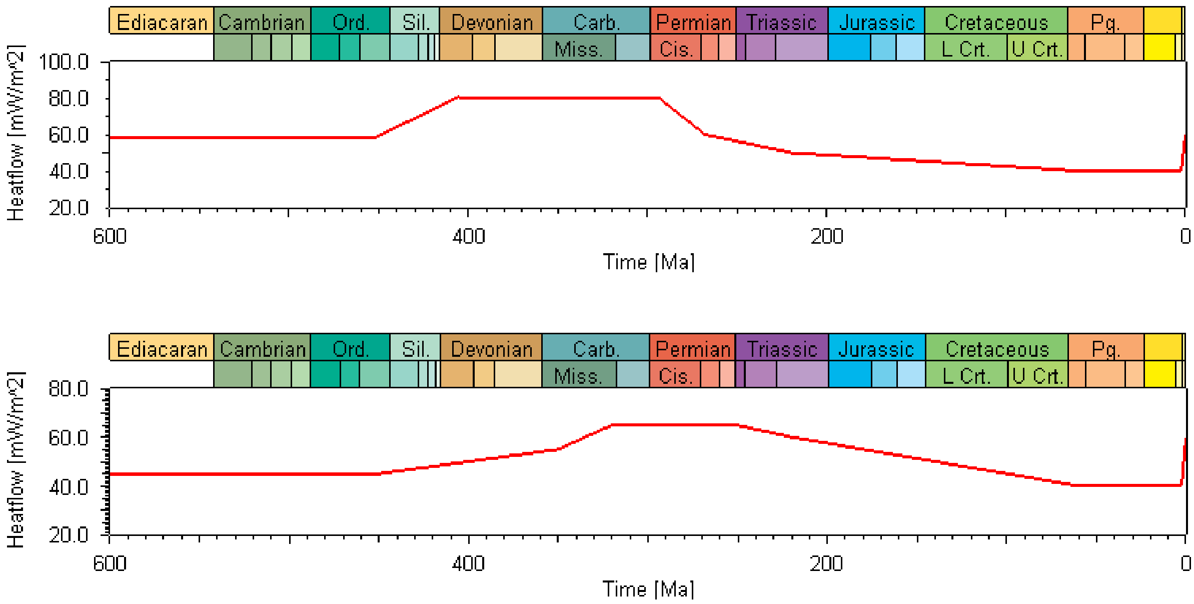


Figure 11. Heat flow models used in the 1D burial models. Top: High heat flow during Devonian - Carboniferous. Base: Low heat flow model with raised heat flow values during mid Carboniferous to late Permian. This slight elevated peak heat flow reflect the onset of rift phase i.e. post-burial. Data is presented in table in Appendix B.

4.1. Results: High heat flow model

The results of the basin modelling are presented in Figures 12-23 and discussed in Section 5 of this report. The high heat flow modelling is shown in Figure 12-16. The modelling is simplified by assuming that the burial occurred in late Silurian and that this deep burial was maintained in the Devonian to Early Carboniferous. In this interval the modelling assumes non-deposition and compaction related thickness reduction only.

Terne-1 well

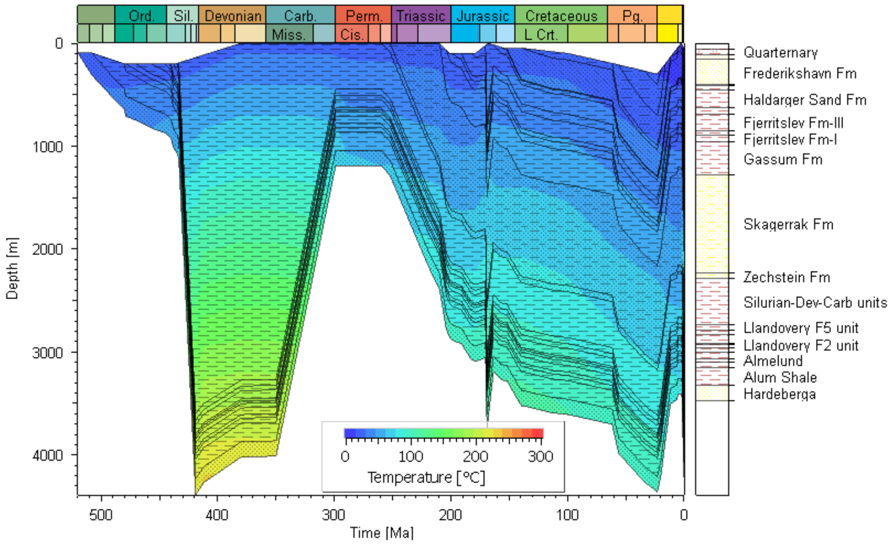


Figure 12. Burial history and temperature profile for the Terne-1 well assuming the high heat flow model. Peak burial of 4.3 km (un-compacted thickness) was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

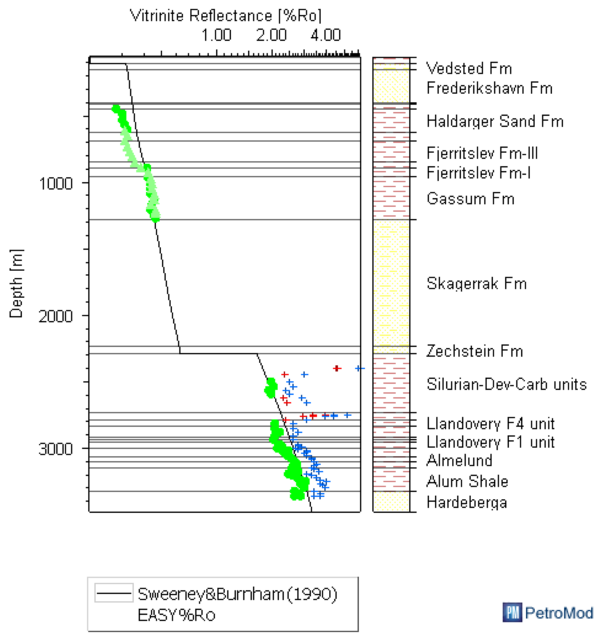


Figure 13. Modelled equivalent vitrinite reflectance profile in the Terne-1 well assuming the high heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance not affected by sill; Red: graptolite reflectance samples affected by sill.

Slagelse-1 well

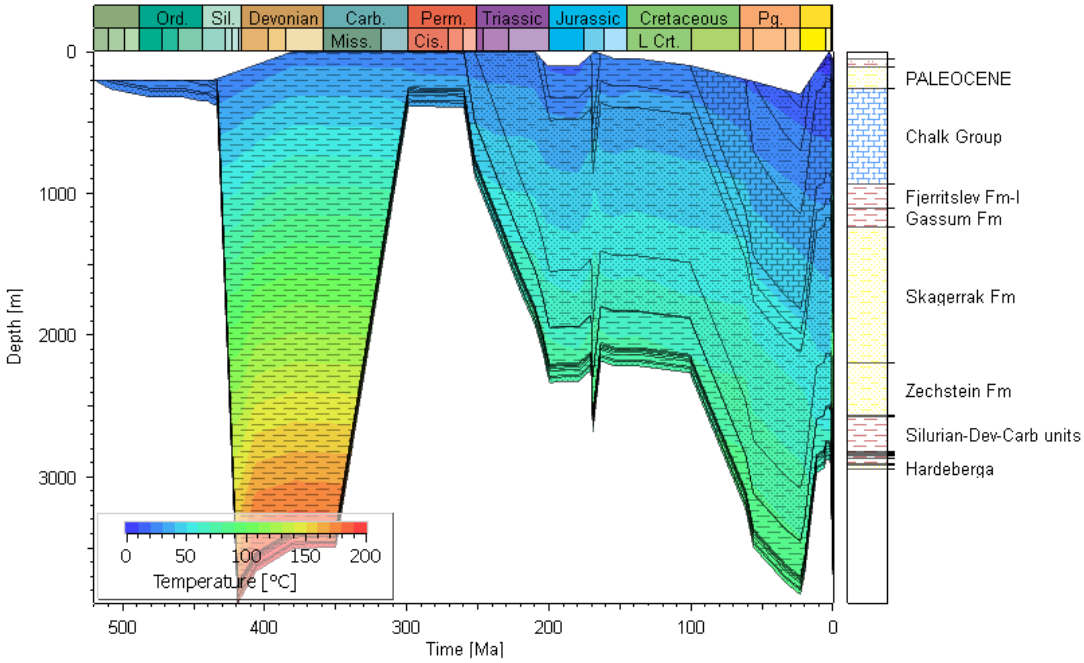


Figure 14. Burial history and temperature profile for the Slagelse-1 well assuming the high heat flow model. Peak burial of 3.8 km (un-compacted thickness) was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

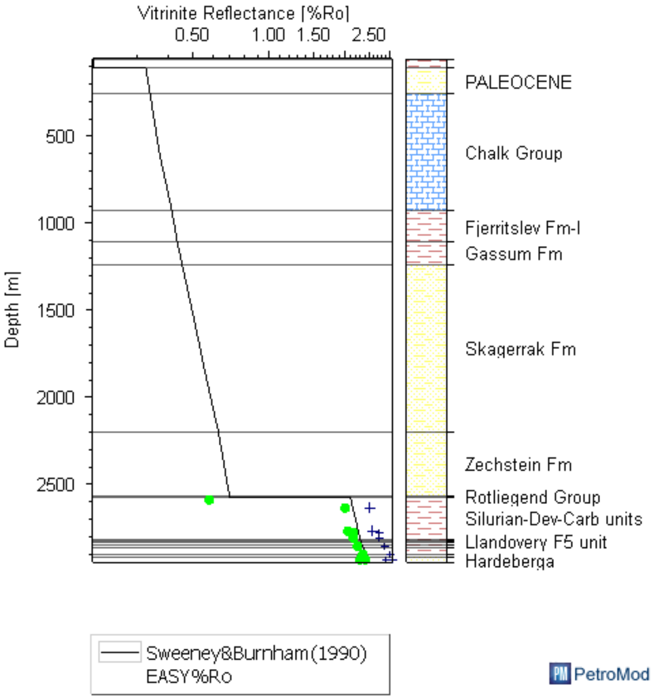


Figure 15. A modelled equivalent vitrinite reflectance profile in the Slagelse-1 well assuming the high heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance.

Lövestad A3-1 well

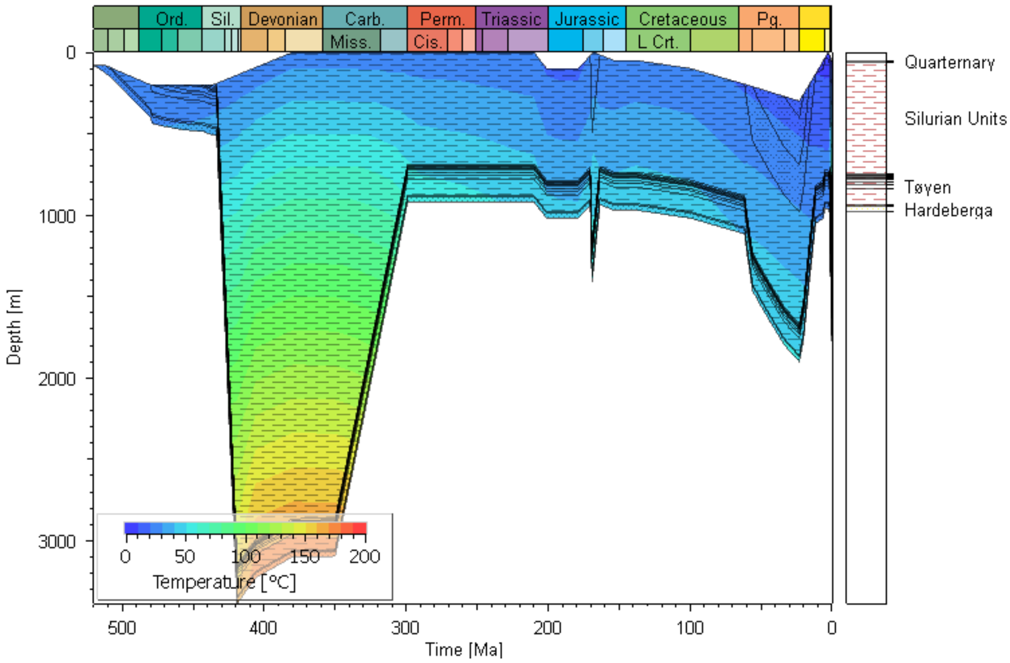


Figure 16. Burial history and temperature profile for the Lövestad A3-1 well assuming the high heat flow model. Peak burial of 3.4 km (un-compacted thickness) was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

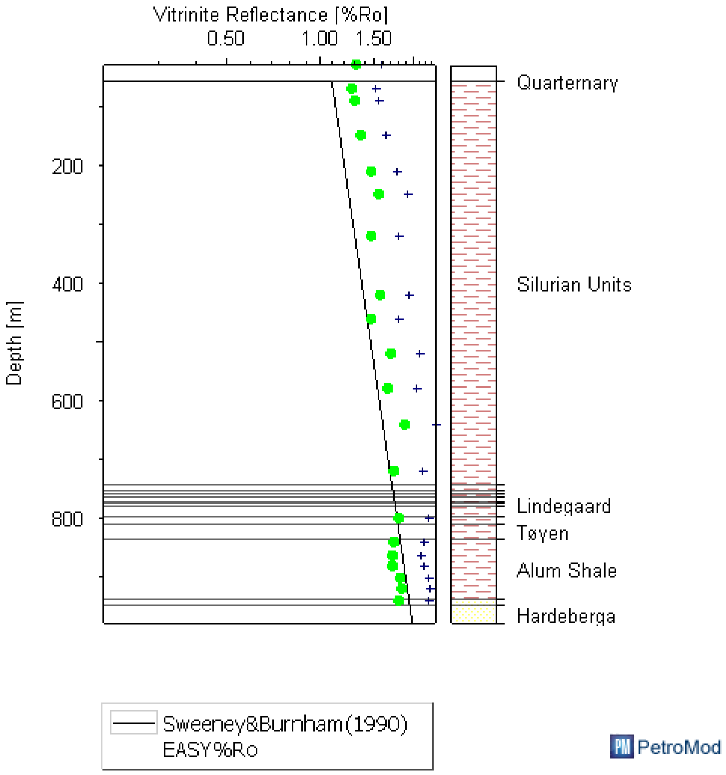


Figure 17. Modelled equivalent vitrinite reflectance profile in the Lövestad A3-1 well assuming the high heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance.

4.2. Results: Low heat flow model

The low heat flow modelling is shown in Figure 17-23. The modelling is simplified by assuming that the burial occurred in late Silurian and that this deep burial was maintained in the Devonian to Early Carboniferous. In this interval the modelling assumes non-deposition and compaction related thickness reduction only.

Terne-1 well

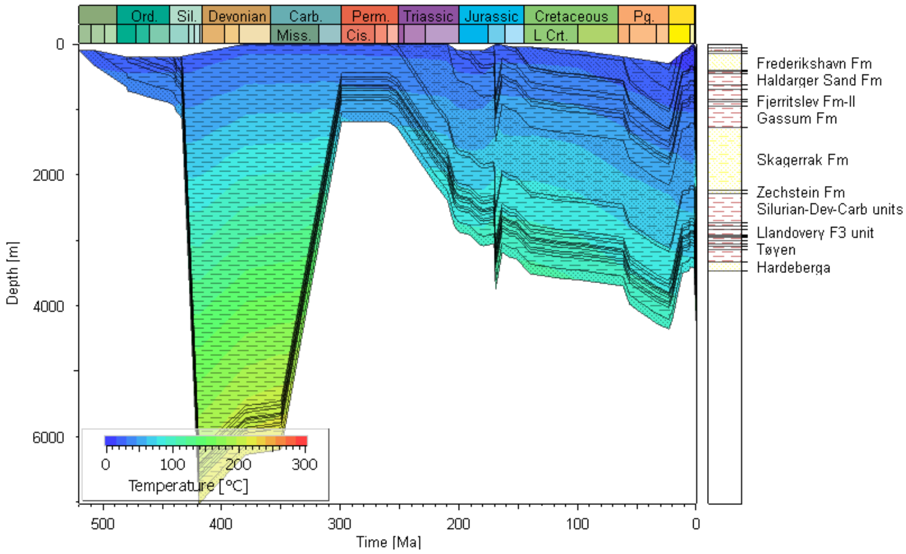


Figure 18. Burial history and temperature profile for the Terne-1 well assuming the low heat flow model. Peak burial of 6.5 km (un-compacted thickness) was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

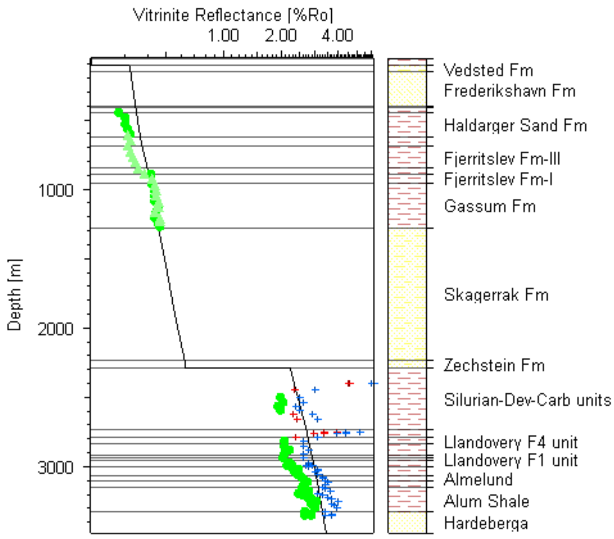


Figure 19. Modelled equivalent vitrinite reflectance profile in the Terne-1 well assuming the low heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance not affected by sill; Red: graptolite reflectance samples affected by sill.

Slagelse-1 well

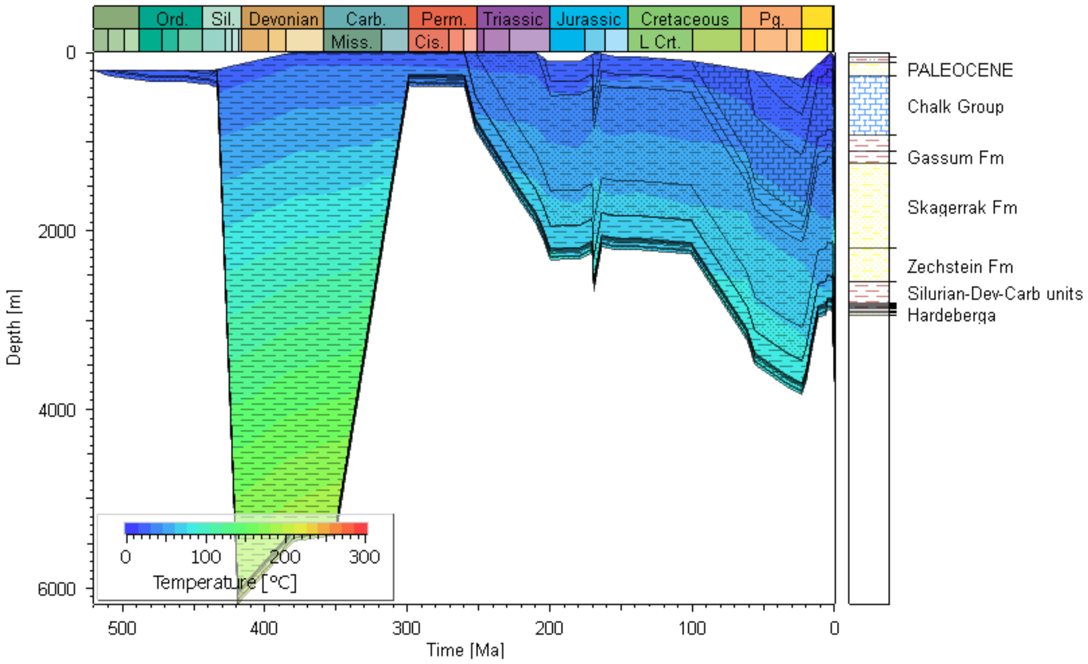


Figure 20. Burial history and temperature profile for Slagelse-1 assuming the low heat flow model. Peak burial of 6.2 km (un-compacted thickness) was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

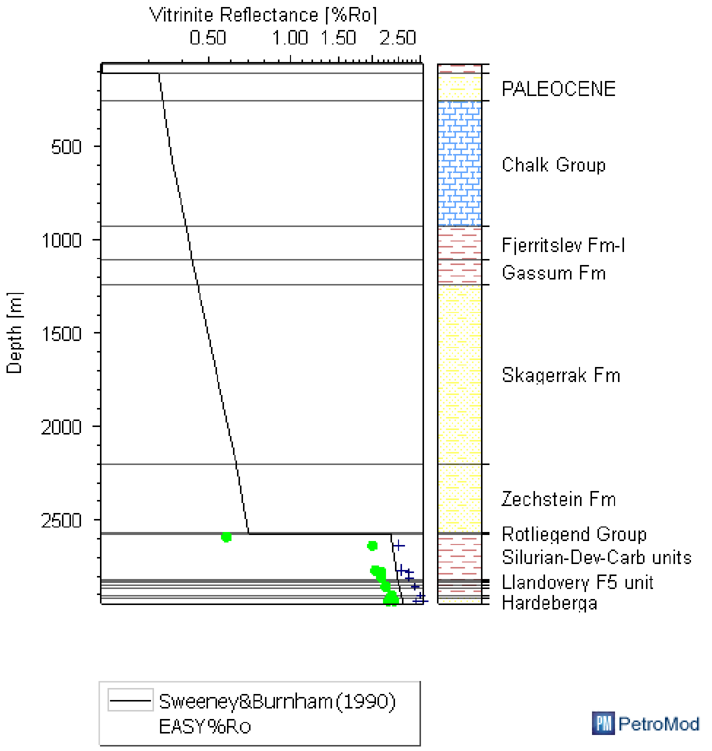


Figure 21. Modelled equivalent vitrinite reflectance profile in the Slagelse-1 well assuming the low heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance.

Lövestad A3-1 well

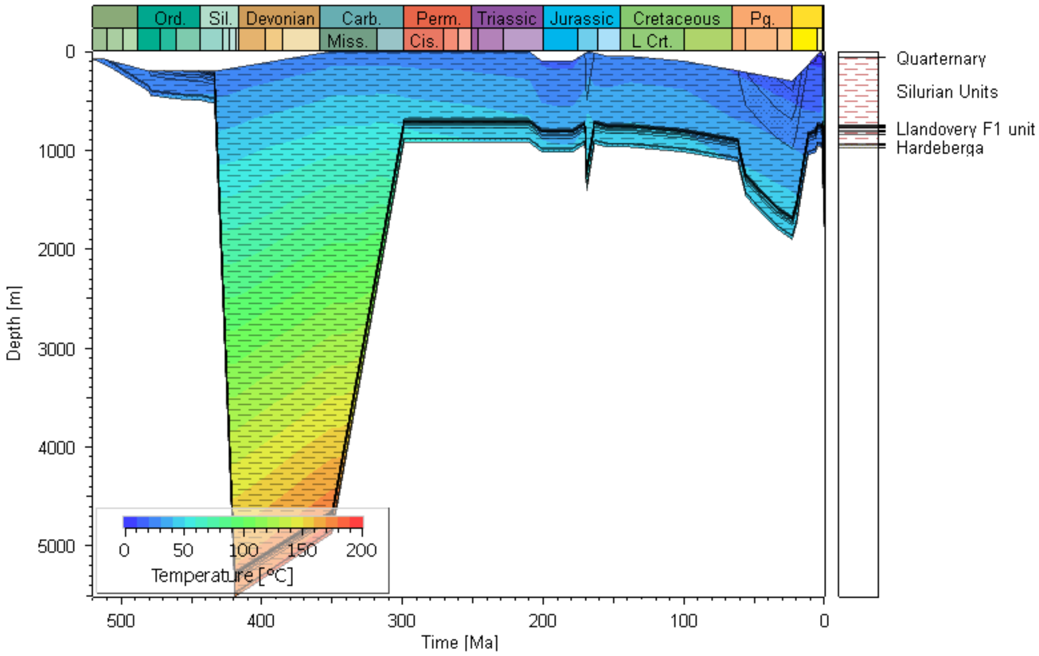


Figure 22. Burial history and temperature profile for the Lövestad A3-1 well assuming the low heat flow model. Peak burial of 5.4 km (un-compacted thickness) and was reached in the Silurian/Devonian. Until mid-Carboniferous compaction to present day thickness and non-deposition is assumed.

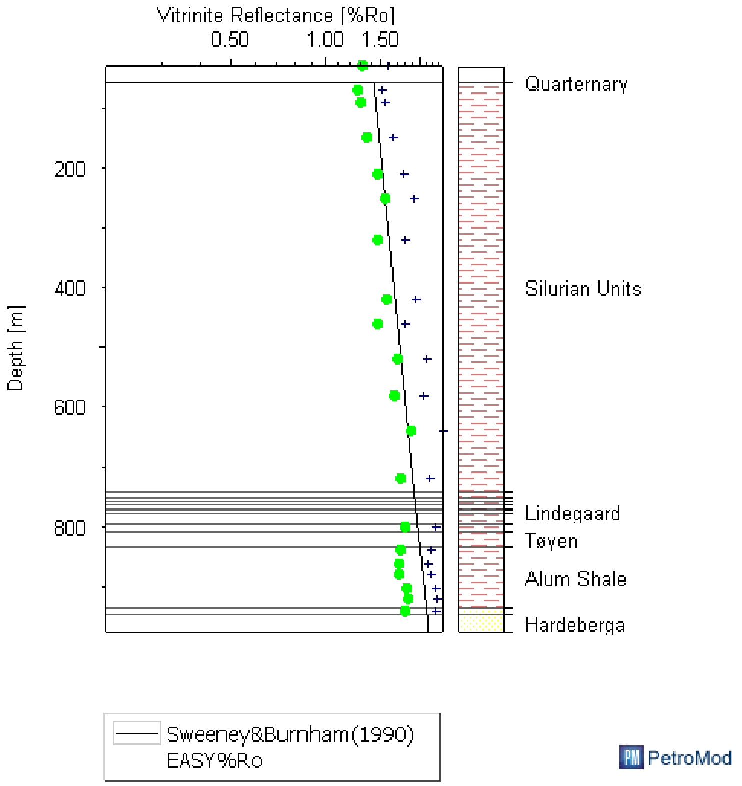


Figure 23. Modelled equivalent vitrinite reflectance profile in the Lövestad A3-1 well assuming the low heat flow model. Legend: Green: vitrinite reflectance (in the Mesozoic and Cenozoic) and equivalent vitrinite reflectance (calculated from graptolite reflectance according to Petersen et al. 2013); Blue: graptolite reflectance.

5. Discussion

In order to examine the sensitivity of the heat flow model with respect to the maximum burial depth and thus the extent of assumed Late Palaeozoic uplift two different heat flow scenarios were considered. The results of the 1D modelling are shown in Figures 12-23 and the main findings are summarized in Table 1.

5.1. Heat flow model and maximum burial depth

The high thermal maturation level of the studied Alum Shale is related to deep burial during the Caledonian Orogeny. Here the Alum Shale was matured to dry gas rank and was newer again buried to similar depth or experienced similar temperatures in the subsequent geological history. The geological development suggests that the Terne-1, Slagelse-1 and Lövestad A3-1 areas were subjected to similar timing and duration of the late Silurian to Devonian deep burial event. This includes onset of deep burial in the late Silurian and onset of uplift in mid Carboniferous time. The main uncertainty concerns the heat flow during deep burial.

The maximum temperatures modelled range from 175-220°C and the resulting geothermal gradient during peak burial was calculated to range between 33-53 °C/km. The modelled temperature level is consistent with the fluid inclusion study made on samples from the Slagelse-1 well, Scania and Bornholm by Jensenius (1987). According to him the temperatures indicate minimum temperatures during the diagenetic processes.

A high geothermal gradient has previously been invoked to explain the high thermal maturity of the Lower Palaeozoic of Scandinavia (Majorowicz et al. 1984; Vejbæk et al. 1994; Jensen & Nielsen 1995; Buchardt et al. 1997). Jensenius (1987) assumed that the geothermal gradient was about 35-45 ^{o}C, however, the method for evaluating the burial depth used in this study cannot be compared with the one used by Jensenius (1987) and thus the gradient cannot be compared directly.

Table 1. Summary of the 1D basin modelling results.

	Terne-1		**Slagelse-1**		**Lövestad A3-1**	
	High Heat flow	Low Heat flow	High Heat flow	Low Heat flow	High Heat flow	Low Heat flow
Maximum burial of Alum Shale during Palaeozoic, Km (pre-compaction thickness)	4,4	6,5	3,9	6,2	3,4	5,5
Maxs temperature reached during the Palaeozoic , °C	220	210	190	210	175	180
Estimated geothermal gradient at maximum burial, °C/km	50	32	50	34	53	33
Late Paleozoic uplift and erosion, Km (compacted thickness)	2,8	4,5	3,1	4,6	2,2	3,8
Present day thickness of Lower Palaeozoic shales, Km	1,0		0,4		0,9	

Maximum burial depth

The two heat flow models critically influences how deep burial it is necessary to invoke. The maximum burial depth in the Devonian thus ranges between 3.5-4.5 km if the high heat flow model is assumed whereas the maximum burial depth ranges between 5.5-6.5 km if the low heat flow model is assumed (Figure 24).

Seismic mapping of the preserved thickness of the Palaeozoic suggests that 5 km is a typical maximum thickness if local Vendian basins are ignored (Figure 25). These mapped present day maximum thicknesses are comparable to the modelled thickness and thus may be an independent constrain of the basin modelling results. Thus the maximum thicknesses resulting from the high heat flow modelling are more in-line with the present day thicknesses seen in the Danish area and is therefore the preferred heat flow model for the Palaeozoic.

In the Terne-1 and Slagelse-1 areas it might be reasonable to suggest that only the high heat flow model is realistic since the low heat flow model models entail a 6-7 km thickness of the Paleozoic shales which is not observed anywhere present day (Figure 24). For Lövestad A3-1 both heat flow models will result in thicknesses that are comparable with those observed on seismic sections outside Scania (Figures 24 and 25) and thus the present day thickness cannot discriminate between the heat flow models. However, it is unlikely that the heat flow varied significantly between the Slagelse/Terne areas and Scania and, hence, it is assumed that the high heat flow also affected Scania.

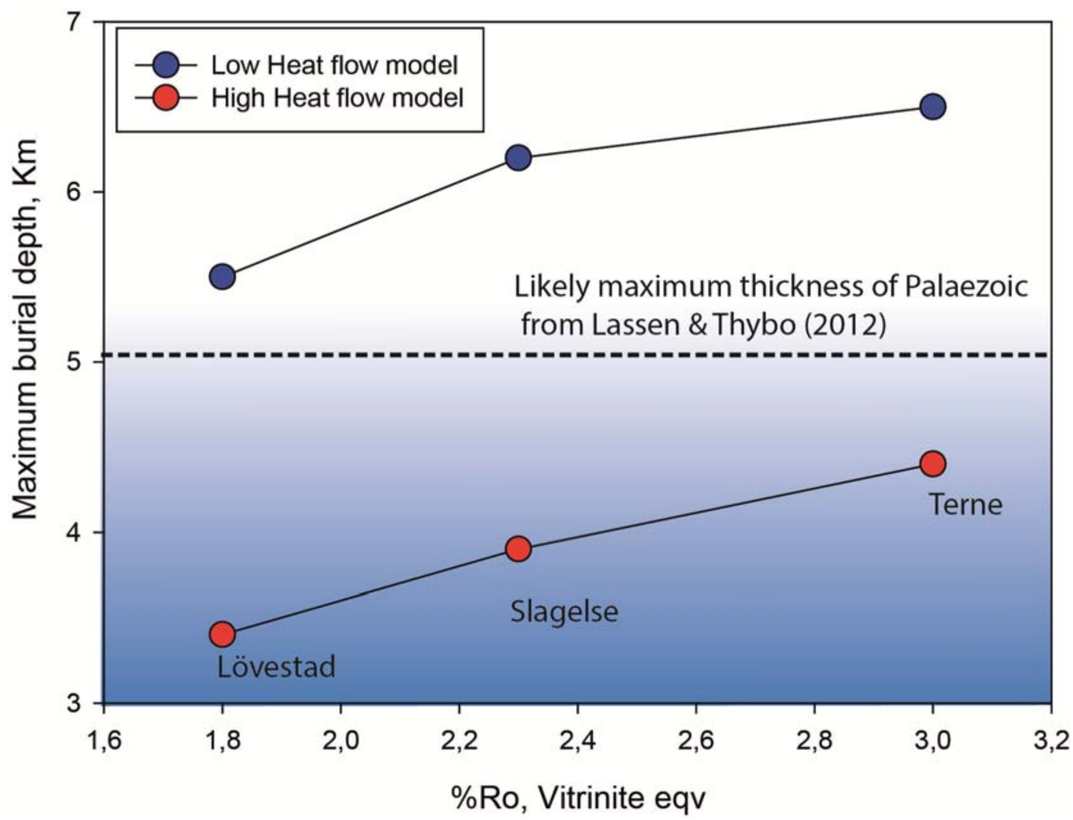


Figure 24. Relationship between modelled maximum pre-compaction burial depth and equivalent vitrinite reflectance. Data from Table 1.

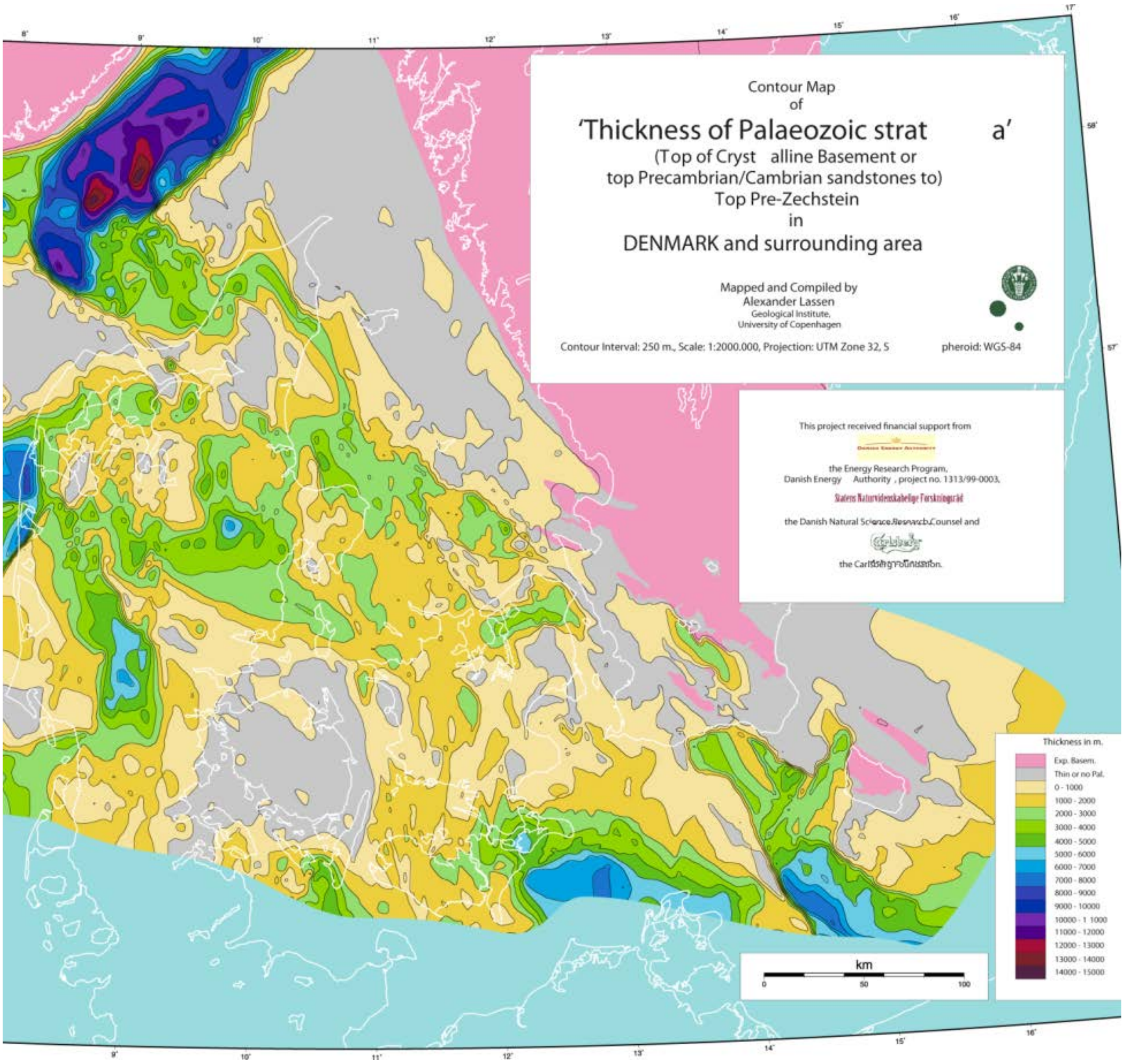


Figure 25. Present day thickness of the pre-Zechstein Palaeozoic strata. Maximum present day thickness of about 5 km can be observed in several parts of Denmark. From Lassen & Thybo (2012).

5.2. Late Palaeozoic uplift and gas retention

The preserved Lower Palaeozoic sequence on Zealand is either thin to absent or less than 1 km thick in most of the area (Figure 25). From the basin modelling we observe that in the Slagelse-1, Terne-1 and Lövestad A3-1 areas some 2.2-3.1 km were removed during the Late Paleozoic uplift assuming that the (preferred) high heat flow model was effective. Accordingly, about 90-70 % of the strata originally present were removed (Figure 26). We thus infer that the Alum Shale in most parts of Zealand was rather shallowly buried during the late Carboniferous - early Permian.

The uplift began in mid-Carboniferous and it was not until the Triassic (Terne-1) or Jurassic (Slagelse-1) that the Alum Shale again was buried below 2 km (Figures 12 and 14). In the Lövestad A3-1 area the Alum Shale was not buried again to any greater depth (Figure 16). The pressure release and associated gas leakage caused by this uplift and lack of re-burial were regarded as the main reason why the Alum Shale in Scania did not contain any producible gas despite its obvious good reservoir quality (Pool et al. 2012, Schovsbo et al. 2014).

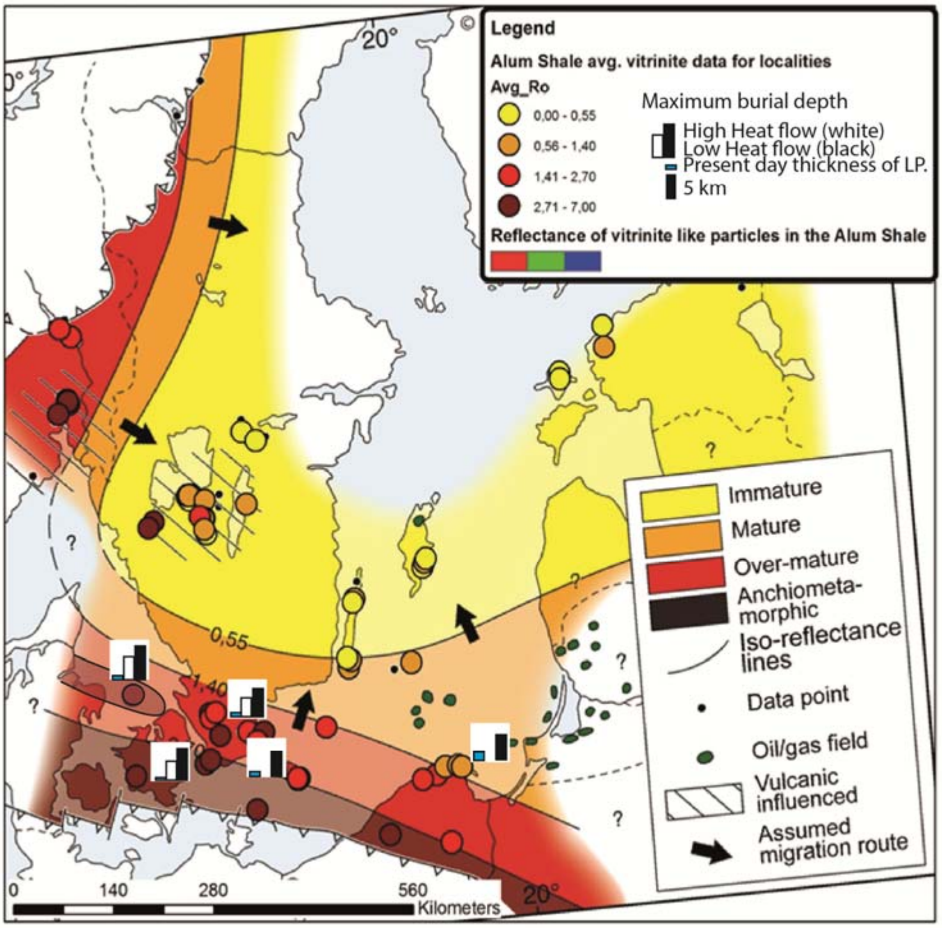


Figure 26. Maximum burial depth modelled based on the high and low heat flow models and the thermal maturity map of the Alum Shale at the time of maximum burial depth during the Caledonian Orogeny. The results from the basin modelling are presented in Table 1. For Bornholm, the Rønne Graben (Pernille-1, GEUS study) and for northern Poland, the Zarnowiec IG-1 (Poprawa et al. 2010), are shown for comparison. The heat flow model for Zarnowiec IG-1 is slightly different than those used here, but resembles the low heat flow model.

6. Conclusions

Vitrinite particles *sensu stricto* is absent from the Cambrian to Early Ordovician Alum Shale Formation due to its deposition before land plants evolved. The thermal maturity of the Alum Shale, as has been common in most other Lower Palaeozoic shales, is instead evaluated based on graptolite reflectance that behaves in a similar manner with respect to thermal maturity as real vitrinite. The precise relationship between temperature and reflectance differ, however, between the two types and in this basin modelling investigation the conversion from graptolite to equivalent vitrinite particles proposed by Petersen et al. (2013) has been used.

The Alum Shale on Zealand is expected to have a thermal maturity ranging between 1.9 and 2.3 % equivalent vitrinite reflectance. The higher thermal maturity of the Terne-1 well (3% equivalent vitrinite reflectance) is interpreted to reflect its position within the Sorgenfrei-Tornquist Zone and is thus not expected to be relevant for Zealand.

The thermal maturation of the Alum Shale reflects deep burial related to the Caledonian Orogeny. Increased subsidence is expected to have been initiated in the Silurian and uplift is suggested to have taken place from the mid Carboniferous.

Two heat flow models have been applied to evaluate the maximum burial depth and temperature history associated with burial. The most likely heat flow model involves an increase in heat flow during deep burial to a depth of about 3.4-4.5 km during the latest Silurian- Devonian and early Carboniferous time. The modelled thicknesses are comparable to the preserved present day maximum thicknesses of the Palaeozoic observed on seismic sections in Denmark.

The Late Palaeozoic uplift eroded most of the Lower Palaeozoic sequence in many areas. In Slagelse-1 the uplift is estimated to have been 3.1 km and about 90% of the original thickness present is assumed removed by erosion. Judging from the preserved thickness of the Lower Palaeozoic on Zealand only the north-eastern and western parts of Zealand did not suffer a similar magnitude of uplift and erosion. We thus infer that the Alum Shale in most parts of the Zealand was exposed to shallow burial depth during the late Carboniferous - early Permian. The uplift and subsequent exposure inflicts a high risk for gas loss from the Alum Shale reservoir and thus downgrades the area for shale gas exploration.

7. References

Bodri, L., Bodri, B., 1985. On the correlation between heat flow and crustal thickness. Tectonophysics 120, 69–81.

Buchardt, B., Clausen, J., Thomsen, E., 1986. Carbon isotope composition of Lower Palaeozoic kerogen: Effects of maturation. Organic geochemistry 10, 127–134.

Buchardt, B., Lewan, M.D., 1990. Reflectance of vitrinite-like macerals as a thermal maturity index for Cambrian-Ordovician Alum Shale, southern Scandinavia. AAPG Bulletin 74, 394–406.

Buchardt, B., Nielsen, A.T., Schovsbo, N.H., 1997. Alun Skiferen i Skandinavien. Geologisk Tidsskrift 3, 1–30.

Eriksson, M., 2012. Stratigraphy, facies and depositional history of the Colonus Shale Trough, Skåne, southern Sweden. Dissertation in Geology at Lund University, master thesis, no 310. Department of Geology Lunds University. 40 pp.

Gautier, D.L., Charpentier R.R., Gaswirth, S.B., Klett, T.R., Pitman, J.K., Schenk, C.J., Tennyson, M.E., Whidden, K.J., 2013. Undiscovered Gas Resources in the Alum Shale, Denmark. U.S. Geological Survey Fact Sheet 2013–3103, 1–4.

Guy-Ohlson, D., Lindquist, B., Norling, E., 1987. Reworked Carboniferous spores in Swedish Mesozoic sediments. GFF 109, 295-306.

Japsen, P., Bidstrup, T., 1999. Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. Bulletin of the Geological Society of Denmark 46, 79–99.

Jensen, S.K., Nielsen, S.B., 1995. Estimating amount and timing of Late Paleozoic uplift and erosion in the Rønne Graben, Bornholm, Denmark. Bulletin of the Geological Society of Denmark 42, 23–33.

Jensenius, J., 1987. Regional studies of fluid inclusions in Paleozoic sediments from southern Scandinavia. Bulletin of the Geological Society of Denmark 36, 221–235.

Lassen, A., Thybo, H., 2012. Neoproterozoic and Palaeozoic evolution of SW Scandinavia based on integrated seismic interpretation Precambrian Research 204–205, 75–104.

Majorowicz, J.A., Marek, S., Znosko, J., 1984. Palaeogeothermal gradients by vitrinite reflectance data and their relation to the present geothermal gradient patterns of the Polish Lowland. Tectonophysics 103, 141–156.

Michelsen, O., Nielsen, L.H., 1991. Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark: Sæby-1, Hans-1 and Terne-1 wells. Danmarks Geologiske Undersøgelse Serie A29, 1–37.

Mogensen, T.E., Korstgård, J.A., 2003. Triassic and Jurassic transtension along part of the Sorgenfrei-Tornquist Zone, in the Danish Kattegat. In Ineson, J.R, Surlyk, F. (eds): The

Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1, 439–458.

Nielsen, A.T., Schovsbo, N.H., 2006. Cambrian to basal Ordovician lithostratigraphy of southern Scandinavia. Bulletin of the Geological Society of Denmark 53, 39–85.

Nielsen, A.T., Schovsbo, N.H., 2011. The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth Science Reviews 107, 207–310.

Petersen, H.I., Schovsbo, N.H., Nielsen, A.T., 2013. Reflectance measurements of zooclasts and solid bitumen in Lower Palaeozoic shales, southern Scandinavia: correlation to vitrinite reflectance. International Journal of Coal Petrology 114, 1–18.

Pool, W., Geluk, M., Abels, J., Tiley, G., 2012. Assessment of an unusual European Shale Gas play: the Cambro-Ordovician Alum Shale, southern Sweden. Society of Petroleum Engineers 152339-MS.

Poprawa, P., Kosakowski, P., Wróbel, M., 2010. Burial and thermal history of the Polish part of the Baltic region. Geological Quarterly 54, 131–142.

Schovsbo, N.H., 2011a. The Lower Palaeozoic sequence in the Terne-1 well. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2011/98, 69 pp.

Schovsbo, N.H., 2011b. The Lower Palaeozoic sequence in the Slagelse-1 well. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2011/84, 49 pp.

Schovsbo, N.H., 2003. The geochemistry of Lower Palaeozoic sediments deposited at the margins of Baltica. Bulletin of the Geological Society of Denmark 50, 11–27.

Schovsbo, N.H., Nielsen, A.T., Nicolas, G., Petersen, H.I., Stouge, S., 2012. Thermal maturity of Lower Palaeozoic shales in north-western Europe: Calibration of proxies. EAGE Meeting in Copenhagen 2012. Extended abstract, 1–4.

Schovsbo, N.H., Nielsen, A.T., Gautier, D.L., 2014. The Lower Palaeozoic shale gas play in Denmark. Geological Survey of Denmark and Greenland Bulletin 31, 19–22.

Thomsen, E., Damtoft, K., Andersen, C., 1987. Hydrocarbon plays in Denmark outside the Central Trough. In J. Brooks, K. Glennin (eds): Petroleum Geology of North West Europe. 375–388. Graham & Trotman.

Vejbæk, O., Stouge, S., Poulsen, K.D., 1994. Palaeozoic tectonic and sedimentary evolution and hydrocarbon prospectivity in the Bornholm area. Geological Survey of Denmark A34, 1–23.

Appendix A: Maturity data Lövestad A3-1

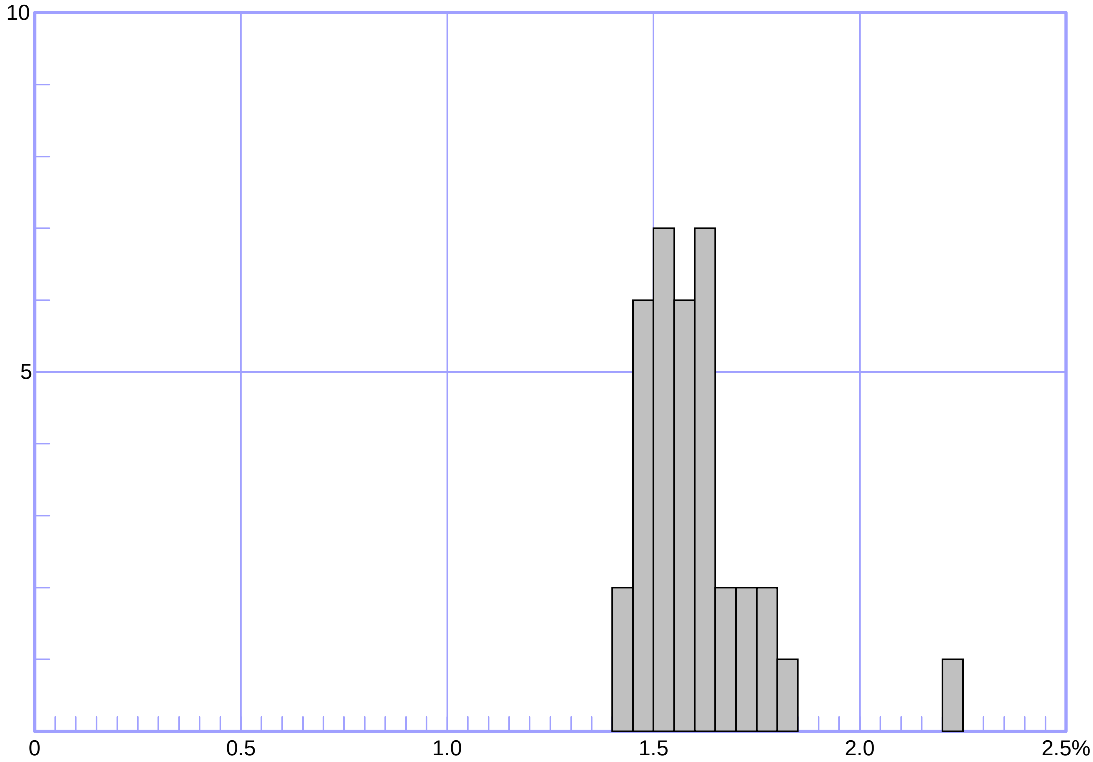
Well	depth, m	TOC, wt%	Tmax (°t)	S1 (mg/g)	S2 (mg/g)	% R Grap.	Std.	N	% R Vit. eqv.*
Lövestad A3-1	10	0.10							
Lövestad A3-1	30	0.19	462	0.01	0.11	1.58	0.11	36	1.31
Lövestad A3-1	50	0.10							
Lövestad A3-1	70	0.14				1.52	0.11	42	1.27
Lövestad A3-1	90	0.18	n.d.	0	0	1.55	0.12	54	1.29
Lövestad A3-1	110	0.13							
Lövestad A3-1	130	0.14							
Lövestad A3-1	150	0.17	452	0	0	1.64	0.11	36	1.36
Lövestad A3-1	170	0.09							
Lövestad A3-1	190	0.14							
Lövestad A3-1	210	0.17	n.d.	0	0	1.78	0.10	63	1.46
Lövestad A3-1	230	0.17							
Lövestad A3-1	250	0.22	n.d.	0.01	0	1.91	0.16	60	1.55
Lövestad A3-1	270	0.16							
Lövestad A3-1	290	0.10							
Lövestad A3-1	300	0.17	n.d.	0	0				
Lövestad A3-1	320	0.12				1.80	0.15	14	1.47
Lövestad A3-1	340	0.19	n.d.	0.02	0				
Lövestad A3-1	360	0.16							
Lövestad A3-1	380	0.24	n.d.	0.02	0				
Lövestad A3-1	400	0.31							
Lövestad A3-1	420	0.29	n.d.	0.1	0.1	1.93	0.14	57	1.57
Lövestad A3-1	440	0.12							
Lövestad A3-1	460	0.22				1.79	0.15	47	1.47
Lövestad A3-1	480	0.31	n.d.	0.04	0				
Lövestad A3-1	500	0.43							
Lövestad A3-1	520	0.47	n.d.	0.16	0.19	2.09	0.13	68	1.69
Lövestad A3-1	540	0.37							
Lövestad A3-1	560	0.42	n.d.	0.05	0				
Lövestad A3-1	580	0.39				2.05	0.13	41	1.66
Lövestad A3-1	600	0.54	n.d.	0.04	0				
Lövestad A3-1	620	0.58							
Lövestad A3-1	640	0.56	n.d.	0.14	0	2.36	0.19	75	1.88
Lövestad A3-1	660	0.64							
Lövestad A3-1	680	0.58	n.d.	0.08	0				
Lövestad A3-1	700	0.26							
Lövestad A3-1	720	0.24	n.d.	0.01	0	2.15	0.15	51	1.73
Lövestad A3-1	740	0.27							
Lövestad A3-1	760	0.33	n.d.	0.02	0				
Lövestad A3-1	780	0.12							
Lövestad A3-1	800	0.56	n.d.	0.11	0.01	2.25	0.15	91	1.80

Well	depth, m	TOC. wt%	Tmax (°t	S1 (mg/g)	S2 (mg/g)	% R Grap	stdv	N	% R Vit. eqv.*
Lövestad A3-1	820	0.28							
Lövestad A3-1	839,5	0.36	n.d.	0.09	0	2.16	0.11	11	1.74
Fågeltofta-2	880	depth assigned to same stratigraphical level as in Lövestad				2.16	0.14	123	1.71
Fågeltofta-2	920					2.28	0.11	100	1.83

* Calculated according to Petersen et al. (2013); n.d.: not defined

Sample : 25554

Activity no: 2014019; Standard: 1.667%
Locality: Loevestad A3-1; Depth: 30 m
Material: Cuttings



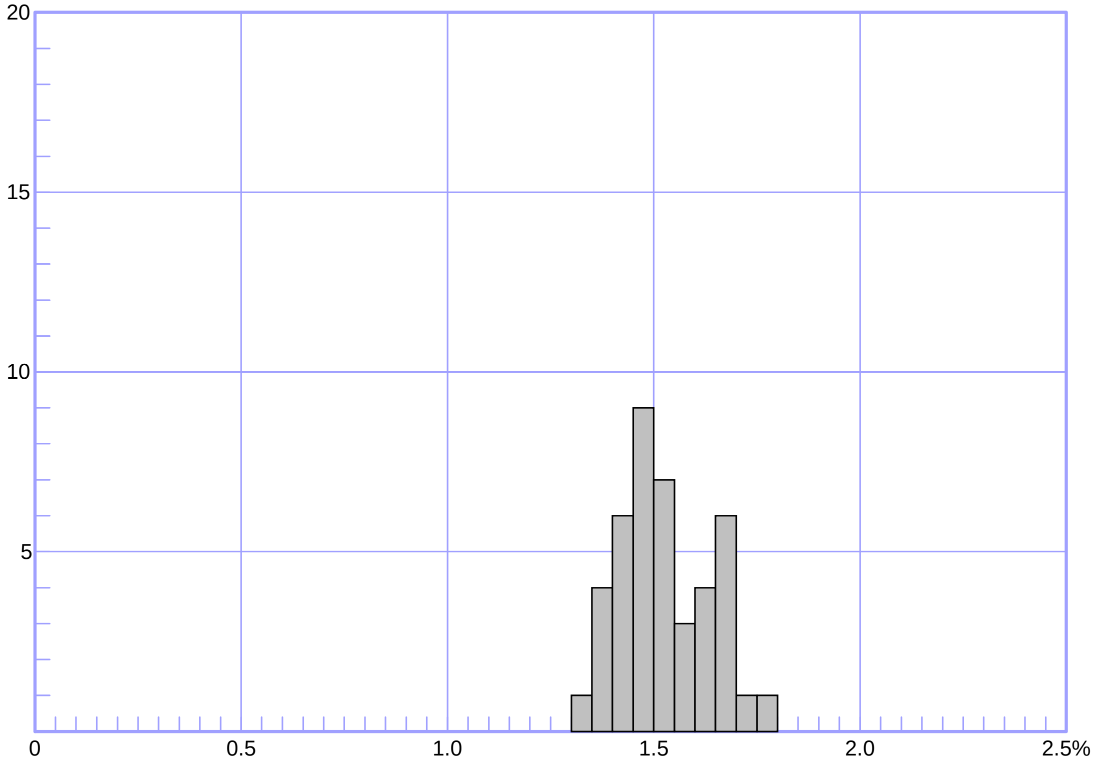
Measure count	=	36	Date	11/5/2014	02:01 PM
Reflectance Rr	=	1.597 %	Operator	cgu	
s	=	0.140 %	Printed	11/6/2014	

1.40 - 1.45 % R	2	1.65 - 1.70 % R	2
1.45 - 1.50 % R	6	1.70 - 1.75 % R	2
1.50 - 1.55 % R	7	1.75 - 1.80 % R	2
1.55 - 1.60 % R	6	1.80 - 1.85 % R	1
1.60 - 1.65 % R	7	2.20 - 2.25 % R	1

F=3.0.5268 D=4.80.8520

Sample : 25556

Activity no: 2014019; Standard: 1.667%
Locality: Loevestad A3-1; Depth: 70 m
Material: Cuttings



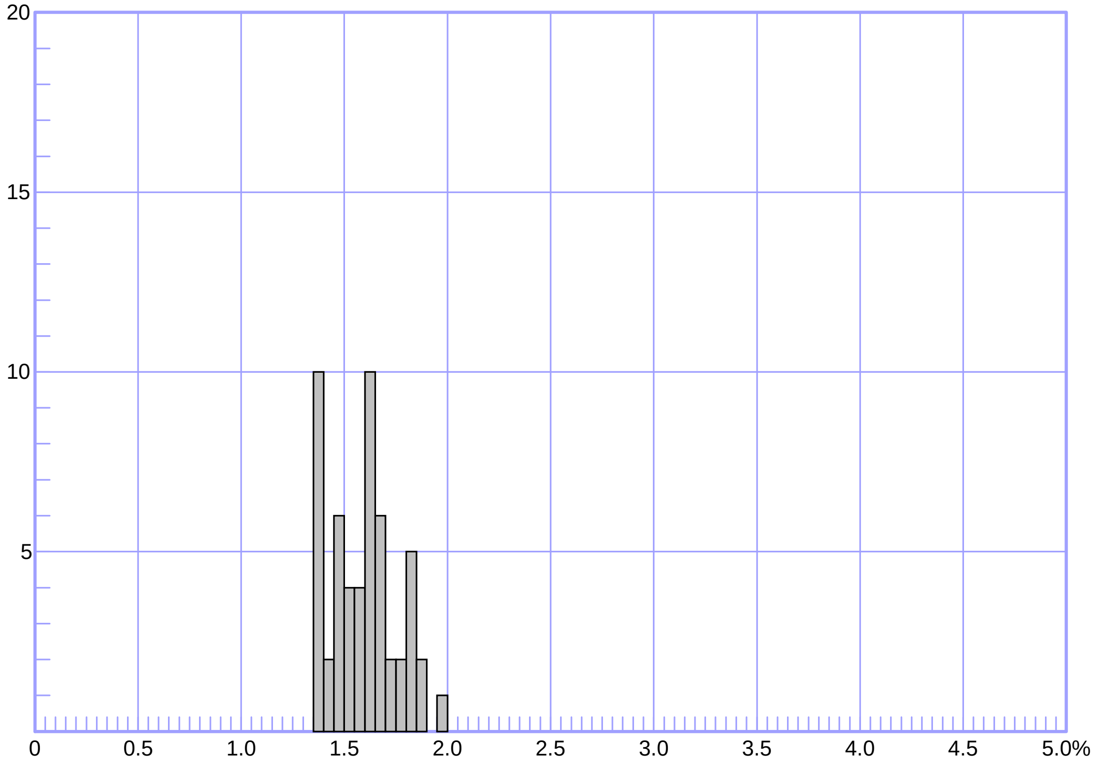
Measure count =	42		Date	11/4/2014 10:28 AM
Reflectance Rr =	1.522 %		Operator	cgu
s =	0.108 %		Printed	11/6/2014

1.30 - 1.35 % R	1	1.55 - 1.60 % R	3
1.35 - 1.40 % R	4	1.60 - 1.65 % R	4
1.40 - 1.45 % R	6	1.65 - 1.70 % R	6
1.45 - 1.50 % R	9	1.70 - 1.75 % R	1
1.50 - 1.55 % R	7	1.75 - 1.80 % R	1

F=3.0.5268 D=4.80.8520

Sample : 25557

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 90 m
Material: Cuttings



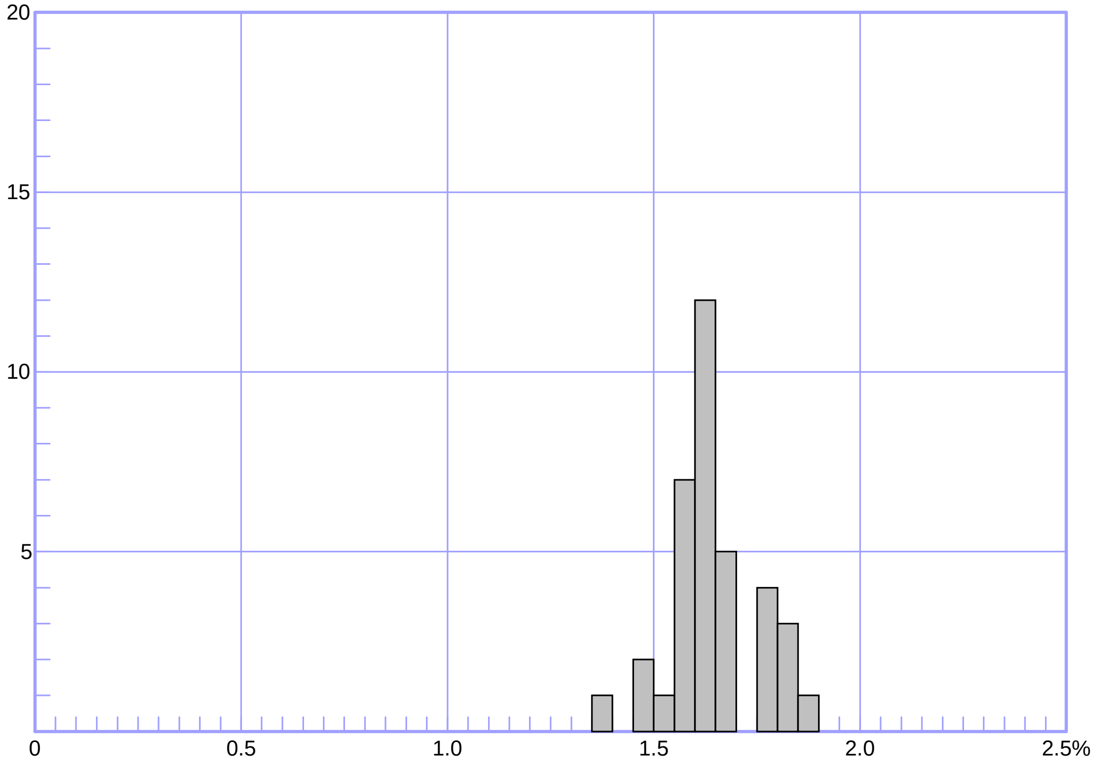
Measure count	=	54		Date	10/20/2014 07:51 AM
Reflectance Rr	=	1.594	%	Operator	cgu
s	=	0.159	%	Printed	10/29/2014

1.35	-	1.40	% R	10		1.65	-	1.70	% R	6
1.40	-	1.45	% R	2		1.70	-	1.75	% R	2
1.45	-	1.50	% R	6		1.75	-	1.80	% R	2
1.50	-	1.55	% R	4		1.80	-	1.85	% R	5
1.55	-	1.60	% R	4		1.85	-	1.90	% R	2
1.60	-	1.65	% R	10		1.95	-	2.00	% R	1

F=3.0.5268 D=4.80.8520

Sample : 25560

Activity no: 2014019; Standard: 1.667%
Locality: Loevestad A3-1; Depth: 150 m
Material: Cuttings



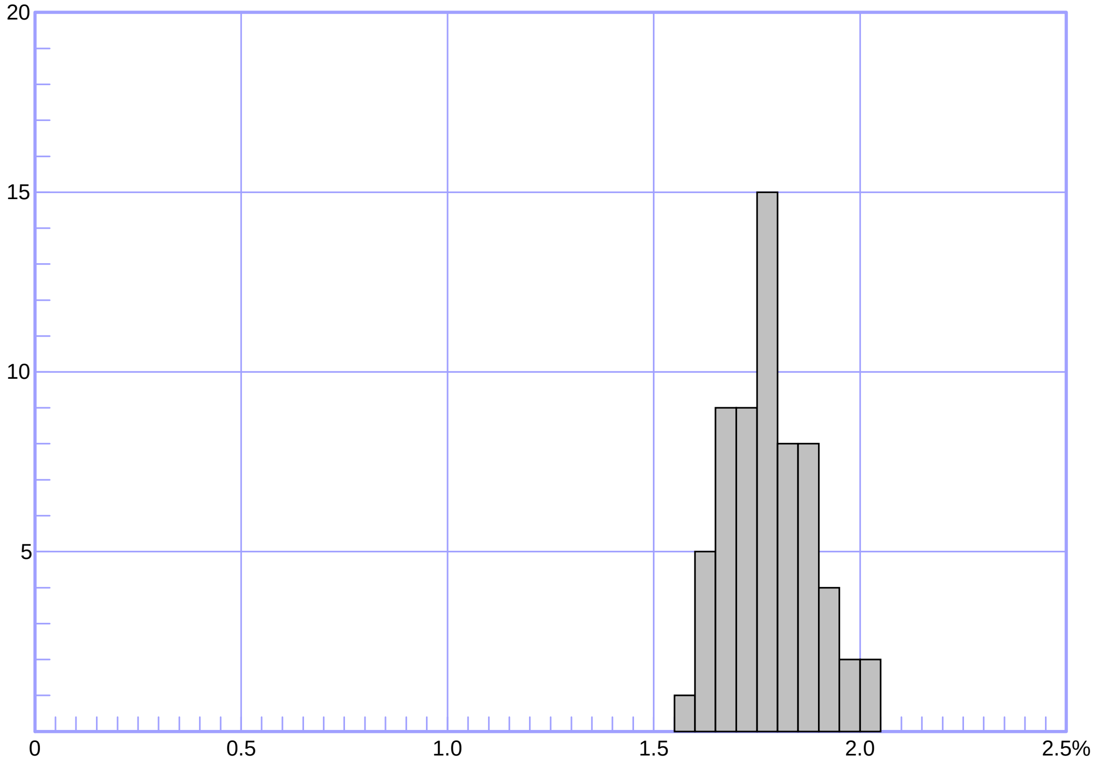
Measure count =	36		Date	11/4/2014 01:41 PM
Reflectance Rr =	1.643	%	Operator	cgu
s =	0.105	%	Printed	11/6/2014

1.35 - 1.40	% R	1	1.65 - 1.70 % R	5
1.45 - 1.50	% R	2	1.75 - 1.80 % R	4
1.50 - 1.55	% R	1	1.80 - 1.85 % R	3
1.55 - 1.60	% R	7	1.85 - 1.90 % R	1
1.60 - 1.65	% R	12		

F=3.0.5268 D=4.80.8520

Sample : 25563

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 210 m
Material: Cuttings



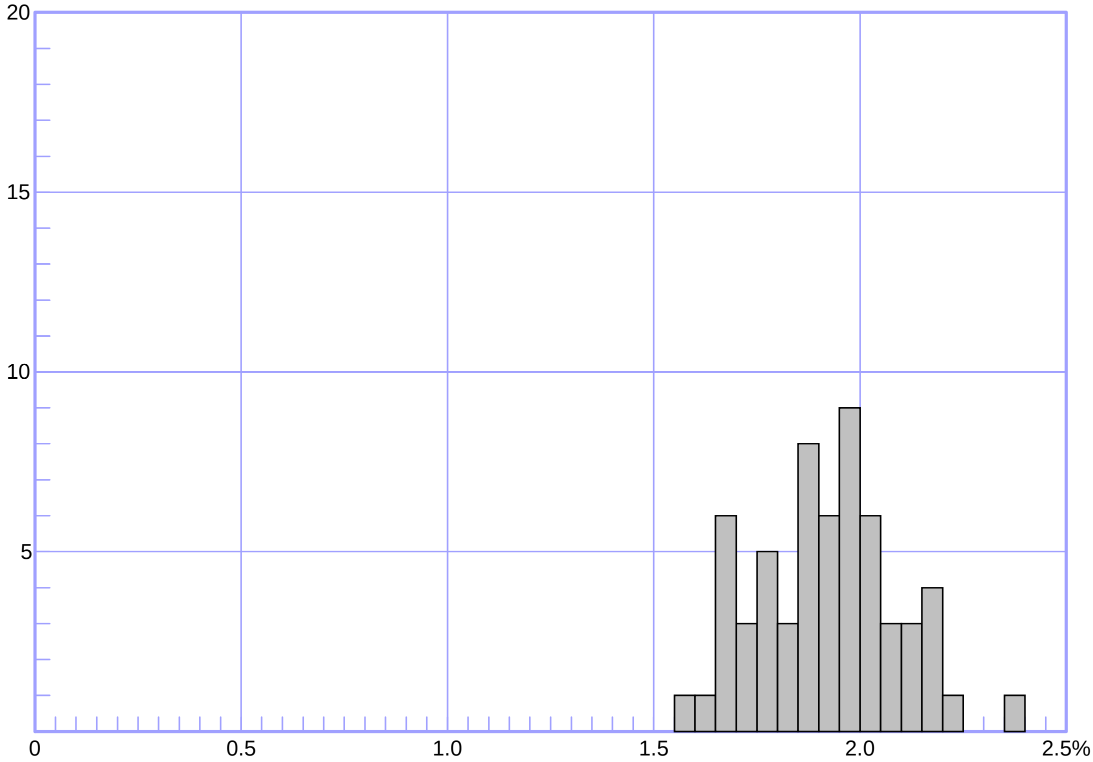
Measure count	=	63	Date	7/23/2015 10:55 AM
Reflectance Rr	=	1.778 %	Operator	cgu
s	=	0.104 %	Printed	8/4/2015

1.55 - 1.60 % R	1	1.80 - 1.85 % R	8
1.60 - 1.65 % R	5	1.85 - 1.90 % R	8
1.65 - 1.70 % R	9	1.90 - 1.95 % R	4
1.70 - 1.75 % R	9	1.95 - 2.00 % R	2
1.75 - 1.80 % R	15	2.00 - 2.05 % R	2

F=3.0.5268 D=4.80.8520

Sample : 25565

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 250 m
Material: Cuttings



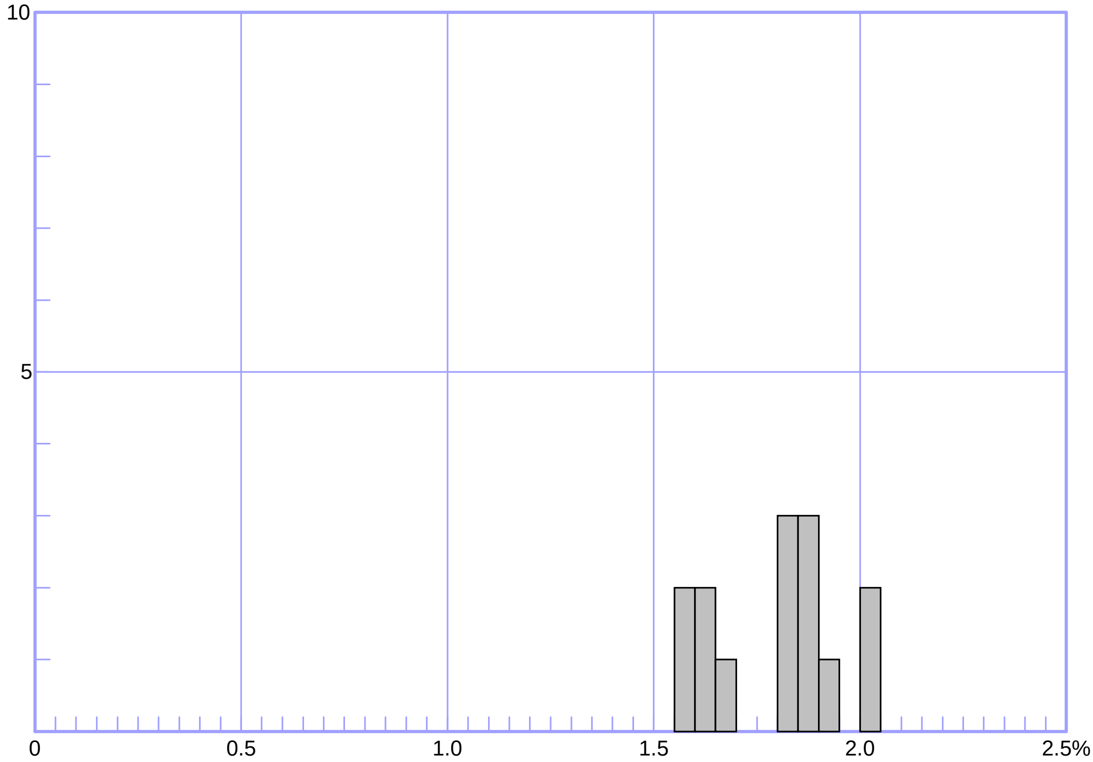
Measure count =	60		Date	10/21/2014	08:35 AM
Reflectance Rr =	1.919	%	Operator	cgu	
s =	0.168	%	Printed	10/29/2014	

1.55	-	1.60	%	R	1	1.95	-	2.00	%	R	9
1.60	-	1.65	%	R	1	2.00	-	2.05	%	R	6
1.65	-	1.70	%	R	6	2.05	-	2.10	%	R	3
1.70	-	1.75	%	R	3	2.10	-	2.15	%	R	3
1.75	-	1.80	%	R	5	2.15	-	2.20	%	R	4
1.80	-	1.85	%	R	3	2.20	-	2.25	%	R	1
1.85	-	1.90	%	R	8	2.35	-	2.40	%	R	1
1.90	-	1.95	%	R	6						

F=3.0.5268 D=4.80.8520

Sample : 25569

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 320 m
Material: Cuttings



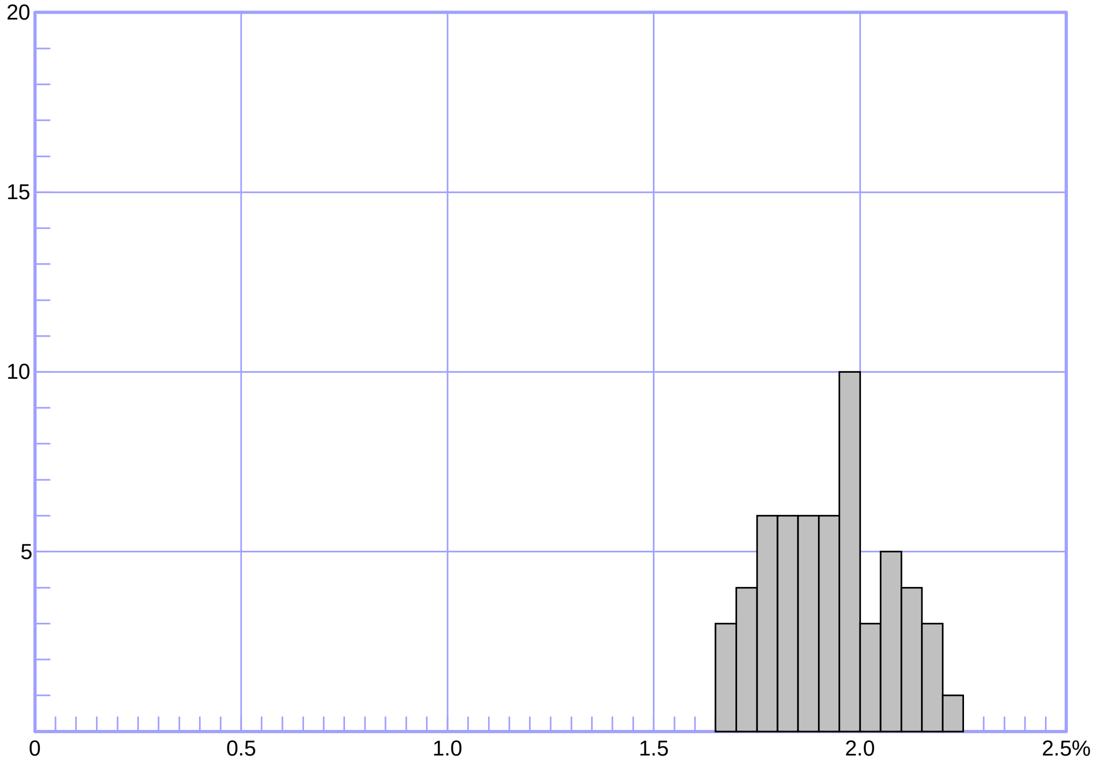
Measure count	=	14	Date	7/31/2015	08:57 AM
Reflectance Rr	=	1.796 %	Operator	cgu	
s	=	0.146 %	Printed	8/4/2015	

1.55 - 1.60	%	R	2		1.85 - 1.90	%	R	3		
1.60 - 1.65	%	R	2		1.90 - 1.95	%	R	1		
1.65 - 1.70	%	R	1		2.00 - 2.05	%	R	2		
1.80 - 1.85	%	R	3							

F=3.0.5268 D=4.80.8520

Sample : 25574

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 420 m
Material: Cuttings



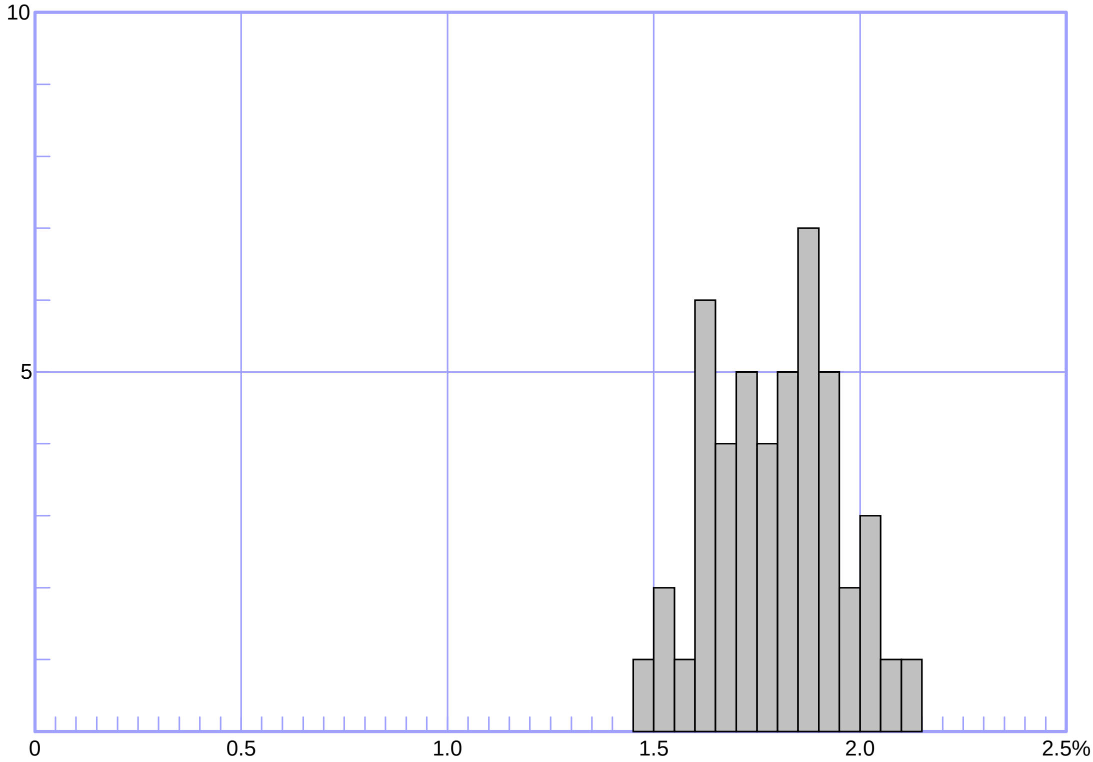
Measure count =	57		Date	10/23/2014 12:17 PM
Reflectance Rr =	1.928 %		Operator	cgu
s =	0.141 %		Printed	10/29/2014

1.65 - 1.70 % R	3	1.95 - 2.00 % R	10
1.70 - 1.75 % R	4	2.00 - 2.05 % R	3
1.75 - 1.80 % R	6	2.05 - 2.10 % R	5
1.80 - 1.85 % R	6	2.10 - 2.15 % R	4
1.85 - 1.90 % R	6	2.15 - 2.20 % R	3
1.90 - 1.95 % R	6	2.20 - 2.25 % R	1

F=3.0.5268 D=4.80.8520

Sample : 25576

Activity no: 2014019; Standard: 1.677%%
Locality: Loevestad A3-1; Depth: 460 m
Material: Cuttings



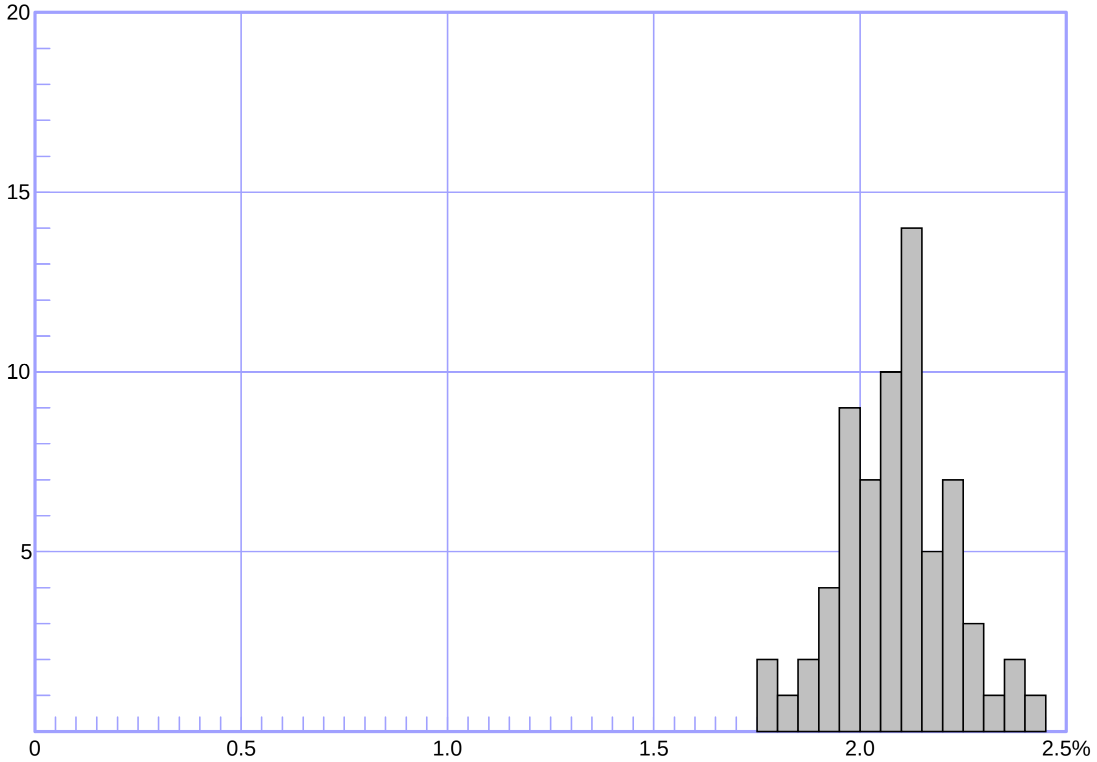
Measure count	=	47	Date	8/3/2015	08:38 AM
Reflectance Rr	=	1.792 %	Operator	cgu	
s	=	0.154 %	Printed	8/4/2015	

1.45 - 1.50	% R	1	1.80 - 1.85	% R	5
1.50 - 1.55	% R	2	1.85 - 1.90	% R	7
1.55 - 1.60	% R	1	1.90 - 1.95	% R	5
1.60 - 1.65	% R	6	1.95 - 2.00	% R	2
1.65 - 1.70	% R	4	2.00 - 2.05	% R	3
1.70 - 1.75	% R	5	2.05 - 2.10	% R	1
1.75 - 1.80	% R	4	2.10 - 2.15	% R	1

F=3.0.5268 D=4.80.8520

Sample : 25579

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 520 m
Material: Cuttings



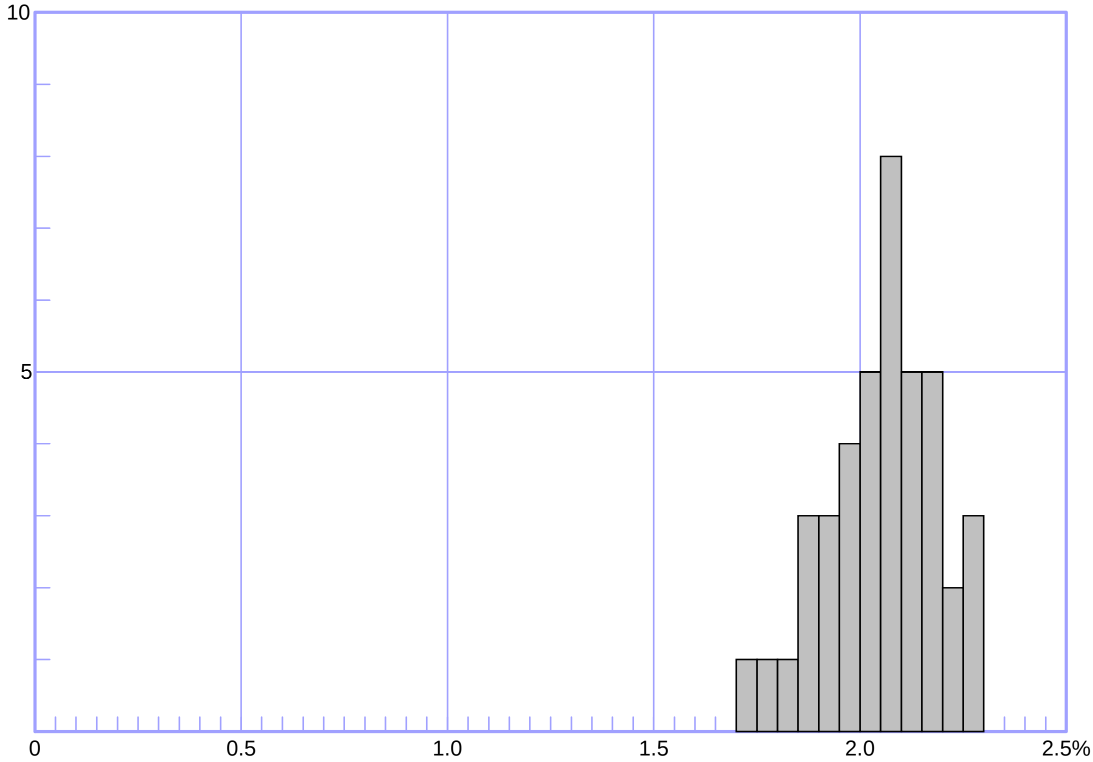
Measure count =	68		Date	10/24/2014	02:13 PM
Reflectance Rr =	2.087	%	Operator	cgu	
s =	0.134	%	Printed	10/29/2014	

1.75	-	1.80	% R	2	2.10	-	2.15	% R	14
1.80	-	1.85	% R	1	2.15	-	2.20	% R	5
1.85	-	1.90	% R	2	2.20	-	2.25	% R	7
1.90	-	1.95	% R	4	2.25	-	2.30	% R	3
1.95	-	2.00	% R	9	2.30	-	2.35	% R	1
2.00	-	2.05	% R	7	2.35	-	2.40	% R	2
2.05	-	2.10	% R	10	2.40	-	2.45	% R	1

F=3.0.5268 D=4.80.8520

Sample : 25582

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 580 m
Material: Cuttings



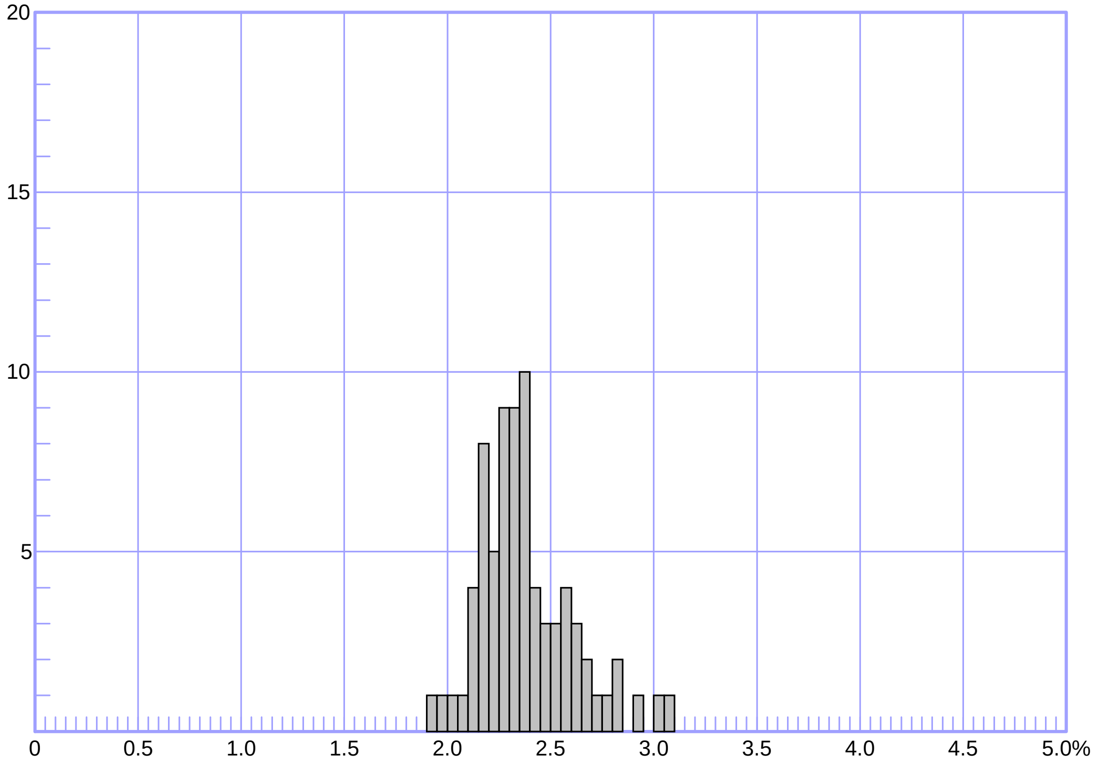
Measure count	=	41	Date	7/23/2015	04:07 PM
Reflectance Rr	=	2.052 %	Operator	cgu	
s	=	0.132 %	Printed	8/4/2015	

1.70 - 1.75	% R	1	2.00 - 2.05	% R	5
1.75 - 1.80	% R	1	2.05 - 2.10	% R	8
1.80 - 1.85	% R	1	2.10 - 2.15	% R	5
1.85 - 1.90	% R	3	2.15 - 2.20	% R	5
1.90 - 1.95	% R	3	2.20 - 2.25	% R	2
1.95 - 2.00	% R	4	2.25 - 2.30	% R	3

F=3.0.5268 D=4.80.8520

Sample : 25585

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 640 m
Material: Cuttings



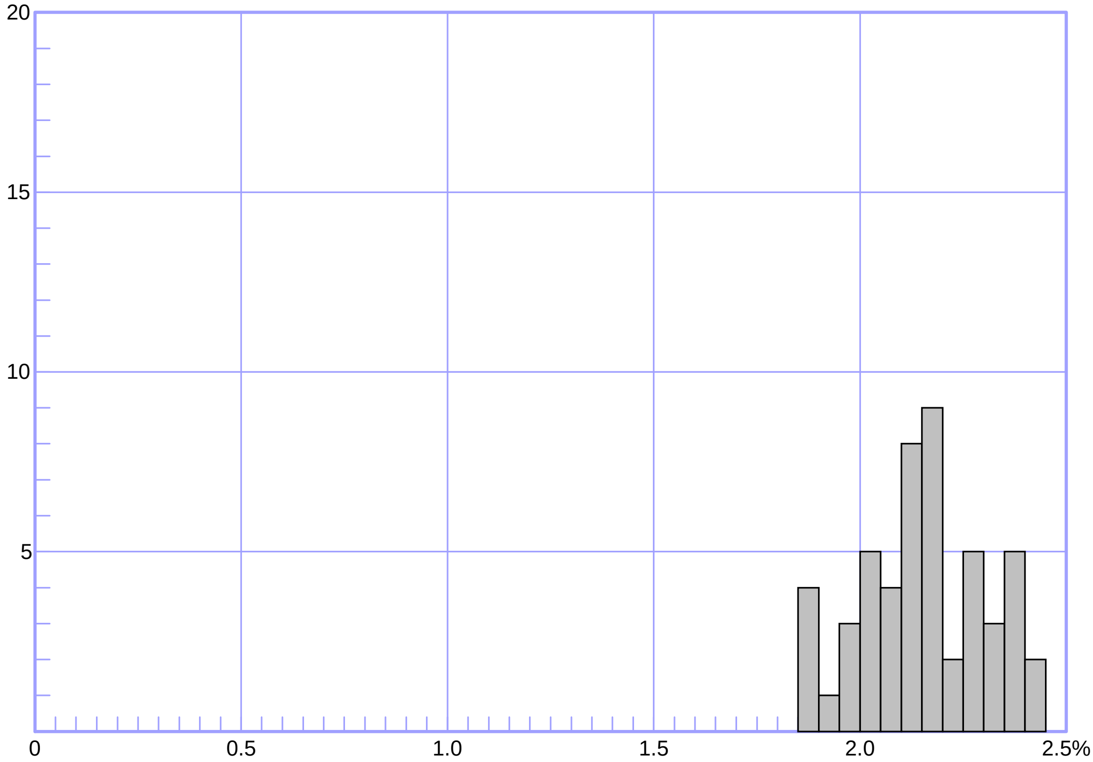
Measure count =	75		Date	10/27/2014	08:09 AM
Reflectance Rr =	2.382	%	Operator	cgu	
s =	0.226	%	Printed	10/29/2014	

1.90 - 1.95	% R	1		2.45 - 2.50	% R	3
1.95 - 2.00	% R	1		2.50 - 2.55	% R	3
2.00 - 2.05	% R	1		2.55 - 2.60	% R	4
2.05 - 2.10	% R	1		2.60 - 2.65	% R	3
2.10 - 2.15	% R	4		2.65 - 2.70	% R	2
2.15 - 2.20	% R	8		2.70 - 2.75	% R	1
2.20 - 2.25	% R	5		2.75 - 2.80	% R	1
2.25 - 2.30	% R	9		2.80 - 2.85	% R	2
2.30 - 2.35	% R	9		2.90 - 2.95	% R	1
2.35 - 2.40	% R	10		3.00 - 3.05	% R	1
2.40 - 2.45	% R	4		3.05 - 3.10	% R	1

F=3.0.5268 D=4.80.8520

Sample : 25589

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 720 m
Material: Cuttings



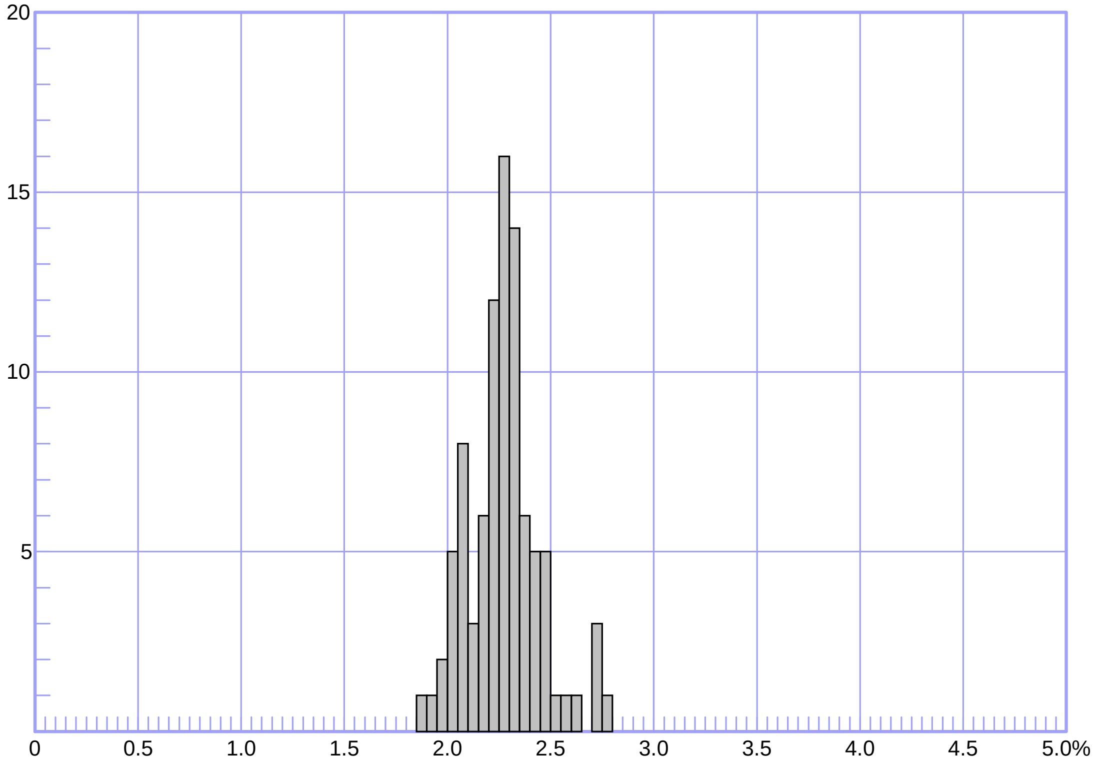
Measure count =	51		Date	7/24/2015	09:31 AM
Reflectance Rr =	2.151	%	Operator	cgu	
s =	0.149	%	Printed	8/4/2015	

1.85 - 1.90	%	R	4	2.15 - 2.20	%	R	9
1.90 - 1.95	%	R	1	2.20 - 2.25	%	R	2
1.95 - 2.00	%	R	3	2.25 - 2.30	%	R	5
2.00 - 2.05	%	R	5	2.30 - 2.35	%	R	3
2.05 - 2.10	%	R	4	2.35 - 2.40	%	R	5
2.10 - 2.15	%	R	8	2.40 - 2.45	%	R	2

F=3.0.5268 D=4.80.8520

Sample : 25593

Activity no: 2014019; Standard: 1.677%
Locality: Loevestad A3-1; Depth: 800 m
Material: Cuttings



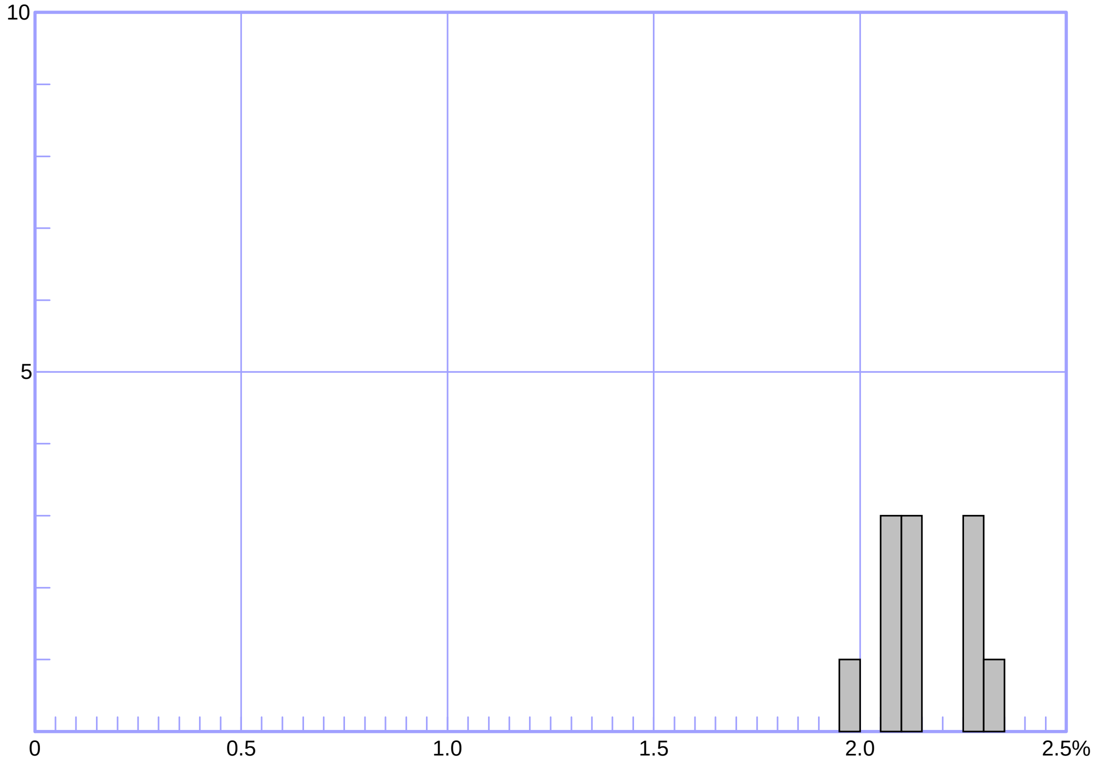
Measure count =	91		Date	10/29/2014	08:14 AM
Reflectance Rr =	2.276	%	Operator	cgu	
s =	0.175	%	Printed	10/29/2014	

1.85 - 1.90 % R	1		2.30 - 2.35 % R	14
1.90 - 1.95 % R	1		2.35 - 2.40 % R	6
1.95 - 2.00 % R	2		2.40 - 2.45 % R	5
2.00 - 2.05 % R	5		2.45 - 2.50 % R	5
2.05 - 2.10 % R	8		2.50 - 2.55 % R	1
2.10 - 2.15 % R	3		2.55 - 2.60 % R	1
2.15 - 2.20 % R	6		2.60 - 2.65 % R	1
2.20 - 2.25 % R	12		2.70 - 2.75 % R	3
2.25 - 2.30 % R	16		2.75 - 2.80 % R	1

F=3.0.5268 D=4.80.8520

Sample : 25595

Activity no: 2014019; Standard: 1.677%%
Locality: Loevestad A3-1; Depth: 839.5 m
Material: Cuttings



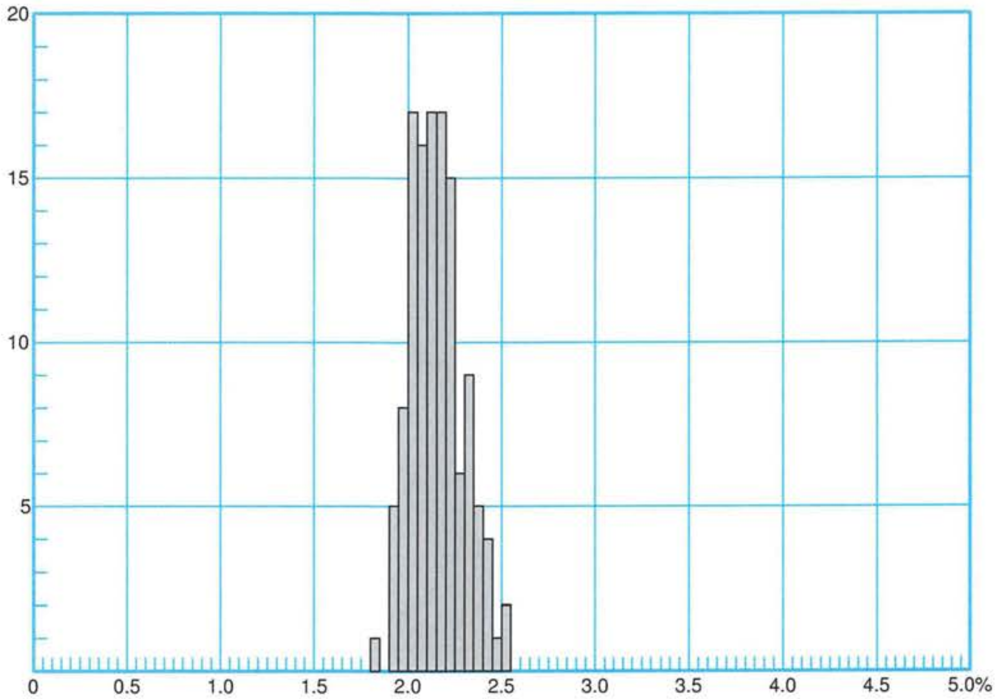
Measure count =	11		Date	7/31/2015	01:22 PM
Reflectance Rr =	2.161	%	Operator	cgu	
s =	0.106	%	Printed	8/4/2015	

1.95 - 2.00 % R	1		2.25 - 2.30 % R	3
2.05 - 2.10 % R	3		2.30 - 2.35 % R	1
2.10 - 2.15 % R	3			

F=3.0.5268 D=4.80.8520

Sample : 25790

Activity no: 2014030; Standard: 1.667%
Locality: Faageltofta--2; Depth: 22.84 - 22.85 m
Material: Core



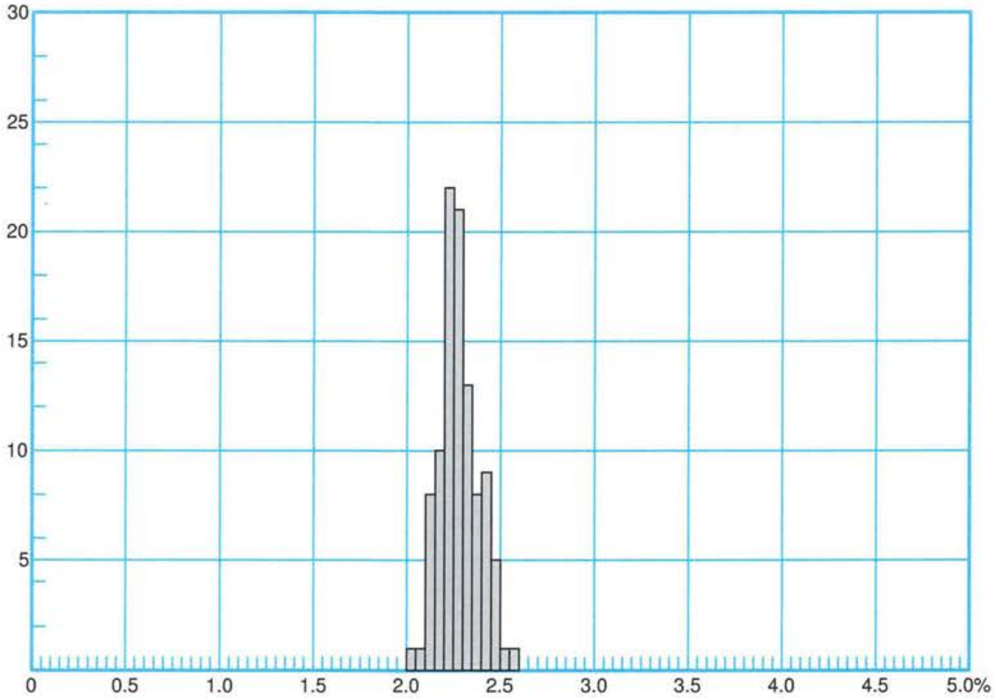
Measure count =	123	Date	11/12/2014 10:54 AM
Reflectance Rr =	2.157 %	Operator	cgu
s =	0.137 %	Printed	11/12/2014

1.80 - 1.85 % R	1	2.20 - 2.25 % R	15
1.90 - 1.95 % R	5	2.25 - 2.30 % R	6
1.95 - 2.00 % R	8	2.30 - 2.35 % R	9
2.00 - 2.05 % R	17	2.35 - 2.40 % R	5
2.05 - 2.10 % R	16	2.40 - 2.45 % R	4
2.10 - 2.15 % R	17	2.45 - 2.50 % R	1
2.15 - 2.20 % R	17	2.50 - 2.55 % R	2

F=3.0.5268 D=4.80.8520

Sample : 25791

Activity no: 2014030; Standard: 1.667%
Locality: Faageltofta--2; Depth: 98.10 - 98.11 m
Material: Core



Measure count =	100		Date	11/20/2014	08:41 AM
Reflectance Rr =	2.282 %		Operator	cgu	
s =	0.105 %		Printed	11/20/2014	

2.00 - 2.05 % R	1	2.30 - 2.35 % R	13
2.05 - 2.10 % R	1	2.35 - 2.40 % R	8
2.10 - 2.15 % R	8	2.40 - 2.45 % R	9
2.15 - 2.20 % R	10	2.45 - 2.50 % R	5
2.20 - 2.25 % R	22	2.50 - 2.55 % R	1
2.25 - 2.30 % R	21	2.55 - 2.60 % R	1

F=3.0.5268 D=4.80.8520

Appendix B: Input parameters in the basin modelling

Table B1. Heat flow models.

High Heat flow model	High Heat flow model	Low Heat Flow model	Low Heat Flow model
Age	**HF mW/m2**	**Age**	**HF mW/m2**
0.00	60.00	0.00	60.00
2.60	40.00	2.60	40.00
5.00	40.00	5.00	40.00
30.00	40.00	30.00	40.00
35.00	40.00	35.00	40.00
40.00	40.00	40.00	40.00
45.00	40.00	45.00	40.00
50.00	40.00	50.00	40.00
55.00	40.00	55.00	40.00
60.00	40.00	60.00	40.00
220.00	50.00	220.00	60.00
270.00	60.00	250.00	65.00
290.00	80.00	320.00	65.00
305.00	80.00	350.00	55.00
450.00	60.00	450.00	45.00
600.00	60.00	600.00	45.00

Table B2. Water depth model.

Age	Water Depth
0.00	56
2.60	0
23.00	300
60.00	200
99.60	100
138.00	50
143.00	50
154.00	50
168.00	0
179.00	100
185.00	100
189.00	100
193.00	100
201.00	100
210.00	0
260.00	0
380.00	0
436.00	200
440.00	200
442.00	200
443.00	200
444.00	200
445.00	200
457.00	200
470.00	200
479.00	200
480.00	200
520.00	50

Table B3. Water temperature model.

Age	Sea-water temperature
0.00	5.00
2.60	6.92
23.00	14.42
60.00	18.78
99.60	23.35
138.00	23.64
143.00	23.15
154.00	22.06
168.00	21.43
179.00	18.00
185.00	18.00
189.00	18.00
193.00	18.00
201.00	18.89
210.00	22.44
260.00	24.38
380.00	25.00
436.00	22.00
440.00	15.00
442.00	15.00
443.00	15.00
444.00	15.00
445.00	15.00
457.00	15.00
470.00	15.00
479.00	15.00
480.00	12.00
520.00	10.00
600.00	10.00

Table B4. Terne-1 burial model.

Formation Name	Formation Top [m]	Formation Base [m]	Formation Thickness [m]	Erosion [m]	Formation Age From [Ma]	Formation Age To [Ma]	Erosion Age From [Ma]	Erosion Age To [Ma]
Quaternary	56,0	109,0	53,0		0.10	0.00		
Quaternary Ice	109,0	109,0	0,0	800	1.80	0.20	0.20	0.10
Pliocene	109,0	109,0	0,0	50	5.30	2.00	2.00	1.80
Miocene	109,0	109,0	0,0	50	11.60	6.00	6.00	5.30
Oligocene	109,0	109,0	0,0	100	33.90	23.00	23.00	20.00
Eocene	109,0	109,0	0,0	300	56.00	33.90	20.00	16.00
Palaeocene	109,0	109,0	0,0	300	61.60	56.00	16.00	11.60
Chalk Group	109,0	109,0	0,0		100.50	61.60		
Rødby Fm	109,0	109,0	0,0		113.00	100.50		
Vedsted Fm	109,0	154,0	45,0		139.40	113.00		
Frederikshavn Fm	154,0	412,0	258,0		152.00	139.40		
Børglund Fm	412,0	420,0	8,0		157.30	152.00		
Flybjerg Fm	420,0	457,0	37,0		163.50	157.30		
Haldager Sand Fm	457,0	630,0	173,0	500	170.30	169.00	169.00	163.50
Fjerritslev Fm-IV	630,0	702,0	72,0		182.70	170.30		
Fjerritslev Fm-III	702,0	858,0	156,0		190.80	182.70		
Fjerritslev Fm-II	858	900,0	42,0		199.30	190.80		
Fjerritslev Fm-I	900	966,0	66,0		204.00	199.30		
Gassum Fm	966,0	1292	326,0		209.50	204.00		
Skagerrak Fm	1292,0	2253	961,0		252.20	209.50		
Zechstein Fm	2253,0	2313	60,0		259.80	252.20		
Rotliegend Group	2313,0	2313	0,0		298.90	259.80		
Silurian-Dev-Carb units	2313,0	2756,0	443,0	Modelled	433.40	419.00	350.00	298.90
Llandovery F5 unit	2756,0	2813,0	57,0		435.00	433.40		
Llandovery F4 unit	2813,0	2858,0	45,0		438.00	435.00		
Llandovery F3 unit	2858,0	2938,0	80,0		440.00	438.00		
Llandovery F2 unit	2938,0	2958,0	20,0		442.00	440.00		
Llandovery F1 unit	2958,0	2982,0	24,0		445.00	442.00		
Lindegård	2982	3024	42		457.00	445.00		
Dicellograptus	3024	3088	64		470.00	457.00		
Almelund	3088	3123	35		479.00	470.00		
Tøyen	3123	3172	49		480.00	479.00		
Alum Shale	3172	3352	180		508.00	480.00		
Hardeberga	3352	3500	148		520.00	508.00		

Table B5. Slagelse-1 burial model.

Formation Name	Formation		Formation		Formation Age		Erosion Age	
	Top [m]	Base [m]	Thickness [m]	Erosion [m]	From [Ma]	To [Ma]	From [Ma]	To [Ma]
Quaternary	56	109	53		0.10	0.00		
Quaternary Ice	109	109	0	800	1.80	0.20	0.20	0.10
Pliocene	109	109	0	50	5.30	2.00	2.00	1.80
Miocene	109	109	0	50	11.60	6.00	6.00	5.30
Oligocene	109	109	0	100	33.90	23.00	23.00	20.00
Eocene	109	109	0	300	56.00	33.90	20.00	16.00
Palaeocene	109	260	151	300	61.60	56.00	16.00	11.60
Chalk Group	260	963	703		100.50	61.60		
Rødby Fm	963	963	0		113.00	100.50		
Vedsted Fm	963	963	0		139.40	113.00		
Frederikshavn Fm	963	963	0		152.00	139.40		
Børglund Fm	963	963	0		157.30	152.00		
Flybjerg Fm	963	963	0		163.50	157.30		
Haldager Sand Fm	963	963	0	500	170.30	169.00	169.00	163.50
Fjerritslev Fm-IV	963	963	0		182.70	170.30		
Fjerritslev Fm-III	963	963	0		190.80	182.70		
Fjerritslev Fm-II	963	963	0		199.30	190.80		
Fjerritslev Fm-I	963	1140	177		204.00	199.30		
Gassum Fm	1140	1277	137		209.50	204.00		
Skagerrak Fm	1277	2247	970		252.20	209.50		
Zechstein Fm	2247	2619	372		259.80	252.20		
Rotliegend Group	2619	2625	6		298.90	259.80		
Silurian-Dev-Carb units	2625	2870	245	Modelled	433.40	419.00	350.00	298.90
Llandovery F5 unit	2870	2880	10		435.00	433.40		
Llandovery F4 unit	2880	2890	10		438.00	435.00		
Llandovery F3 unit	2890	2903	13		440.00	438.00		
Llandovery F2 unit	2903	2903	0		442.00	440.00		
Llandovery F1 unit	2903	2903	0		445.00	442.00		
Lindegård	2903	2920	17		457.00	445.00		
Dicellograptus	2920	2920	0		470.00	457.00		
Almelund	2920	2920	0		479.00	470.00		
Tøyen	2920	2920	0		480.00	479.00		
Alum Shale	2920	2957	37		508.00	480.00		
Gislöv	2957	2969	12		512.00	508.00		
Hardeberga	2969	3000	31		520.00	512.00		

Table B6. Lövestad A3-1 burial model.

Formation Name	Formation Top [m]	Formation Base [m]	Formation Thickness [m]	Formation Erosion [m]	Formation Age From [Ma]	Formation Age To [Ma]	Erosion Age From [Ma]	Erosion Age To [Ma]
Quaternary	56	58	2		0.10	0.00		
Quaternary Ice	58	58	0	800	1.80	0.20	0.20	0.10
Pliocene	58	58	0	50	5.30	2.00	2.00	1.80
Miocene	58	58	0	50	11.60	6.00	6.00	5.30
Oligocene	58	58	0	100	33.90	23.00	23.00	20.00
Eocene	58	58	0	300	56.00	33.90	20.00	16.00
Palaeocene	58	58	0	300	61.60	56.00	16.00	11.60
Chalk Group	58	58	0		100.50	61.60		
Rødby Fm	58	58	0		113.00	100.50		
Vedsted Fm	58	58	0		139.40	113.00		
Frederikshavn Fm	58	58	0		152.00	139.40		
Børglund Fm	58	58	0		157.30	152.00		
Flybjerg Fm	58	58	0		163.50	157.30		
Haldager Sand Fm	58	58	0	500	170.30	169.00	169.00	163.50
Fjerritslev Fm-IV	58	58	0		182.70	170.30		
Fjerritslev Fm-III	58	58	0		190.80	182.70		
Fjerritslev Fm-II	58	58	0		199.30	190.80		
Fjerritslev Fm-I	58	58	0		204.00	199.30		
Gassum Fm	58	58	0		209.50	204.00		
Skagerrak Fm	58	58	0		252.20	209.50		
Zechstein Fm	58	58	0		259.80	252.20		
Rotliegend Group	58	58	0		298.90	259.80		
Silurian Units	58	750	692	Modelled	433.40	419.00	350.00	298.90
Llandovery F5 unit	750	760	10		435.00	433.40		
Llandovery F4 unit	760	765	5		438.00	435.00		
Llandovery F3 unit	765	770	5		440.00	438.00		
Llandovery F2 unit	770	777	7		442.00	440.00		
Llandovery F1 unit	777	780	3		445.00	442.00		
Lindegård	780	786	6		457.00	445.00		
Dicellograptus	786	803	17		470.00	457.00		
Almelund	803	817	14		479.00	470.00		
Tøyen	817	843	26		480.00	479.00		
Alum Shale	843	946	103		508.00	480.00		
Gislöv	946	955	9		512.00	508.00		
Hardeberga	955	986	31		520.00	512.00		