Chapter 6

Thermal maturity

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Two of the aims of the 'Nordolie' project were to investigate the thermal maturity pattern of potential source rocks in North Greenland and to provide information on the thermal history of the basin.

Organic diagenesis of source rocks is a function of the burial and thermal history of a basin with the two most important factors being temperature and time. In the present study a multidisciplinary approach has been applied to the maturity concept and a large number of different maturity parameters with varying sensitivities have been combined. Each sedimentary basin in the world has its own unique thermal history which is expressed by the maturity parameters. Consequently it is important to establish the local empirical relations between the various parameters and especially in oil-related studies to deduce parameters corresponding to the possible onset of both oil generation and oil cracking, in other words to define 'the oil window'.

In Lower Palaeozoic basins a number of particular problems arise due to their age. The history of such old basins is often complicated to unravel. This is also true in central North Greenland where no post-Silurian deposits have been preserved (see Chapter 2). The lack of plant material in the early stages of evolution inhibits the use of the universal maturity parameters such as vitrinite reflectance (e.g. Tissot & Welte, 1984) and spore coloration (Staplin, 1969) and instead less reliable reflectance measurements are carried out on amorphous kerogen and bitumen; the Thermal Alteration Index (TAI) is determined from the colour of amorphous kerogen. On the other hand the limited variation in composition of the organic matter (dominance of Type II kerogen) is an advantage in the interpretation of geochemical maturity parameters, especially the T_{max} of the Rock Eval pyrolysis and the parameters derived from high molecular weight cyclic biomarkers.

Thermal maturity mapping of most sedimentary basins, especially petroliferous, starts as a one-dimensional study (single well data) and expands to two-dimensional (few wells projected onto cross-sections) or even three-dimensional studies (control from numerous wells). In all cases an expected down-hole increase in maturity facilitates interpretation; the main problem is the variation in type of organic matter with depth, i. e. comparison of parameters measured on different materials. In North Greenland the basin is deeply eroded and well exposed but there are no wells. No details were known on maturity gradients prior to sampling although an increase towards the north was expected due to the position of the metamorphic belt.

The maturity study presented below is essentially two-dimensional, the present-day surface being projected into a horizontal plane. This broad simplification seems valid although the terrain is rough; only minor variations of maturity with altitude have been observed (see a following section).

The maturity mapping concerns the outcropping organic-rich units. An attempt to predict the maturity spatially for any given unit has been made. In this context the thick organic-lean sequences are problematic, especially the shallow-water carbonates towards the south and the turbidite sandstones towards the north. The only applicable maturity parameters in such sediments are the Conodont Alteration Index (Epstein *et al.*, 1977) and X-ray diffraction data on clay minerals (e.g. Foscolos *et al.*, 1976). Both parameters provide little specific data on petroleum generation and destruction and provide no reliable input data for thermal modelling, although various authors have tried to correlate them to other, better established indicators (Heroux *et al.*, 1979; Bustin *et al.*, 1985a).

Measured maturity parameters

The analytical programme including details on sample preparation and laboratory techniques is described in Chapter 3. Most of the measured parameters are based on physical and chemical properties of the residual kerogen or its generation products, hydrocarbons (bitumen).

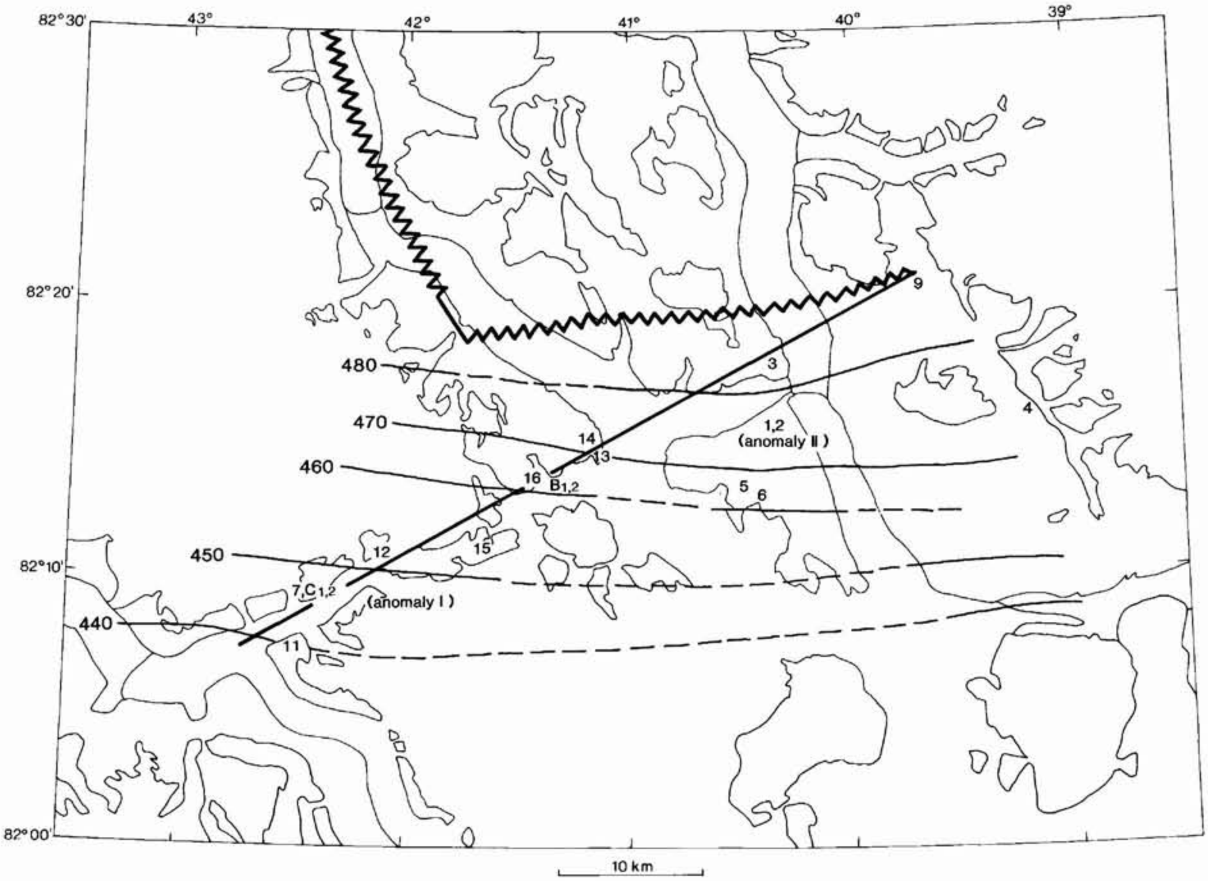


Fig. 25. Maturity map of the area where the Henson Gletscher Formation is exposed. The iso-T_{max} lines are taken from Christiansen *et al.* (1987), the line corresponds to the maturity profile shown in fig. 36.

For screening purposes a combination of Rock Eval pyrolysis (T_{max}) and palynological studies (TAI) has been applied. Preliminary results covering most of the region were published by Christiansen *et al.* (1985) and these were followed by more detailed studies on the Cambrian and Silurian source rocks (Christiansen *et al.*, 1987; Christiansen & Nøhr-Hansen, 1989).

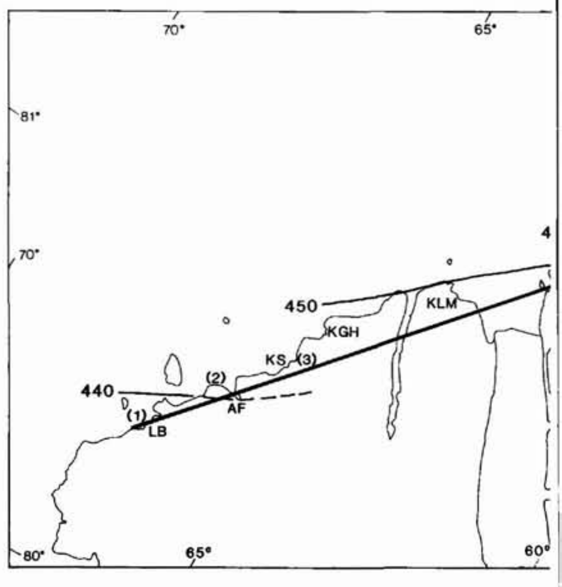
A number of other maturity parameters have subsequently been included in the study, generally determined on a much smaller number of samples, but employing more sophisticated techniques. Gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS) provide several maturity parameters both from extraction data and from specific molecular compounds. Coal petrographic methods on polished samples give reflectance and in rare cases fluorescence values for both kerogen and bitumen. In addition graptolite reflectance studies have been carried out. Finally a number of less commonly used methods such as X-ray diffraction of kerogen ('kerogen crystallinity') were applied at a later stage.

In the following the different parameters obtained are presented regionally method by method. This is followed by considerations of thermal maturity parameters and the boundaries of the oil window. The interdependence of the various parameters, both regionally (composite maps and profiles) and sample by sample (cross plots), is discussed in a succeeding section. Finally, the few local thermal anomalies are described and the limited data available from Peary Land are reviewed.

Rock Eval pyrolysis: T_{max}

Rock Eval pyrolysis is the most widely applied technique in this maturity study. More than 600 samples were analysed providing more than 260 reliable T_{max} values. All pyrogrammes were inspected visually, whereupon a number of T_{max} values were excluded from

Fig. 26. Maturity map of central and western North Greenland, based mainly on data for the Silurian from Christiansen & Nøhr-Hansen (1989). The line in Washington Land corresponds to the maturity profile shown in fig. 37, the numbers in brackets refer to the rank in maturity in the composite maturity profile in fig. 38.



further consideration. Samples with small S2 values (< 0.2 mg HC/g rock) were omitted; only values from visually well defined S2 peaks were included (see fig. 10). Bitumen-stained samples were also excluded; these were typically recognized by high S1/TOC and S1/S2 ratios, skewness of S2 peaks towards the S1 peak and overlap between S1 and S2 peaks (see fig. 10). Generally these bitumen-stained samples exhibit anomalously low T_{max} values which are not representative of the thermal maturity.

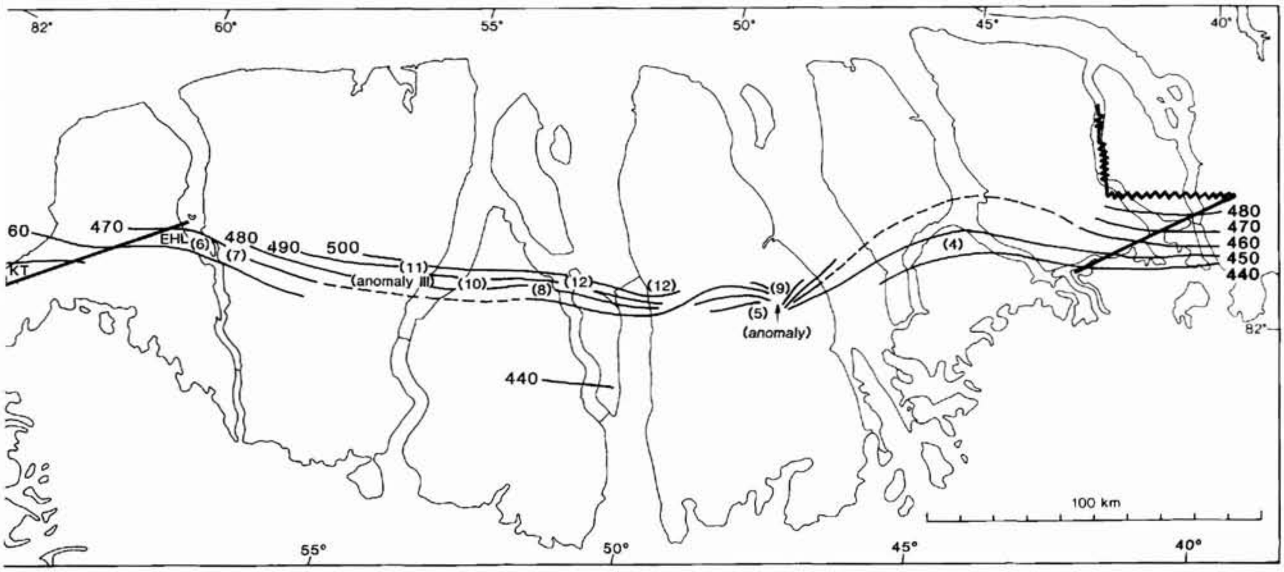
Usually there is only minor variation of T_{max} values within individual cores, sections or smaller areas. For T_{max} values < 440°C a scatter of ± 5° is typical; for values ~ 450°C a variation of ± 10° is commonly observed, and the variation increases for poorly defined T_{max} values above 470°C (see e.g. figs 35–39). These variations are small compared to most Mesozoic basins, and would be much smaller if only the most organic-rich samples were considered (e.g. TOC > 2%). The constant Type II kerogen composition prior to subsidence and thermal alteration (see Chapter 5; Christiansen & Nøhr-Hansen, 1989) can be expected to reduce the variation compared to regions with lacustrine (mainly Type I kerogen) or terrestrially dominated (mainly Type III kerogen) deposits.

As a consequence it is possible to utilize T_{max} average values in the preparation of thermal maturity maps, typically calculated for single sections or smaller areas. Two examples are shown in figs 25 and 26, one including the area where the Henson Gletscher Formation is exposed, the other covering the whole region. The tentatively drawn iso-T_{max} lines clearly define a distinct thermal maturity trend with a strong gradient from south to north.

The maturity map for the Cambrian source rocks is relatively detailed and the calculated values are typically spaced at intervals of 5 to 10 km. Due to the systematic increase in maturity from south to north contouring the T_{max} values is easy. The iso-T_{max} lines are closely spaced; the distance from the 440° ('early mature') to the 460° ('end of generation') is only 8 to 12 km, and from 440° to 500° (no hydrocarbons preserved at all) about 25 km (fig. 25). The map of the whole region is based mainly on values from the Silurian shales (fig. 26). In this case the values are more scattered with typical distances between 10 and 30 km. Contouring the data is difficult, and the result is probably not as accurate as the Cambrian map, since the iso-lines have the same trend as the strike of the exposed Silurian shales. The distance between iso-lines increases towards the west and south, especially for the early mature to mature areas in Hall Land and Washington Land (fig. 26).

Thermal Alteration Index (TAI)

Measurements of the Thermal Alteration Index (TAI) were widely applied for screening purposes in combination with Rock Eval analyses (Christiansen *et al.*, 1985, 1987; Christiansen & Nøhr-Hansen, 1989). In order to obtain consistent results the samples were all examined by one person (HN-H) using constant microscope conditions. The TAI value was visually evaluated from the colour of the rim of the relatively large amorphous kerogen particles using a scale from 1 to 5 with a



± subdivision (Staplin, 1969; Burgess 1974; Dow, 1977). Selected examples with a progressive coloration are shown in Plate 5. Increase in thermal alteration not only changes the colour of the kerogen but also the structure. Immature to early mature kerogen which has expelled only minor amounts of hydrocarbons has a fluffy structure (not illustrated), mature kerogen has a granular to flaky appearance (Plate 6 A) whereas post-mature amorphous kerogen has a more spongy character (Plate 6 B). Newly generated bitumen was also observed in the palynological slides. It occurs typically as angular particles reflecting the crystal faces of pores or as fine stringers (see Chapter 7 and Plate 10). The bitumen often has a paler colour than the associated kerogen and was therefore avoided in TAI determinations.

The TAI values are fairly constant within single cores or smaller areas, typically with one or two, occasionally three, dominating values (e.g. 2^+, $2^+ - (3^-)$ or $(2^+) - (-3^-) -3$) (figs 35–38; Christiansen *et al.*, 1985, fig. 5; Christiansen & Nøhr-Hansen, 1989, fig. 6). Hence it has been possible to prepare TAI maps with tentatively drawn iso-TAI lines for the Cambrian Henson Gletscher Formation (Christiansen *et al.*, 1987) and for the Silurian shales (Christiansen & Nøhr-Hansen, 1989). Both maps are in good agreement with maps of T_{max} confirming the distinct trend with rapidly increasing maturity from south to north (see also the profiles in figs 35 to 38).

Gas chromatography and gas chromatography/mass spectrometry

GC and GC/MS analyses provide a number of maturity parameters, both from extraction data and from specific molecular compounds. Furthermore evaluation of gas chromatograms may, at least qualitatively, support interpretation of the thermal maturity. The analytical programme included investigations of both extracts of shale and lime mudstones (source rocks) ($n > 25$) and of migrated bitumens ($n > 25$). The source rock data are easily applied in the thermal maturity study whereas the bitumen data should be treated with caution as they represent not only the thermal history of source rocks prior to expulsion but also the post-migrational history of the reservoir.

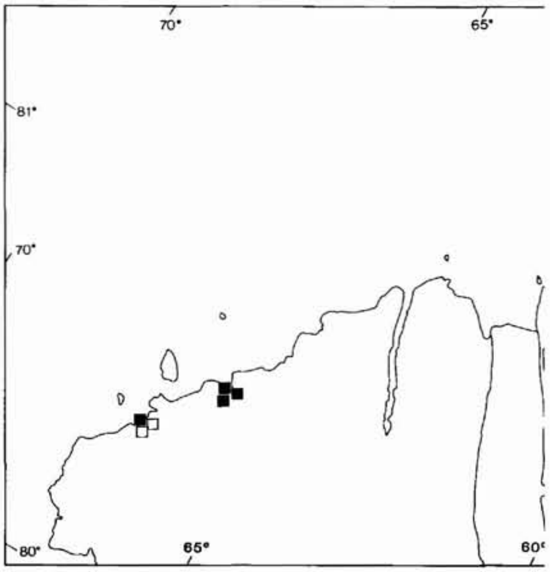
The analysed samples are divided into three main catagories according to maturity (fig. 27):

1) Samples with very low extractabilities; almost all of the original hydrocarbons are cracked to carbon and methane. These samples occur in the postmature zone where the T_{max} is higher than 480°C or not defined.

2) Samples with low to high extractability but without any preserved high molecular weight cyclic biomarkers such as steranes and hopanes. These samples are from the mature to postmature zone with corresponding T_{max} values between 440°C and 480°C.

3) Samples with high extractabilities and with cyclic biomarkers present. They only occur in early mature areas south of the 440°C iso-T_{max} line.

Fig. 27. Map of central and western North Greenland showing regional variation of maturity parameters derived from the GC and GC/MS methods.



The first category is not considered further. The data from the second category are additionally supported by the gas chromatograms which show that the saturates are highly paraffinic with a pronounced light-end bias (Østfeldt, 1987b). This suggests a high maturity, probably ranging from peak generation to post generation. The samples cannot, however, be ranked in detail using this method only. The third group is also dominated by paraffins, extending up to C_{35}, and with some light-end bias towards light hydrocarbons. The presence of cyclic biomarkers allows the thermal maturity and history of these early mature samples to be determined in detail, employing isomerization ratios of steranes and hopanes.

Four ratios, all rising with increasing thermal maturity, were applied (fig. 28; see review by Mackenzie, 1984, and analytical details by Østfeldt, 1987a,b, and in Chapter 3).

C_{31} and C_{32} hopanes were measured for the 22R to 22R + 22S conversion both of which reach equilibrium values of 0.6 at pre- to early oil window maturity. Both Washington Land source rocks and bitumen and also the migrated bitumens from southern Warming Land and Wulff Land have reached these values (fig. 28). C_{29} steranes were measured for the 20R to 20R + 20S conversion. The equilibrium value of approximately 0.5 is reached just before peak generation. Such values were obtained in southern Warming Land and Wulff Land whereas the Washington Land samples display slightly lower values (fig. 28). The $\beta\beta/\alpha\alpha + \beta\beta$ ratio reaches equilibrium late in the oil window with a value of about 0.63 using the present technique. It is questionable whether any of the samples have reached equilibrium; especially the values for the samples from Warming Land and Wulff Land are rather scattered (fig. 28), probably due to biodegradational effects (see Chapter 7).

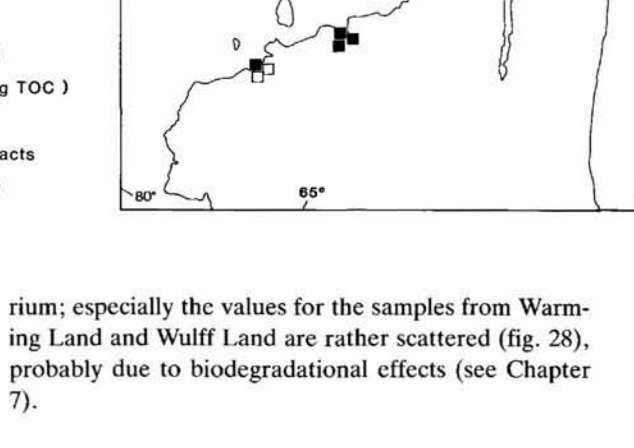
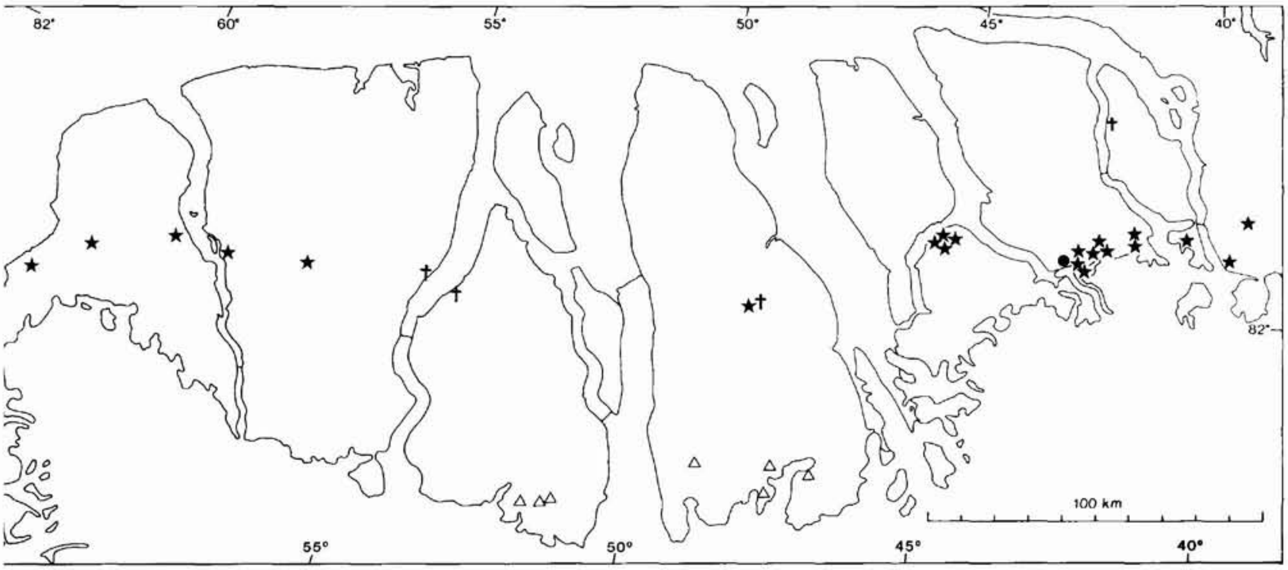


Fig. 28. Thermal maturity parameters based on isomerization of steranes and hopanes. (A) Empirical relations between measured values, equilibrium values and oil generation. Based on Mackenzie (1984) and Østfeldt (1987a). (B) Measured values from Washington Land (filled squares: source rock extracts; open squares: bitumen) and southern Warming Land and Wulff Land (open triangles: bitumen).



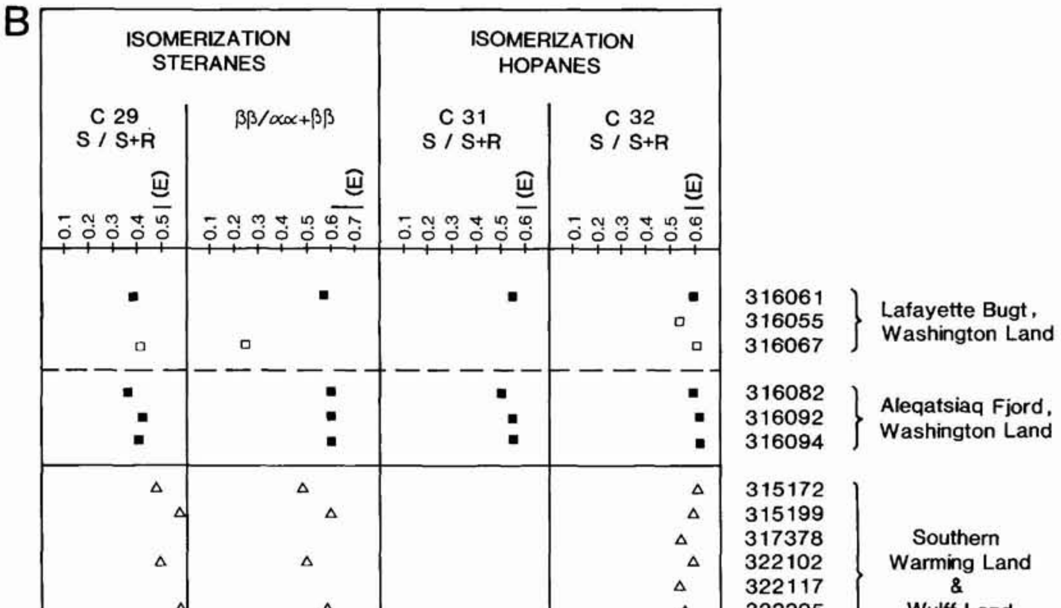
Organic petrological parameters

Organic petrological investigations of samples from North Greenland have been carried out in order to:

1) support the thermal maturity mapping based on screening methods (T_{max} and TAI) with reflectance measurements on kerogen and indigenous bitumen (R_o^k, R_o^{kb}, R_o^b), especially in the area where the Cambrian Henson Gletscher Formation is exposed;

2) study the migrated bitumens, both in order to use bitumen reflectance (R_o^B) in the maturity study (this chapter) and for a general discussion of the migration and diagenesis history (Chapter 7);

3) use fluorescence measurements as maturity indicators in these Early Palaeozoic sediments where most



other organic petrological parameters are rather difficult to apply;

4) calibrate the until now little applied maturity parameter based on graptolite reflectance ($R_{max}{}^G$, or alternatively $R_r{}^G$ or $R_{min}{}^G$) with other parameters.

Details are provided by Stouge *et al.* (1988) and Thomsen & Guvad (1987).

Due to lack of vitrinite *sensu stricto* in the Early Palaeozoic, the reflectance studies were restricted to kerogen and its maturation products, indigenous bitumen in the source rocks or migrated bitumen. Previous examples of reflectance measurements in Lower Palaeozoic sediments with relevance to the present work include studies of bitumen (Robert, 1974; Sikander & Pittion, 1978; Ogunyami *et al.*, 1980), graptolites and other zooclasts (e.g. Goodarzi *et al.*, 1985; Goodarzi & Norford, 1985; Bertrand & Heroux, 1987) and 'vitrinite-like compounds' in the kerogen (e.g. Kisch, 1980; Buchardt *et al.*, 1986).

The studied kerogen from North Greenland is amorphous (Type II) and derived from marine algae (Chapters 4 and 5). In terms of organic constituents it is dominated by the liptinite maceral group (Gutjahr, 1983). However, some stringers of vitrinitic type of organic matter are also observed. Measurements were carried out mainly on these stringers ($R_o{}^k$) and on the generated bitumen ($R_o{}^b$), in many cases, especially at higher maturities, with a common population ($R_o{}^{kb}$). Reflectance of migrated bitumen ($R_o{}^B$) may also be applied as a maturity parameter, and a linear relation between reflectance of true vitrinite and solid bitumen has been suggested (Jacob, 1985).

The reflectance values from the Cambrian sequence in Freuchen Land support the maturity trend outlined by screening methods (figs 29, 30 and 36). The values are, however, rather scattered making ranking based on single samples questionable. The reflectance of kerogen and migrated bitumen ($R_o{}^k$, ($R_o{}^{kb}$), $R_o{}^B$) seems to follow the same trend with a general increase from $R_o \sim 0.75\%$

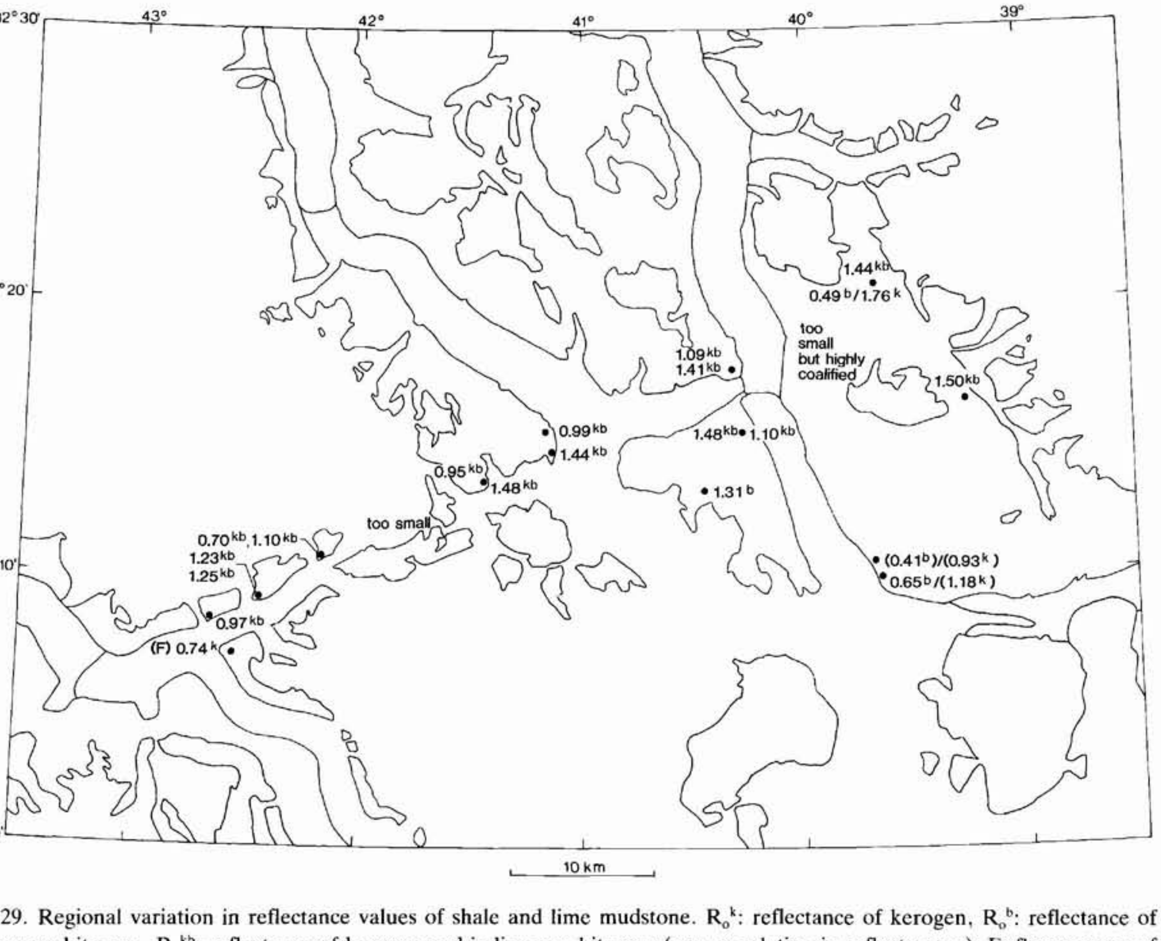


Fig. 29. Regional variation in reflectance values of shale and lime mudstone. $R_o{}^k$: reflectance of kerogen, $R_o{}^b$: reflectance of indigenous bitumen, $R_o{}^{kb}$: reflectance of kerogen and indigenous bitumen (one population in reflectogram); F: fluorescence of kerogen or indigenous bitumen.

($T_{max} < 440$°C) in the southern part to $R_o \sim 1.75\%$ in the northern part of the area ($T_{max} > 500$°C) (figs 29 and 30). In contrast indigenous bitumen (R_o^b, (R_o^{kb})) often shows rather low values, even in highly mature areas, pointing towards a limited new generation of hydrocarbons late in the subsidence history.

In the remaining region a similar strong south to north gradient is supported by the reflectance values. All the samples from southern Warming Land and Wulff Land ($T_{max} < 440$°C) have R_o^B values in the range 0.1 to 0.5%. Also the Washington Land samples ($T_{max} <$ 445°C) have low reflectance values with R_o^B from 0.15 to 0.6% and R_o^k, R_o^b and R_o^{kb} between 0.5 and 0.9% (figs 31, 32, 36, 37 and 38). In the mature to postmature areas in Nares Land, Wulff Land and Nyeboe Land significantly higher reflectance values have been recorded (figs 31 and 32).

Fluorescence of bitumen and liptinitic kerogen has only been reported from a limited number of samples, and systematic measurements of λ-max and Q values have only been carried out on bitumen samples from Washington Land, southern Freuchen Land and Nares Land (see details in Thomsen & Guvad, 1987).

Measurements of graptolite reflectance on a number of samples of Silurian shale with a regional distribution and a few Ordovician shales from the northern folded part of the region are included in the study.

Two of the measured parameters, $R_{max}{}^G$ (maximum reflectance) and $R_r{}^G$ (random reflectance), seem applicable in the regional maturity mapping and support the previously mentioned increase in maturity from south to north (fig. 33).

The lowest values are recorded from Washington Land ($R_r{}^G < 0.77\%$, $R_{max}{}^G < 0.87\%$), followed by southern Nares Land and southern Hall Land (fig. 33). The Silurian shales in the region between show higher, but relatively constant values. The few samples from the folded northern part of the region yield very high values of graptolite reflectance ($R_r{}^G$: 4.34–7.24%, $R_{max}{}^G$: 8.39–9.03%).

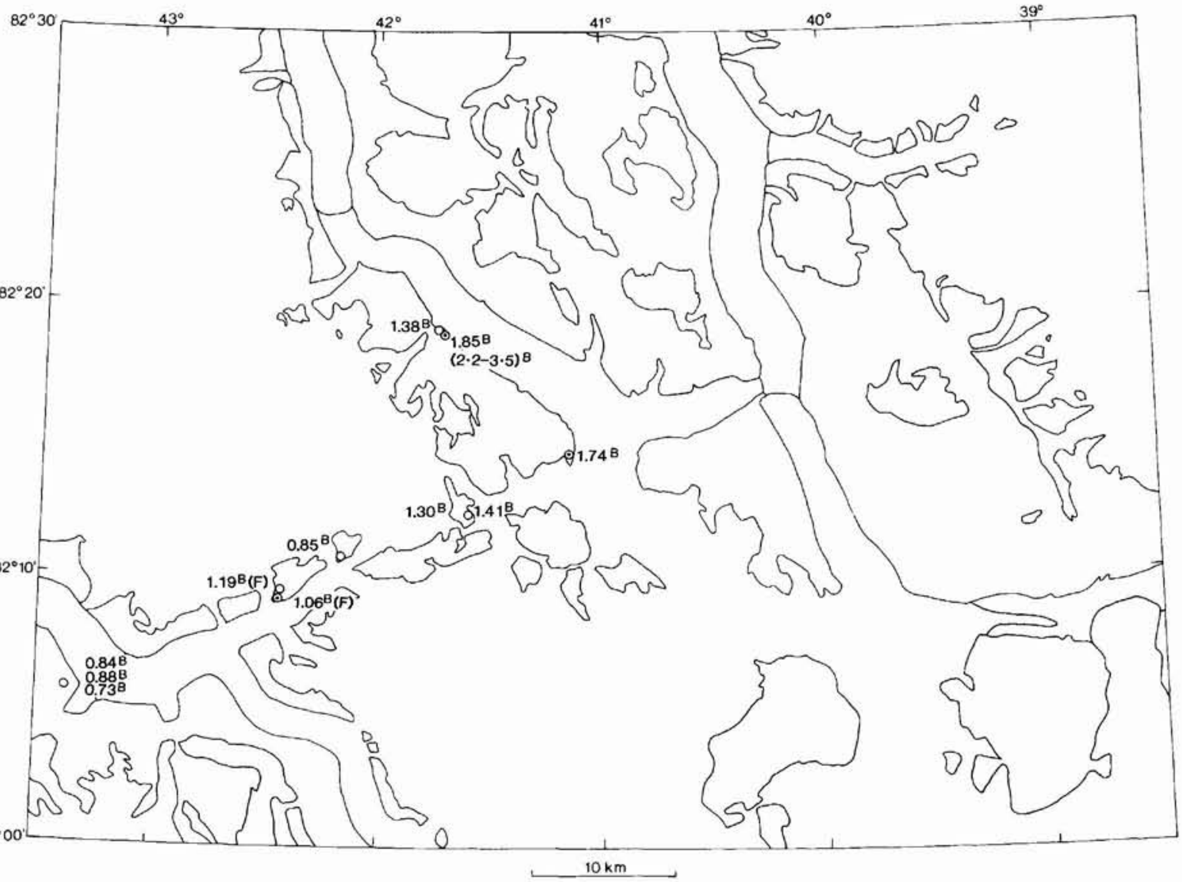
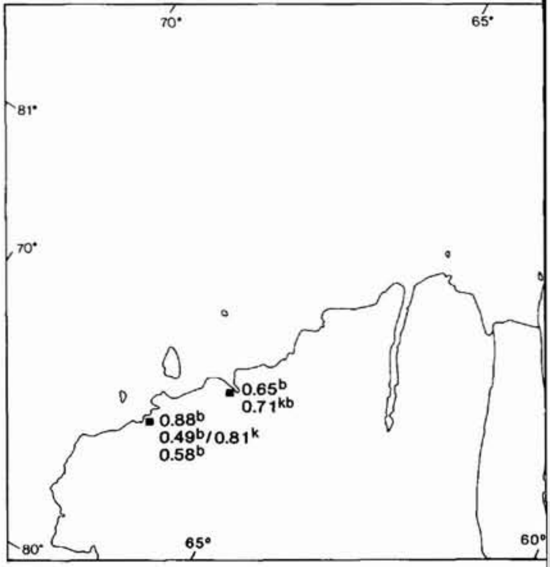


Fig. 30. Regional variation in reflectance values of migrated bitumen (circles with dots: macroscopic bitumen in vugs, veins; open circles: stained carbonates and sandstones). F: fluorescence of migrated bitumen.

Fig. 31. Regional variation in reflectance values of Silurian shales.



Ro (reflectance) of kerogen (k), indigenous bitumen (b), both (kb), and graptolites (G) in Silurian source rocks

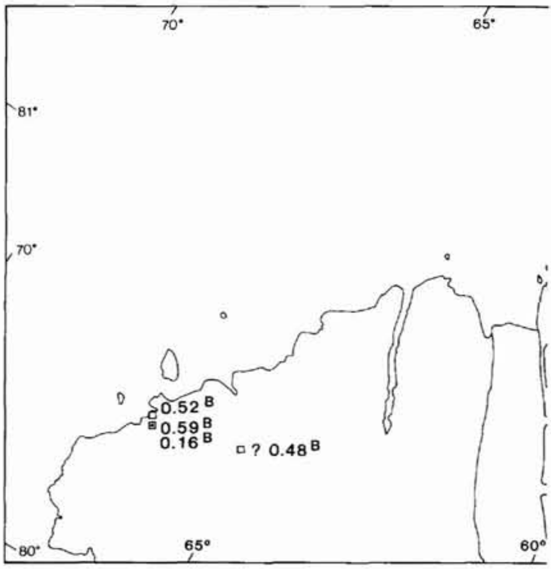
X-ray diffraction of kerogen

X-ray diffraction of kerogen provides a potential maturity indicator, although it has been little used in hydrocarbon studies (see Koch, 1987). The structural state of the kerogen, which changes with increasing thermal maturity, is described by employing two parameters d_{002} (d-spacing of 002 in 'graphite') and WHH_{002} (width at half height of the 002 peak in 'graphite') (see analytical details in Chapter 3; Wedeking & Hayes, 1981; Koch, 1987).

The material includes eight organic-rich Cambrian to Ordovician samples representing a profile with known increase in thermal maturity (figs 25 and 36) and seven organic-rich Silurian shales which are regionally scattered but easily ranked in order of increasing thermal maturity (figs 26 and 38; Koch, 1987).

The immature to early mature samples are characterized by very broad diffraction peaks, WHH values above 5, and an intense scattering in the angular range 10–30° 2θ (figs 34, 36 and 38). Samples with higher maturities (mature to postmature) show sharper diffrac-

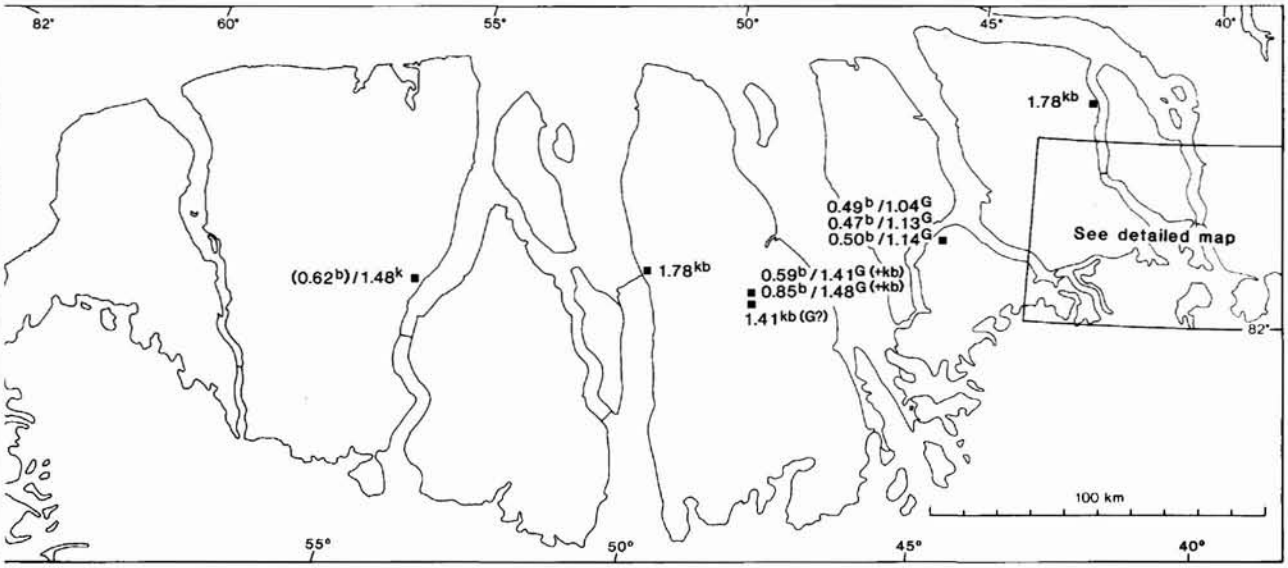
Fig. 32. Regional variation in reflectance values of migrated bitumen (vugs, veins, stained carbonates and sandstones).



Ro (reflectance) of migrated bitumen in:

▲ ■ Macroscopic bitumen

△ □ Bitumen stained sandstone and carbonates



tion peaks, WHH values between 4 and 2.5, and a decrease in the scattering (figs 34 and 36). The two analysed postmature to low metamorphic samples have broad but well defined diffraction peaks, WHH between 4 and 5, and only little scattering (figs 34 and 36). The presence of 101 diffraction is noted in these samples.

Thermal maturity and the oil window

In the foregoing it has been demonstrated how each of the measured maturity parameters support the general mapped pattern of rapid increase in organic diagenesis from south to north. The parameters vary considerably in applicable range of maturity as well as in exactness. Only a few of the parameters provide specific information on the four most important thresholds in petroleum exploration: (1) onset of petroleum generation, (2) peak generation, (3) end of petroleum generation, (4) end of petroleum preservation.

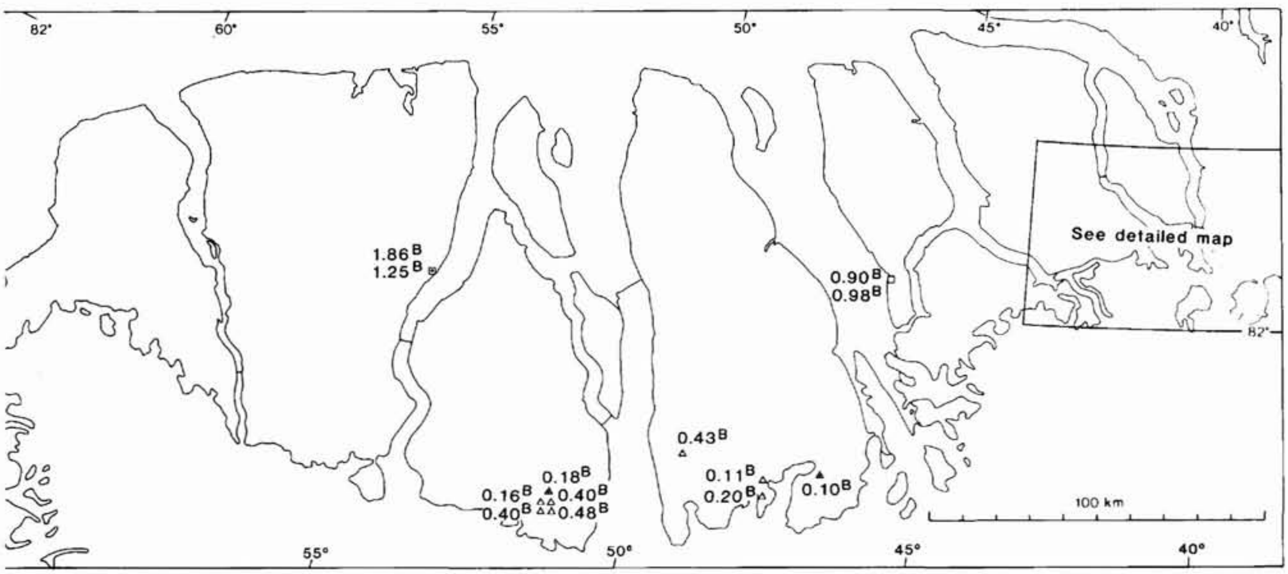
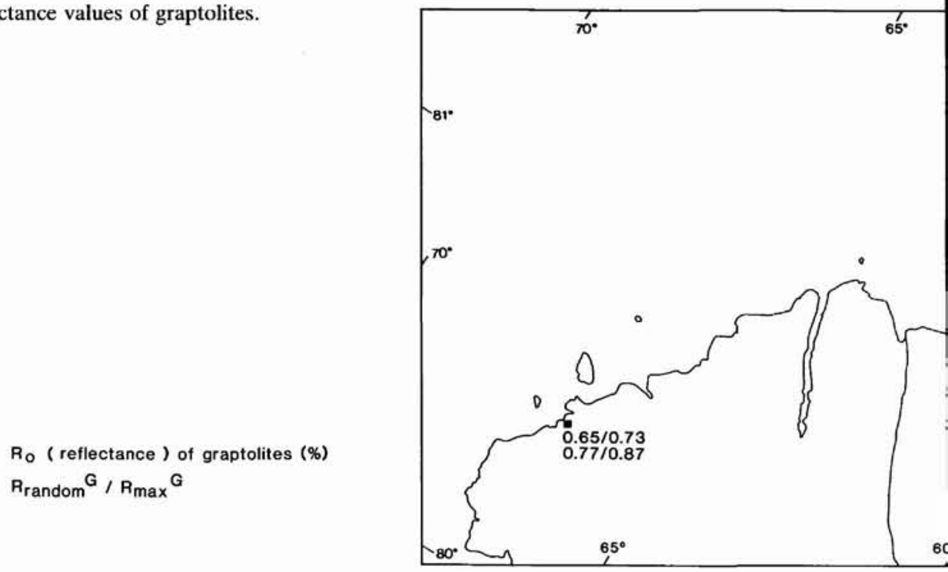


Fig. 33. Regional variation in reflectance values of graptolites.



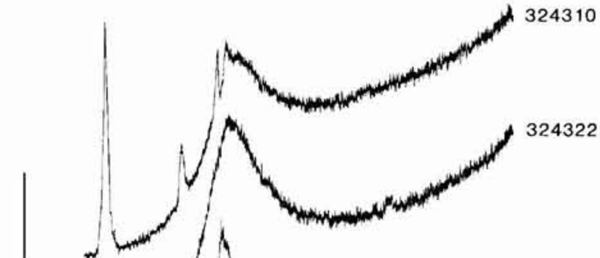
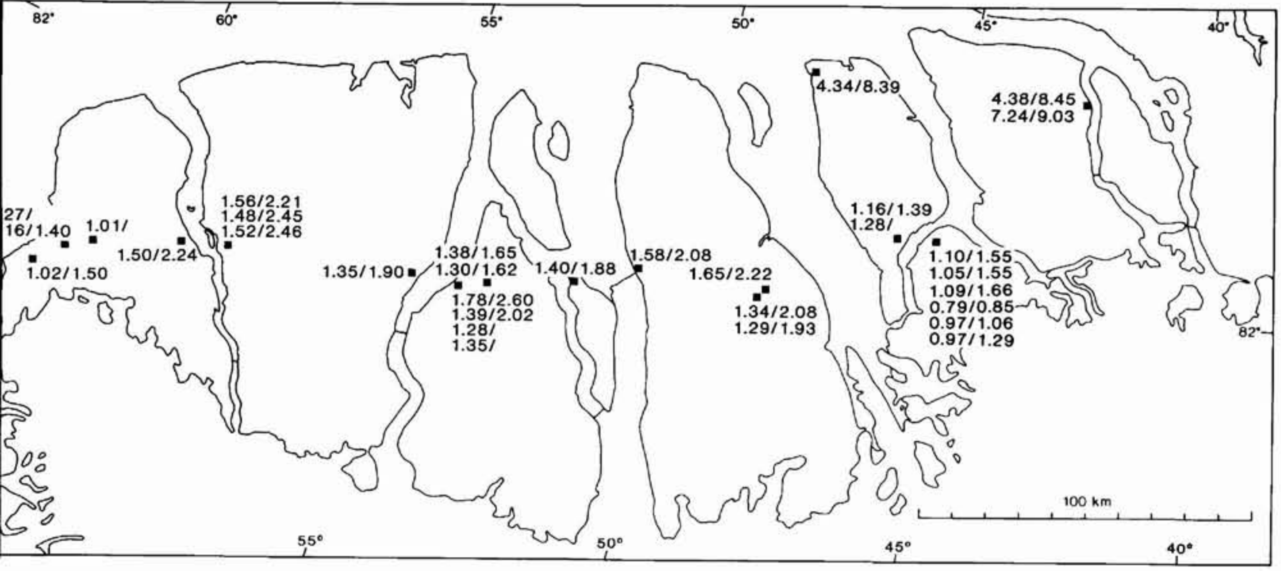


Fig. 34. X-ray diffractograms of Cambrian samples ranked in order of increasing thermal maturity (from south to north).

In North Greenland where the distribution and maturity gradient of source rocks are known in considerable detail, the generation of petroleum is systematically registered as a decrease in residual potential of the kerogen and as an increase in hydrocarbon content of the source rocks.

The variation of these factors with increasing thermal maturity, in this case expressed as T_{max} values, is shown as circumscribed curves of the Hydrogen Index, S1/TOC, and SOM/TOC (fig. 35). The Hydrogen Index curve, which reflects the residual generation potential of the organic matter, decreases drastically between T_{max} values of 438°C and 445°C ('peak generation'). The onset value is not known exactly but probably corresponds to a T_{max} value of ~ 435°C. No significant potential is present at maturities higher than a T_{max} of 460°C to 470°C ('end of generation'). The other two curves reflect the presence of generated hydrocarbons in the source rocks, either as the bitumen transformation ratio (mg SOM/g TOC) or as the Rock Eval parameter S1/TOC. Despite differences in number of analysed samples and in the techniques themselves, the two curves are similar (fig. 35). Maximum values are obtained at conditions corresponding to 'peak generation' and 'just after peak generation' (T_{max}: 440°C to 455°C). The petroleum content is drastically reduced at maturities between T_{max} of 470°C and 475°C ('bottom of preservation') and virtually no petroleum is preserved at T_{max} values higher than 485°C (fig. 35).

Although the two generation curves follow the classical 'Phillippi-trend' it must be noted that one quantitative difference from other petroleum provinces is that



the highest bitumen ratios observed in North Greenland are only about 60 mg SOM/g TOC compared to maximum values between 150 and 200 in many other basins (Tissot & Welte, 1984). These high values are often from actively generating and expelling source rocks, conditions which the North Greenland source rocks reached during the Devonian (?) (see Chapter 8 for further discussion). Since that time significant amounts of hydrocarbons have been lost by further migration and degradation, by surface alteration and evaporation.

The interpretation of generation/degradation with increasing thermal maturity is further supported qualitatively by direct observation of petroleum or its altered relicts in the field, in palynological preparations and in polished samples. The decrease in generation potential of the kerogen is also observed as increasing coloration, degradation and reflectance. However, threshold values for onset, peak and end of generation can only be determinated empirically by comparison with the above-mentioned parameters.

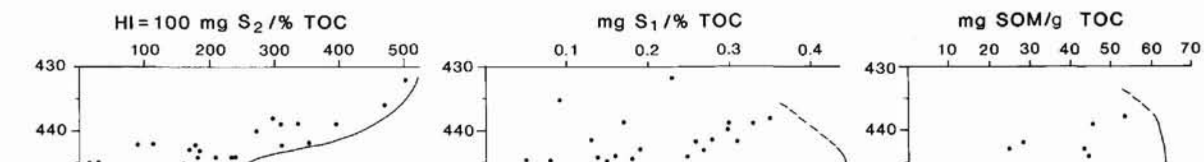


Fig. 35. Plots of hydrocarbon generation parameters versus thermal maturity (sample T_{max}) for Cambrian and Silurian source rocks. (A) Hydrogen Index (100 × mg S_2/% TOC), only samples with TOC > 2.0% are included. (B) (mg S_1/% TOC), only samples with TOC > 2.0% are included. (C) Extractability (mg SOM/g TOC), samples with TOC < 2.0% are in parenthesis.

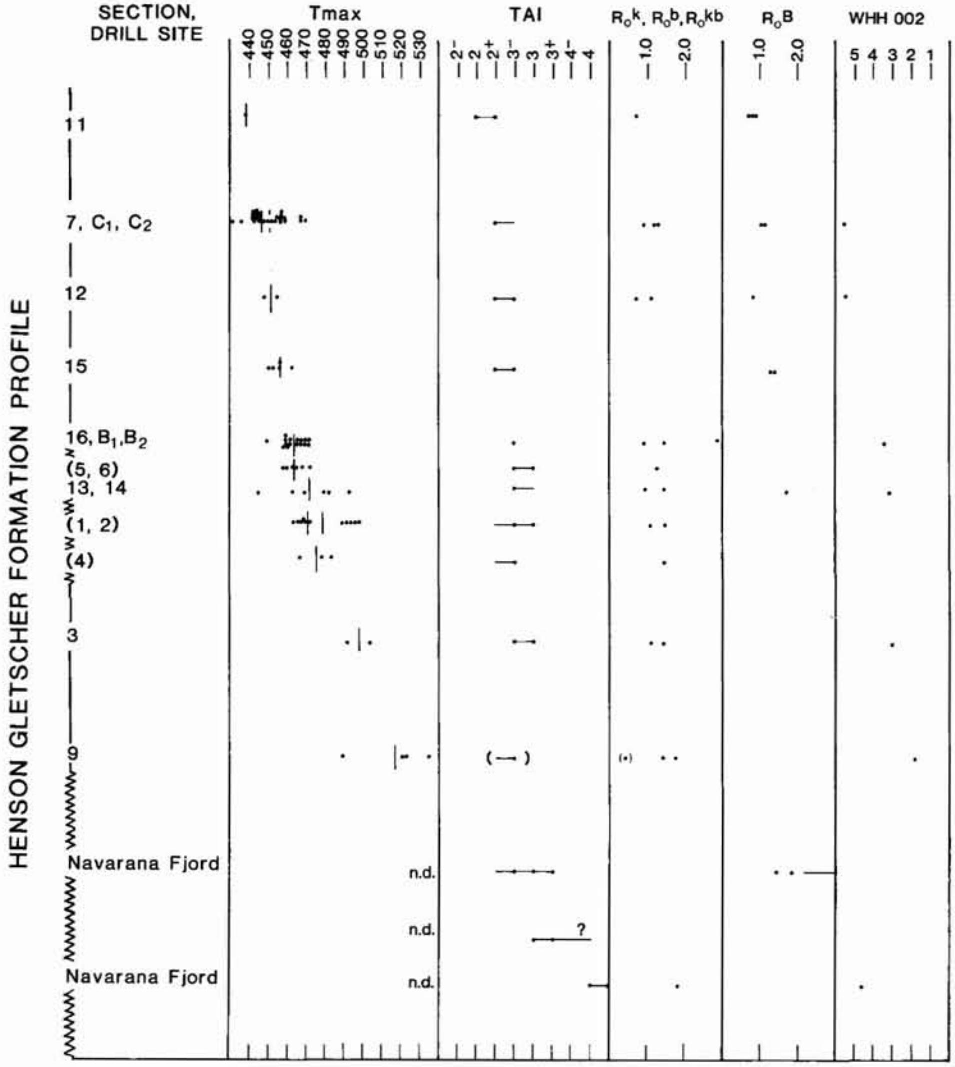


Fig. 36. Maturity profile through the area where the Henson Gletscher Formation is exposed showing the relations between most of the measured maturity parameters. See fig. 25 for location.

Empirical correlation of maturity parameters

The empirical relations between the maturity parameters employed are illustrated in various ways as profiles, composite profiles, cross plots and finally as a synoptic figure.

Two profiles at an oblique angle to the maturity trend illustrate the scatter and the sensitivity of the measured values. One of them is from the area where the Henson Gletscher Formation is exposed (fig. 36), the other is from the Silurian shales outcrop area in Washington Land and Hall Land (fig. 37). Similar information is shown in the composite profile (fig. 38) where subareas with outcropping Silurian shales are ranked in order of increasing maturity (based on T_{max} average values). All three profiles illustrate that a large number of analyses are necessary, and that none of the methods are fully adequate by itself.

A number of cross plots are included to show the direct relations between measured maturity indicators, especially of T_{max} versus other parameters. Fig. 39 shows the relation between calculated T_{max} average values (Reg. T_{max}) and T_{max} values for individual samples. In many subareas, especially with T_{max} below 460°C, only minor variation is observed. A number of observed anomalies (I, II and III) will be discussed in the following section.

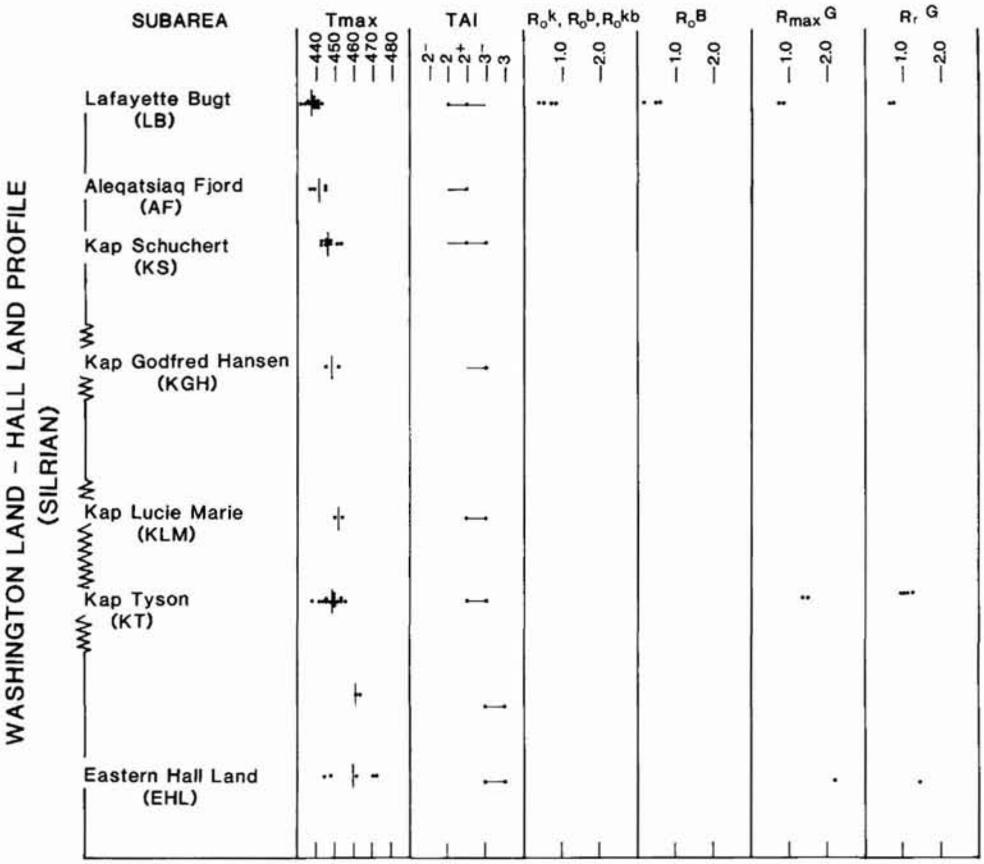


Fig. 37. Maturity profile through western Washington Land and Hall Land showing the relations between most of the obtained maturity parameters. See fig. 26 for location.

A consistent relation between Reg. TAI values and Reg. T_{max} is observed (fig. 40). The TAI values are most sensitive at early to peak generation (below T_{max} of 450°C) and at the beginning of metamorphism with only little distinction between.

The relation between reflectance of kerogen (R_o^k and R_o^{kb}) and Reg. T_{max} or sample T_{max} is not sufficiently clear to be easily applicable. A considerable scattering around a roughly linear (?) correlation may be suggested (fig. 41).

Reflectance of migrated bitumen (R_o^B) is much more sensitive to increasing thermal maturity and displays a well defined correlation with the Reg. T_{max} (fig. 42). The reflectance of graptolites, whether expressed as R_r^G or as R_{max}^G, shows a distinct correlation with measured T_{max} values (fig. 43). Both graptolite parameters are very sensitive in the T_{max} range from 435°C to 460°C and show a dramatic increase in postmature to low metamorphic rocks.

There is also a consistent relation between the regional T_{max} values and WHH_{002} with a roughly linear trend in the T_{max} range from 450°C to 520°C and the high, but scattered, WHH values at T_{max} < 450°C (fig. 44). The pattern of high WHH values in the postmature samples from the northern part of the region is not fully outlined but appears comparable to the results by Wedeking & Hayes (1983).

All measured parameters with increasing maturity showing onset, peak, end of oil generation, end of oil preservation and beginning of metamorphism are compiled in fig. 45. Note the following empirically determined threshold values which seem to be valid for both the Cambrian and the Silurian source rocks in North Greenland:

Onset of petroleum generation: Reg. T_{max}: 435–437°C, TAI: 2^-–2, R_o^k: 0.5–0.8, R_o^B: 0.1–0.5, R_{max}^G: 0.5–0.9, R_r^G: 0.5–0.7, WHH: > 6.

Peak generation: Reg. T_{max}: 440–445°C, TAI: 2–2^+, R_o^k: 0.7–1.0, R_o^B: 0.5–1.0, R_{max}^G: 0.7–1.2, R_r^G: 0.6–1.1, WHH: 4.5–6.

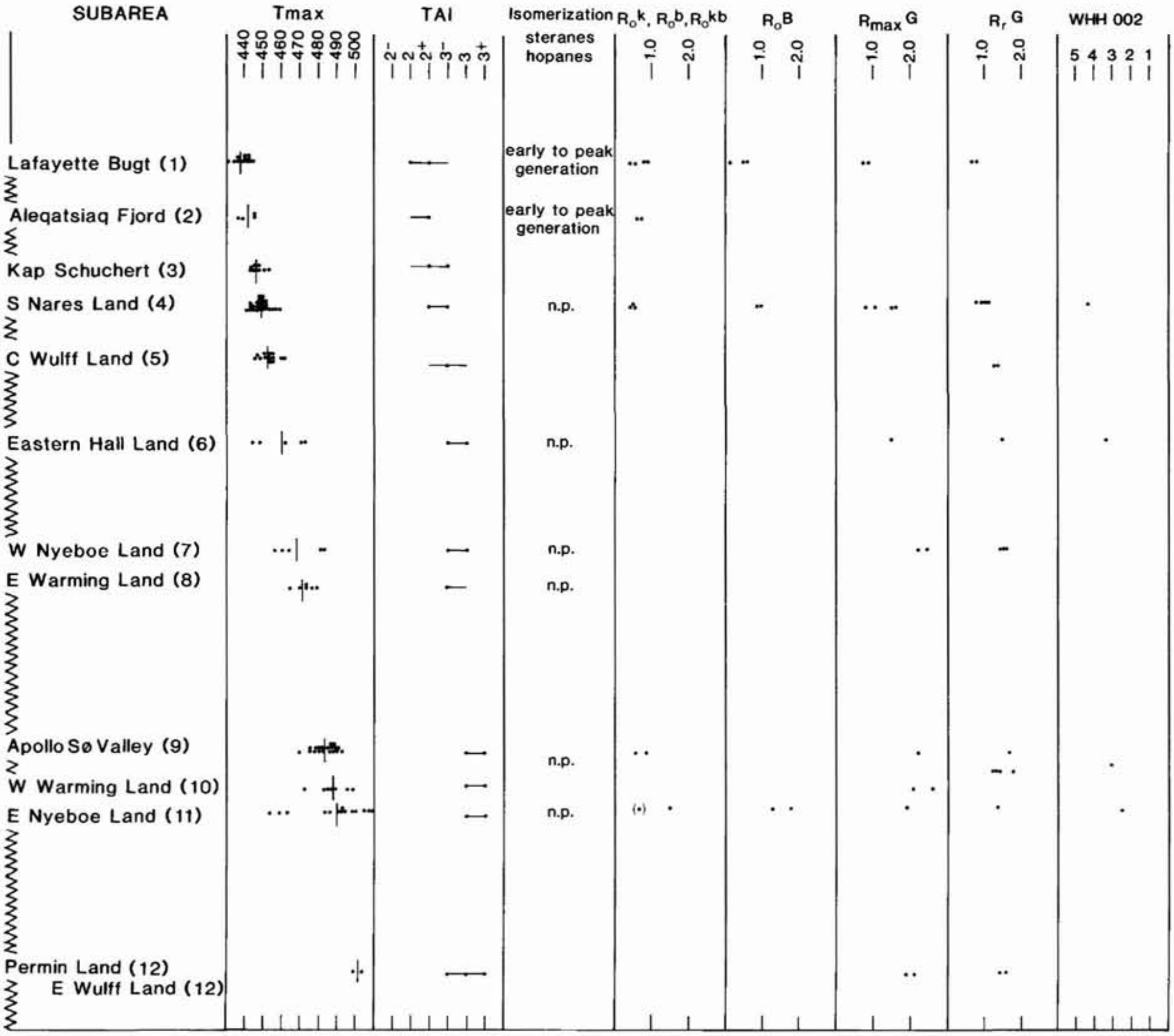


Fig. 38. Composite maturity profile of the Silurian shales showing the relations between most of the measured maturity parameters. The ranking of the different subareas is based on T_{max} data. The location of the areas is shown (with number) in fig. 26.

End of generation: Reg. T_{max}: 465°C, TAI: 3^-–3, R_o^k: 1.0–1.5, R_o^B: 1.0–1.5, R_{max}^G: 1.4–2.4, R_r^G: 1.1–1.6, WHH: 4–3.5.

End of preservation: Reg. T_{max}: 475°C, TAI: 3^-–3, R_o^k: 1.1–1.6, R_o^B: 1.2–1.8, R_{max}^G: 1.5–2.5, R_r^G: 1.2–1.7, WHH: 3.5–3.

These threshold values and the empirical relations between the measured maturity indicators in general are comparable with many previously proposed maturation schemes (e.g. Dow, 1977; Heroux *et al.*, 1979; Tissot & Welte, 1984; Bustin *et al.*, 1985a,b; Macauley *et al.*, 1985). However, a number of minor differences should be noted:

1) Large variation in reflectance values of kerogen in North Greenland and relatively low values of the preservation limit.

2) A surprisingly good correlation of R_o^B (reflectance of migrated bitumen) with other parameters.

3) Lack of fluorescence in many early mature to mature source rocks.

4) A systematic and good correlation between WHH_{002} and other indices throughout the maturity scale.

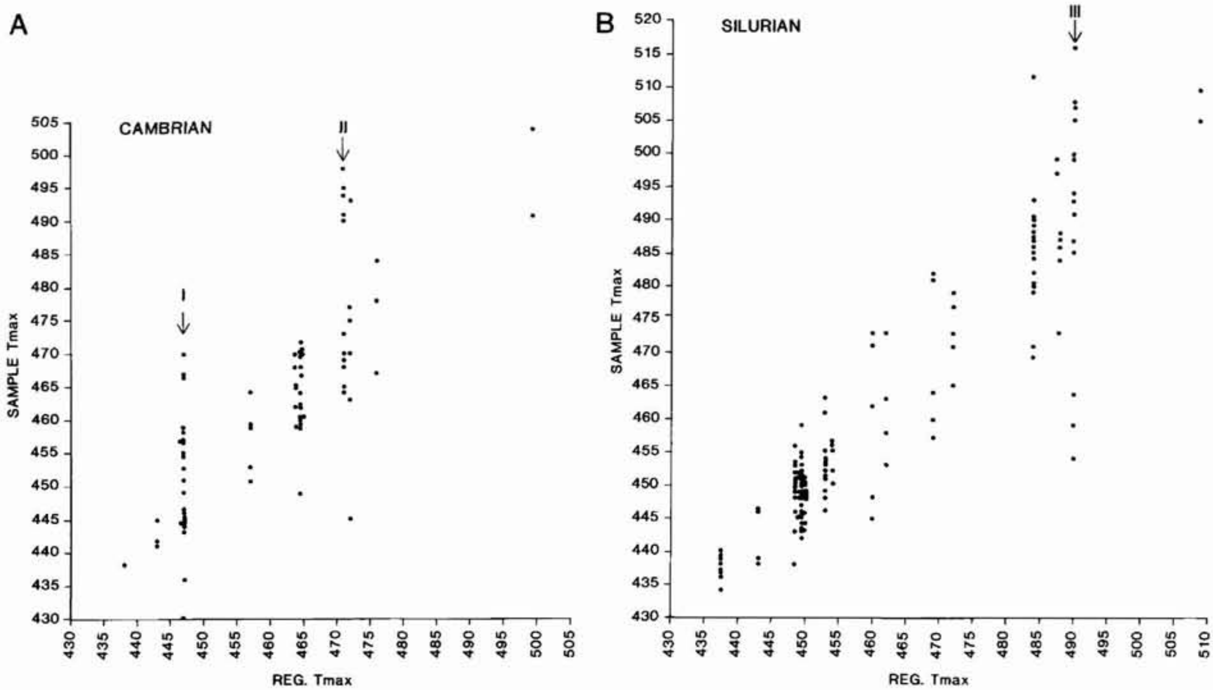


Fig. 39. Relation between calculated T_{max} average for subareas (Reg. T_{max}) and T_{max} of individual samples. A: Cambrian source rocks; B: Silurian source rocks. The Roman numbers refer to areas with thermal maturity anomalies (see figs 25, 26 and 46).

The above compilation illustrates that the various parameters applied vary considerably in exactness, sensitivity and range of application. All the recorded parameters are very sensitive and applicable in the range from early mature to peak generation conditions. In the range from peak to late or end of generation only a few of the data available provide a significant distinction (mainly T_{max} and WHH, to a lesser degree R_o^B). In the

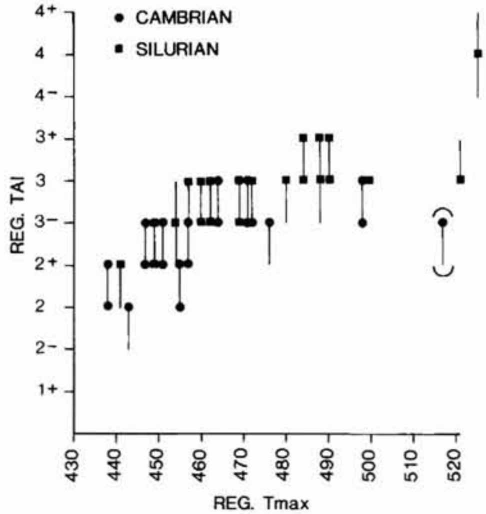


Fig. 40. Relation between Reg. T_{max} and Reg. TAI.

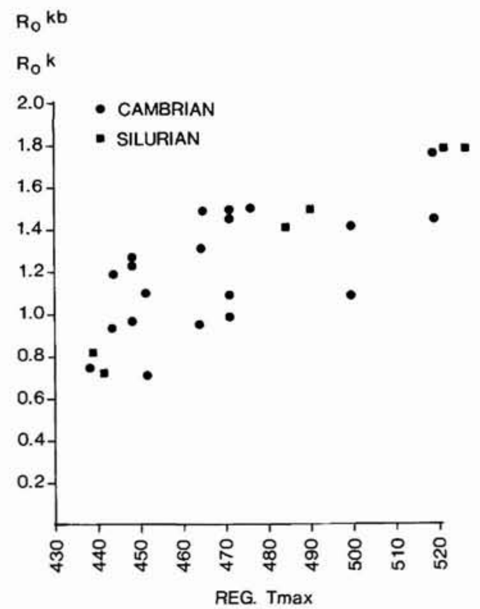


Fig. 41. Relation between Reg. T_{max} and reflectance of kerogen and indigenous bitumen (R_o^k and R_o^{kb}).

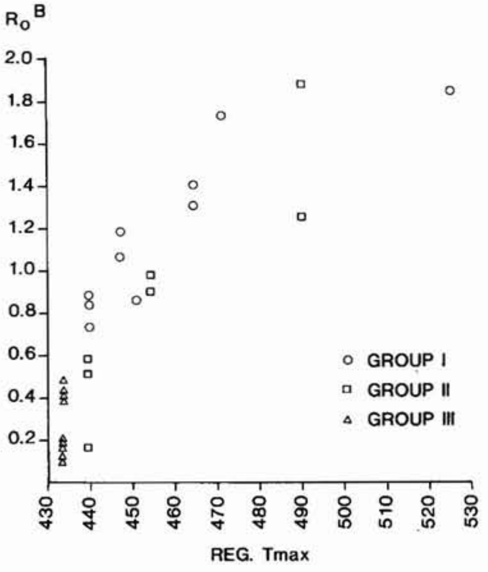


Fig. 42. Relation between Reg. T_{max} and reflectance of migrated bitumen (R_o^b).

postmature to low metamorphic range detailed mapping seems difficult due to the loss of hydrocarbons (no T_{max}). Some of the reflectance values (R_{max}^G, R_o^G, R_o^B, (R_o^{kb})) and WHH are the most sensitive parameters in this range.

Local maturity anomalies

Although most of the data presented support a very distinct maturity pattern, a number of anomalies have been recorded in the form of either single sections, localities, or smaller areas. The anomalies were detected by variation in T_{max} or occasionally in TAI, and later supported by reflectance and GC analyses.

Two obvious examples occur in the Cambrian sequence, and two more in the Silurian. In the area around the type section of the Henson Gletscher Formation (fig. 25) the T_{max} values are very scattered. Samples with well defined S2 peaks have T_{max} close to 470°C whereas other samples have considerably higher values in the range 480°C to 490°C (figs 36 and 39). These local high maturation values are probably associated with the

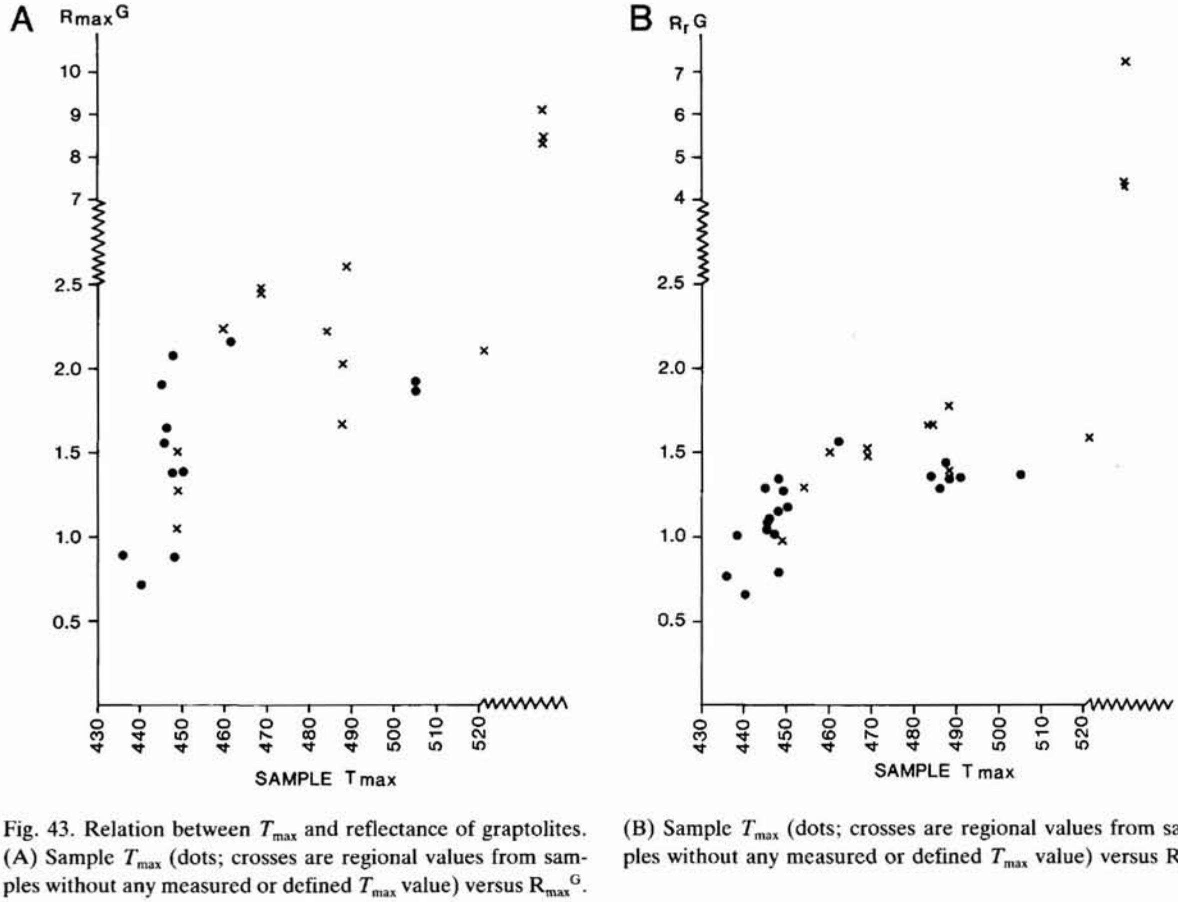


Fig. 43. Relation between T_{max} and reflectance of graptolites. (A) Sample T_{max} (dots; crosses are regional values from samples without any measured or defined T_{max} value) versus R_{max}^G. (B) Sample T_{max} (dots; crosses are regional values from samples without any measured or defined T_{max} value) versus R_r^G.

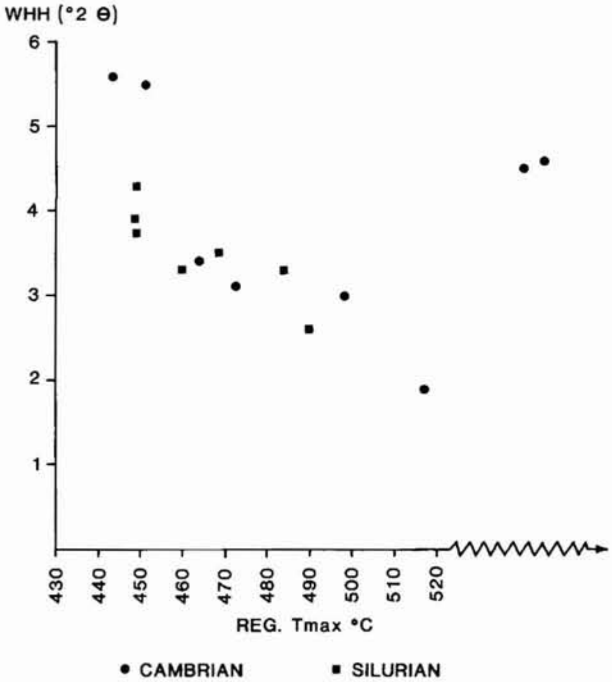


Fig. 44. Relation between Reg. T_{max} and X-ray diffraction of kerogen (WHH_{002} = width at half height).

fault zones or basic dykes present in the area. Also the area around the C1 and C2 drill sites (fig. 25) displays scattered T_{max} values. In this case the well defined T_{max} values close to 445°C are from the uppermost shales of the Henson Gletscher Formation, whereas the lower shales have higher and poorly defined values in the range 455°C to 470°C.

Both Silurian anomalies show a striking variation in maturity depending on stratigraphic and topographic height (fig. 46). At two locations, around the N1 and N2 drill sites in eastern Nyeboe Land and in central Wulff Land (the valley compared to neighbouring hills), the shales overlying the carbonate shelf sequence have a very high maturity (T_{max} 480°C) and those a few hundred metres higher a considerably lower maturity (fig. 46). These systematic differences are comparable to those at the C1–C2 locality and are too large to be caused by differences in subsidence depth and too well documented to be caused by analytical errors.

The local high maturity of the lowermost shales is more likely to be the result of major shearing/thrusting along the contact zone between carbonates and shales which may represent a major décollement surface (Larsen & Escher, 1985), or as interaction of hot basinal fluids penetrating through the same zone. In the case of

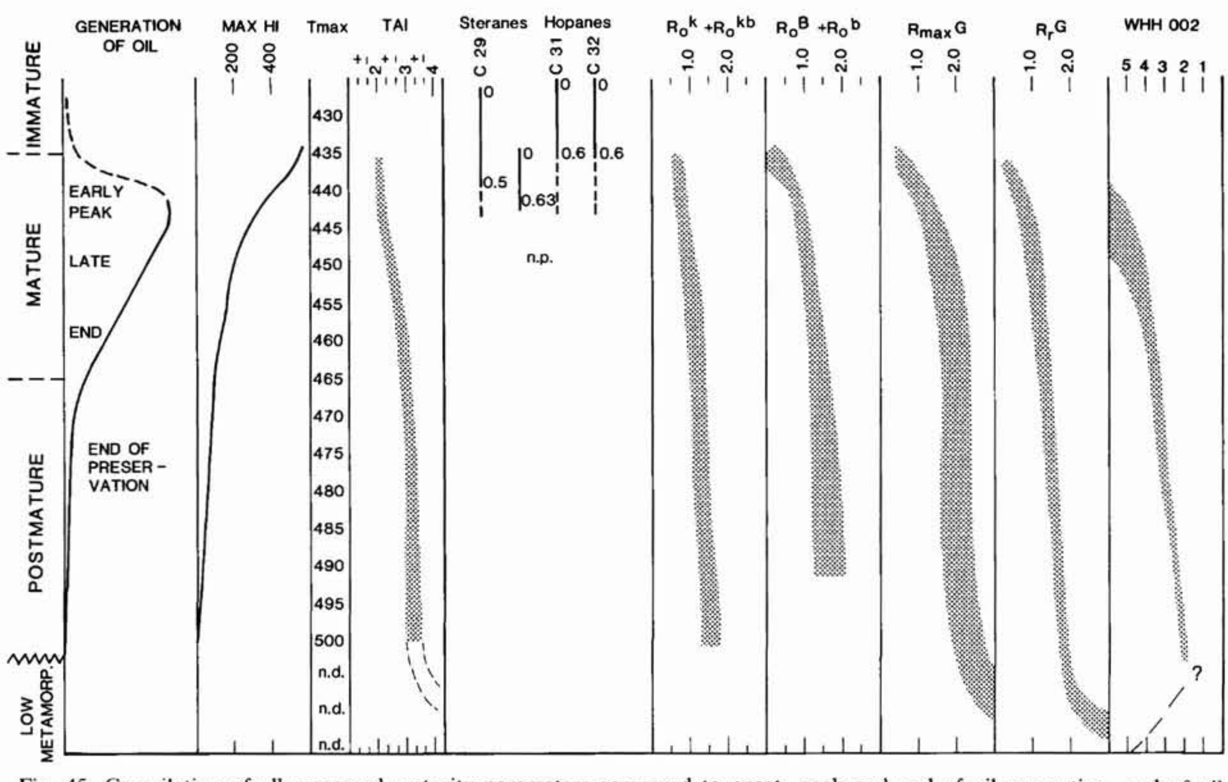


Fig. 45. Compilation of all measured maturity parameters compared to onset, peak and end of oil generation, end of oil preservation and beginning of metamorphism.

the valley in central Wulff Land an additional factor may have been a fault/joint zone striking parallel to the lake, which could also have permitted migration of hot fluids.

Thermal maturity of the Peary Land region

In the Peary Land region the available data are less systematic as regards both regional distribution and measured parameters. However, knowledge of the distribution of potential source rocks and their thermal maturity pattern west of this region allows a re-evaluation of analytical work carried out previously by Rolle (1981) and Rolle & Wrang (1981).

The Silurian deep-water sequence including organic-rich shales can be traced for at least 250 km east of Freuchen Land before it is overlain/truncated by thermally immature to mature Upper Palaeozoic and Mesozoic sediments (fig. 47; Christiansen *et al.*, in press). The Henson Gletscher Formation can only be traced for about 80 km in the western part of Peary Land and the lack of organic-rich units in the Cambrian shelf sequence further east makes detailed maturity mapping difficult.

More than 120 samples of Lower Palaeozoic sediments from the Peary Land region were analysed with GC (Rolle & Wrang, 1981) and the same samples have since been complemented by Rock Eval analyses. A small number of additional samples have been analysed recently by various other methods.

All of the studied Silurian shales have, despite reasonably high TOC contents (1–3%), virtually no generation potential (S2 < 0.1 mg HC/g sample), very low extractabilities (< 10 mg SOM/g TOC), no defined T_{max} values, and are consequently considered as postmature or even low metamorphic (fig. 47).

Most other samples with TOC > 1% are from the Brønlund Fjord Group, especially from the Henson Gletscher Formation, and are, with the exception of one locality, included in the 'Nordolie' study area (see figs 15, 19 and 30). In the Løndal area, just south of Hans Tavsen Iskappe (fig. 47), the Henson Gletscher Formation seems early mature with a T_{max} average of 441°C, high extractability, preserved cyclic biomarkers, and a high generative potential (S2 up to 25 mg HC/g sample, HI up to 300).

Organic-rich shales (1–10% TOC) from the Ordovician Vølvedal and Amundsen Land Groups occurring in Johannes V. Jensen Land are postmature to low metamorphic with no defined T_{max} values and very low extractabilities (fig. 47). One sample containing highly coalified impsonite has a R_o^b of 4.70 (Thomsen & Guvad, 1987) corresponding to a vitrinite reflectance of approximately 3.3 using the equation of Jacob (1985).

Most of the remaining samples provide very little information on the thermal maturity due to their low organic carbon and hydrocarbon content. The presence of minor amounts of migrated bitumen cannot be excluded, the gas chromatograms of these samples all have a strong light-end bias suggesting a high maturity.

Despite the limited data base, it is concluded that the

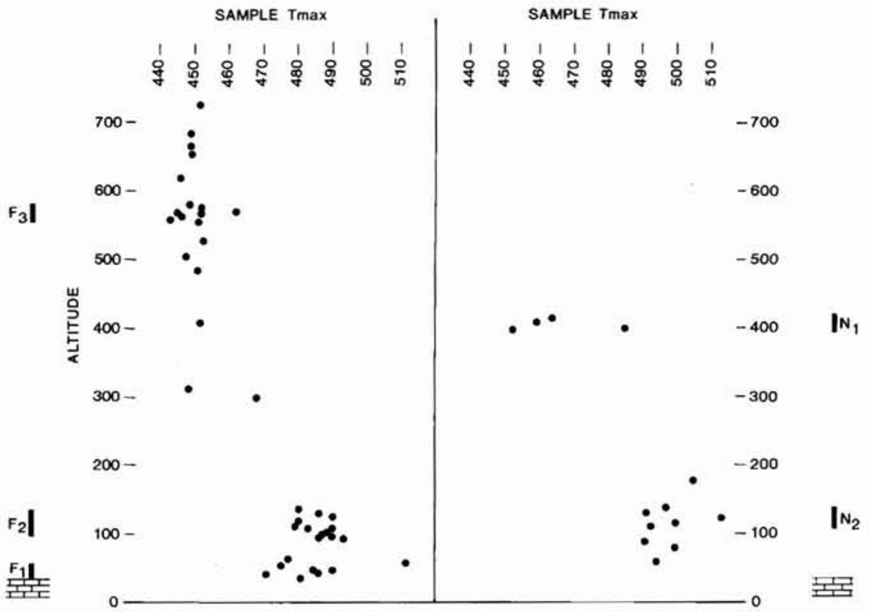


Fig. 46. Variation in maturity (T_{max}) with increasing vertical distance from the shale-carbonate contact in central Wulff Land and eastern Nyeboe Land. F_1, F_2, F_3, N_1 and N_2 indicate cores.

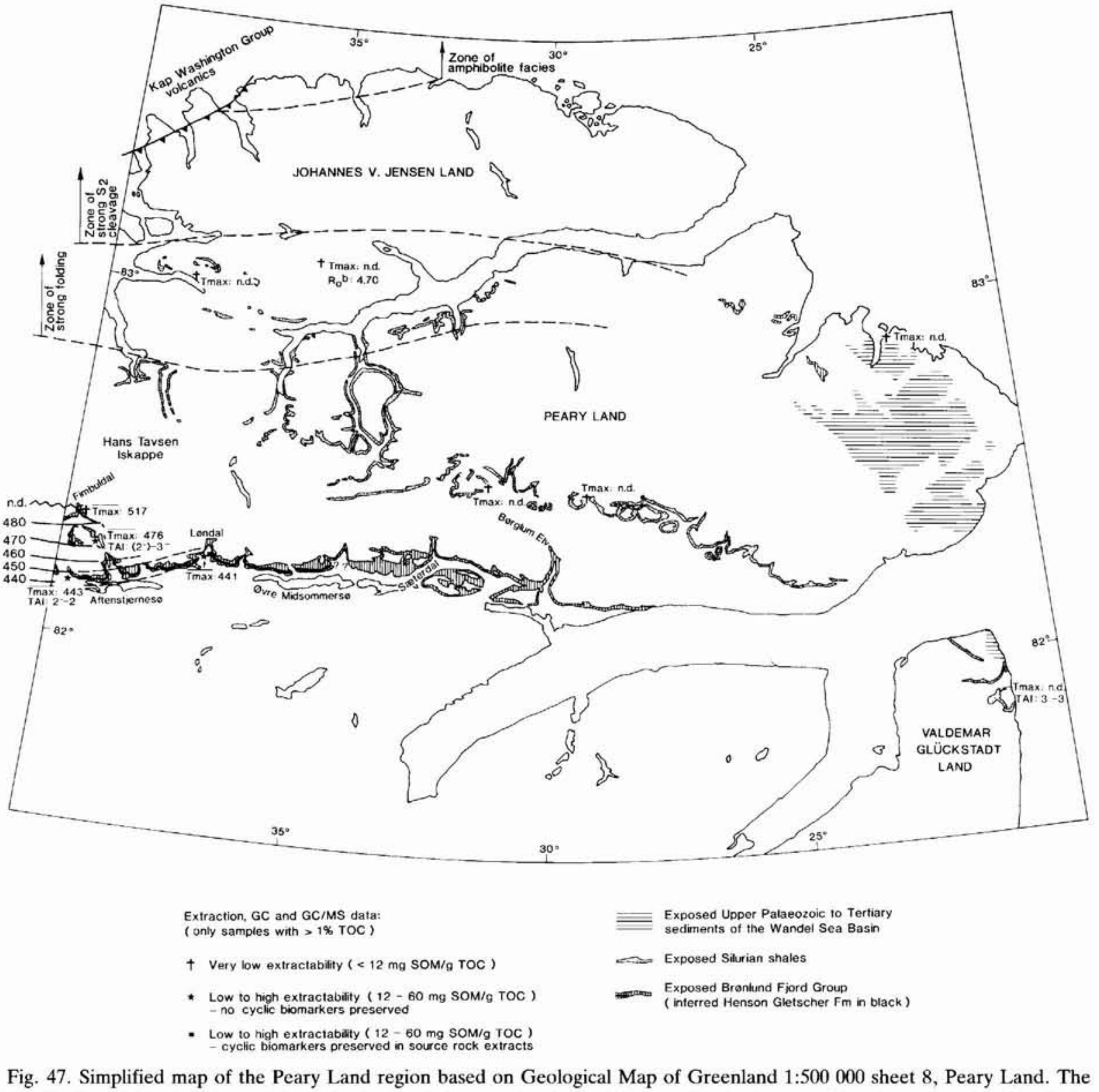


Fig. 47. Simplified map of the Peary Land region based on Geological Map of Greenland 1:500 000 sheet 8, Peary Land. The distribution of Silurian shales (stippled), the Cambrian Brønlund Fjord Group with the Henson Gletscher Formation (vertically hatched/black) and Upper Palaeozoic, Mesozoic and Cenozoic Wandel Sea Basin sediments (horizontally hatched) is indicated. Furthermore the following maturity values are shown: T_{max} (e.g. 441 or n.d.), TAI, reflectance of bitumen/kerogen, extractability (very low: cross, low to high: star; only shown for samples with more than 2% TOC). The tectono-metamorphic zones are taken from Higgins *et al.* (1985).

northern postmature (to low metamorphic) zone of central and western North Greenland continues eastwards where it covers all of Johannes V. Jensen Land and most, if not all, of the southern part of Peary Land. The expected transition to mature or immature areas towards south cannot be mapped with the data available.

Summary

The thermal maturity pattern of the organic-rich units in North Greenland has been mapped by screening methods and later by a number of other, more sophisticated, methods. All measured maturity indicators have been empirically correlated with special emphasis on

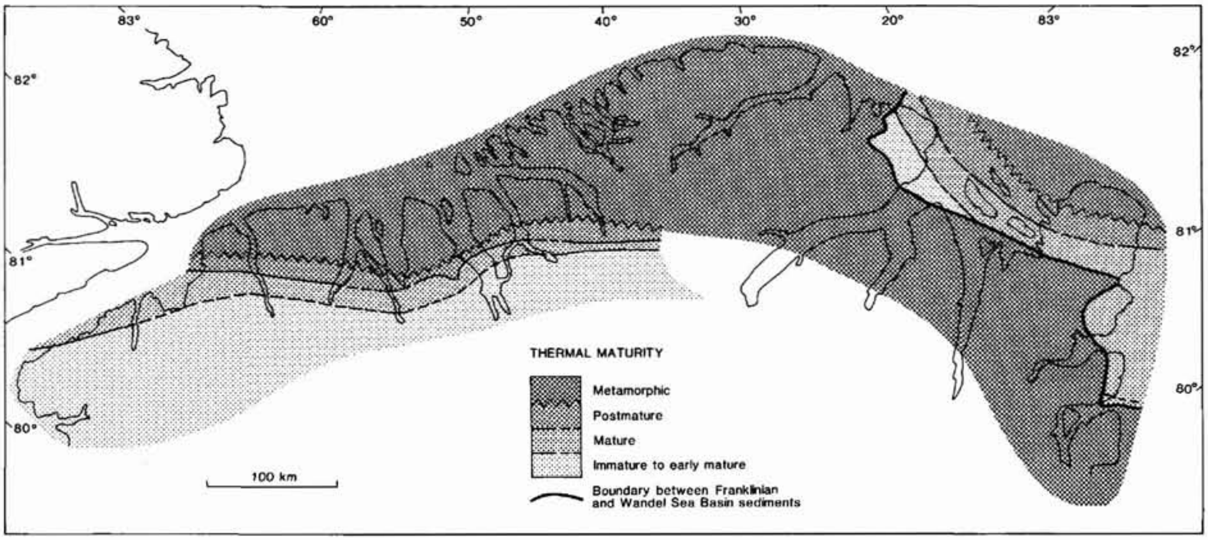


Fig. 48. Simplified thermal maturity map of North Greenland based on all available data. The Lower Palaeozoic pattern is based on data from the present chapter, Upper Palaeozoic and Mesozoic values are from Christiansen *et al.* (in press).

threshold values for (1) onset of petroleum generation, (2) peak generation, (3) end of generation and (4) end of petroleum preservation.

Generally a consistent and simple maturity pattern is observed, with the exception of a few maturity anomalies probably caused by intrusions or tectonism. The regional pattern is simplified in fig. 48 which shows a very large northern area, which is considered as low metamorphic in terms of organic diagenesis. South of this zone, two relatively narrow east–west trending zones with thermally postmature and mature surface rocks are defined. The southern part of the region includes thermally immature to early mature surface rocks.

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Plate 1. Kerogen

A. Sample with a relatively low (0.21% TOC) kerogen content and a dominance of finely disseminated amorphous kerogen in a silica gel, Lafayette Bugt Formation, Nyeboe Land, GGU 316490–1, unsieved organic material.
B. As A., Lafayette Bugt Formation, Nyeboe Land, GGU 316490–2, sieved organic material (on 10 μm nylon mesh).
C. Sample with a relatively moderate (1.15% TOC) kerogen content and small to moderate amounts of large amorphous kerogen particles, Thors Fjord Member, Nares Land, GGU 318007–18–1 unsieved organic material.
D. As C., Thors Fjord Member, Nares Land, GGU 318007–18–2, sieved organic material (on 10 μm nylon mesh).
E. Sample with a relatively large (5.09% TOC) kerogen content and a dominance of large amorphous kerogen particles, Thors Fjord Member, Nares Land, GGU 318007–32–1, unsieved organic material.
F. As E., Thors Fjord Member, Nares Land, GGU 318007–32–2, sieved organic material (on 10 μm nylon mesh).

Scale bar: 20 μm.

Plate 2. Cambrian palynomorphs

A. Acritarch-like folded alga. Middle Cambrian Sydpasset Formation, Freuchen Land, MGUH 19334 from GGU 315873–2; 139.5–13.9.
B. Acritarch-like folded alga. Middle Cambrian Sydpasset Formation, Freuchen Land, MGUH 19335 from GGU 315873–2; 150.6–7.0.
C. Two acritarch-like folded algae. Middle Cambrian Sydpasset Formation, Freuchen Land, MGUH 19336 (large light body), MGUH 19337 (dark small body), both from GGU 315873–2; 122.0–15.3.
D. Acritarch-like folded alga. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19338 from GGU 324217–2; 139.2–14.9.
E. Acritarch-like folded alga. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19339 from GGU 324300–2; 131.2–13.4.
F. Acritarch-like folded alga. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19340 from GGU 324217–2; 141.9–11.4.
G. Lump of algal or spore-like elements. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19341 from GGU 324300–2; 127.8–14.4.
H. Diad-like lump of algal or spore-like elements. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19342 from GGU 314300–2; 138.5–17.8.
I. Lump of alga or spore-like elements. Middle Cambrian, Ekspedition Bræ Formation, Freuchen Land, MGUH 19343 from GGU 324300–2; 157.7–14.7.

Scale bar: 20 μm.

Plate 3. Ordovician palynomorphs

A. Acritarch. Upper Ordovician Troedsson Cliff Member, Washington Land, MGUH 19344 from GGU 316968–2; 145.3–17.8.
B. Acritarch. Upper Ordovician – Lower Silurian Aleqatsiaq Fjord Formation, Washington Land, MGUH 19345 from GGU 316085–4; 124.1–21.3.
C. Graptolite fragment, Upper Ordovician Troedsson Cliff Member, Washington Land, MGUH 19346 from GGU 316968–2; 128.1–2.9.
D. Scolecodont, Upper Ordovician, Troedsson Cliff Member, Washington Land, MGUH 19347 from GGU 316968–2; 148.8–15.1.
E. Alga. Upper Ordovician – Lower Silurian Aleqatsiaq Formation, Nyeboe Land, MGUH 19348 from GGU 316103–2; 135.0–15.0.
F. Filamentous alga. Upper Ordovician – Lower Silurian Aleqatsiaq Formation, Washington Land, MGUH 19349 from GGU 316058–2; 135.1–4.2.
G.-L. Spores with trilete rays. Upper Ordovician, Troedsson Cliff Member, Washington Land (Nøhr-Hansen & Koppelhus, 1988).
G.-I. *Besselia nunaatica*, MGUH 17539 from GGU 316968–2; 125.5–8.3.
G. Distal view illustrating the minute ornamentation.
H. Equatorial view.
I. Internal proximal view.
J. *Besselia nunaatica*, two connected spores, internal proximal view, MGUH 17541 from GGU 316968–2; 155.1–11.9.
K.-L. *Besselia nunaatica*. MGUH 17542 from GGU 316968–2; 123.8–15.9.
K. Distal view illustrating the ornamentation.
L. Internal proximal view.

Scale bar: 20 μm.

Plate 4. Silurian palynomorphs

A. Chitinozoan, *Angochitina* cf. *A. elongata*. Upper Silurian Wulff Land Formation, Wulff Land, MGUH 19350 from GGU 315950–3; 136.9–17.2.
B. Chitinozoans, *Linochitina erratica*. Upper Silurian Wulff Land Formation, Wulff Land, MGUH 19351 from GGU 315950–2; 154.3–9.6.
C. *Retiolites*, graptolite fragment. Upper Silurian, Wulff Land Formation, Wulff Land, MGUH 19352 from GGU 315950–3; 155.1–11.1.
D. Graptolite fragment, Upper Silurian, Wulff Land Formation, Wulff Land, MGUH 19353 from GGU 315950–2; 127.3–5.7.
E.-H. Trilete spore-like bodies, figs E and F with a degraded bitumen-like appearance.
E. Lower Silurian Lafayette Bugt Formation, Washington Land, MGUH 19354 from GGU 211760–2; 143.3–17.2.
F. Upper Silurian Wulff Land Formation, Wulff Land, MGUH 19355 from GGU 315950–3; 15950–3; 155.5–8.2.
G. Upper Silurian Nyeboe Land Formation, Nyeboe Land, MGUH 19356 from GGU 319234–2; 119.3–11.0.
H. Upper Silurian Nyeboe Land Formation, Wulff Land, MGUH 19357 from GGU 319210–3; 130.6–21.4.
I. Spherical folded algae, acritarchs? Lower Silurian Lafayette Bugt Formation, Hall Land, MGUH 19358 from GGU 324157–2; 144.2–8.5.
J. Tubular structure. Upper Silurian Nyeboe Land Formation, Wulff Land, MGUH 19359 from GGU 319210–3; 146.6–16.5.
K. Tubular structure. Upper Silurian Nyeboe Land Formation, Nyeboe Land, MGUH 19360 from GGU 319234–2; 138.8–8.0.
L. Rounded drop-shaped palynomorphs. Lower Silurian Lafayette Bugt Formation, Washington Land, MGUH 19361 from GGU 316061–2; 137.1–14.8.

Scale bar: 20 μm.

Plate 1. Kerogen

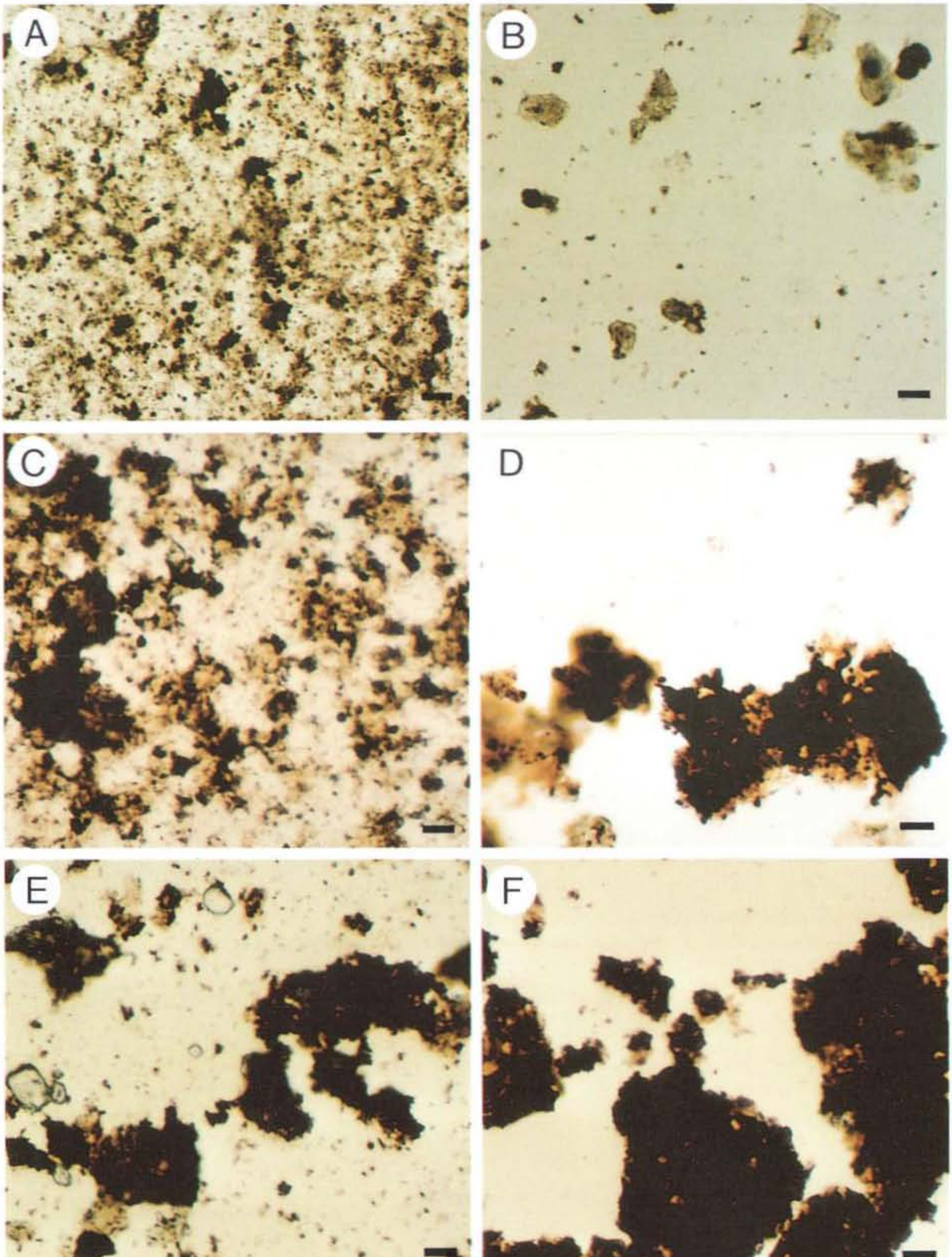


Plate 2. Cambrian palynomorphs

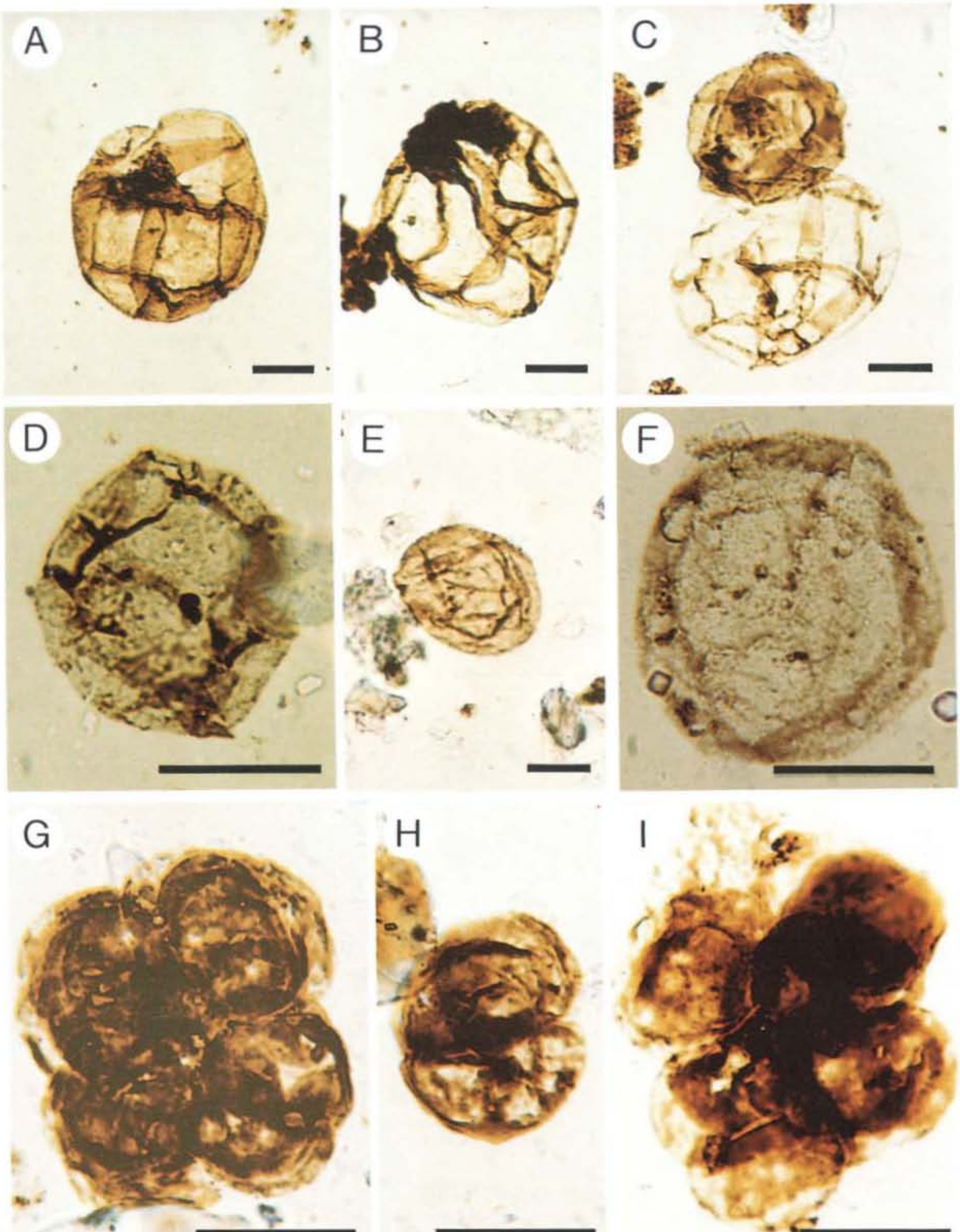


Plate 3. Ordovician palynomorphs

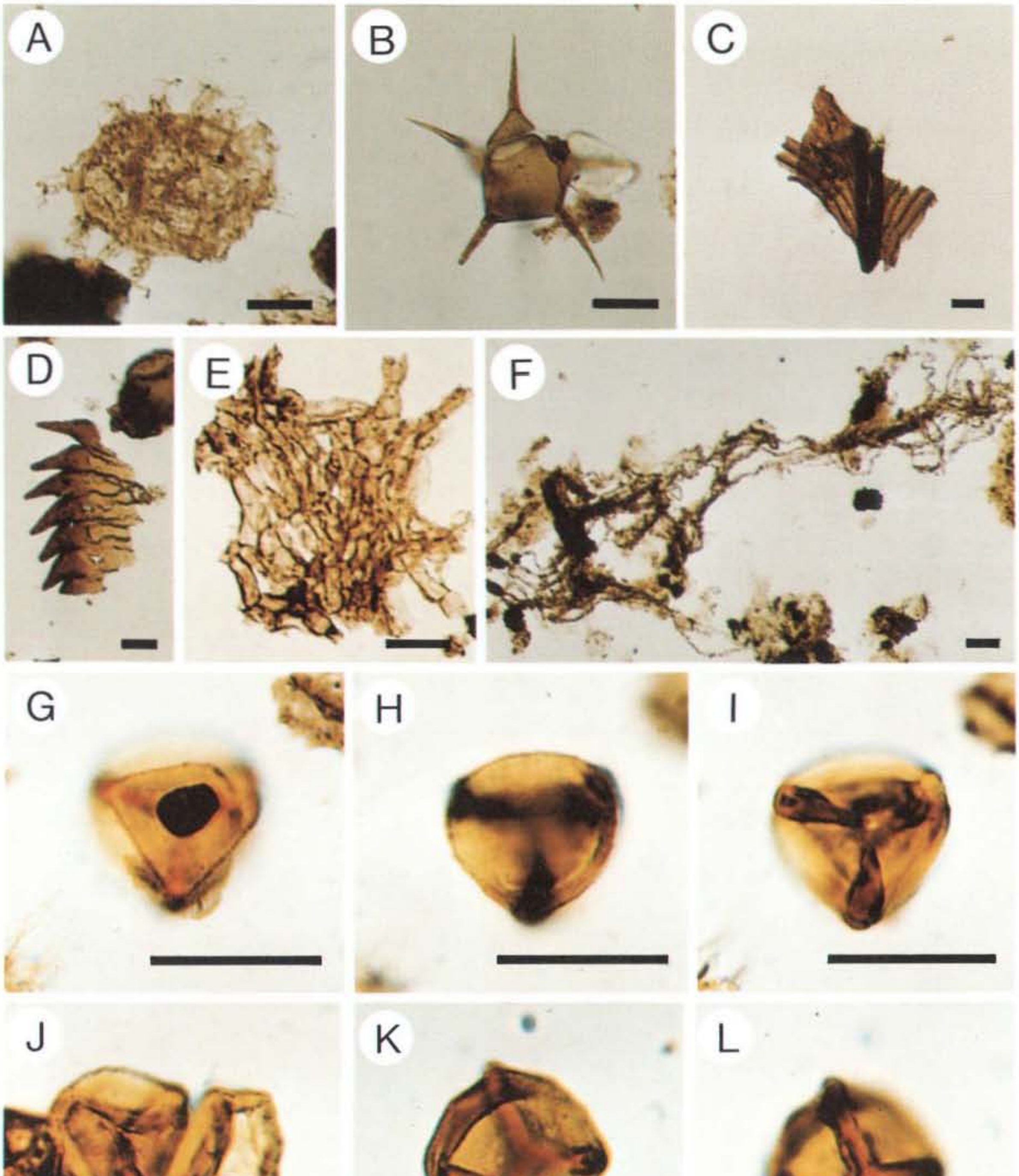


Plate 4. Silurian palynomorphs

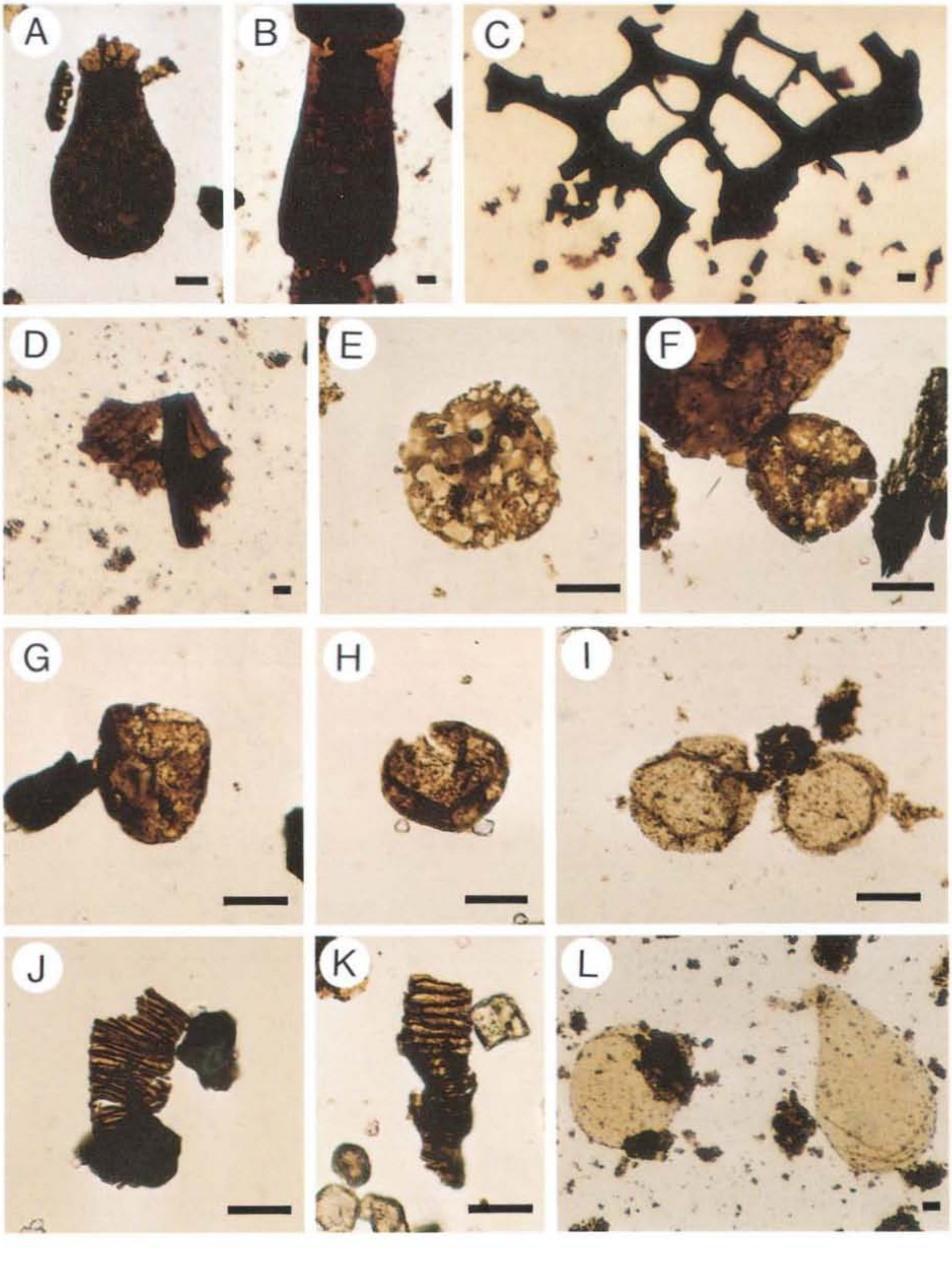


Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

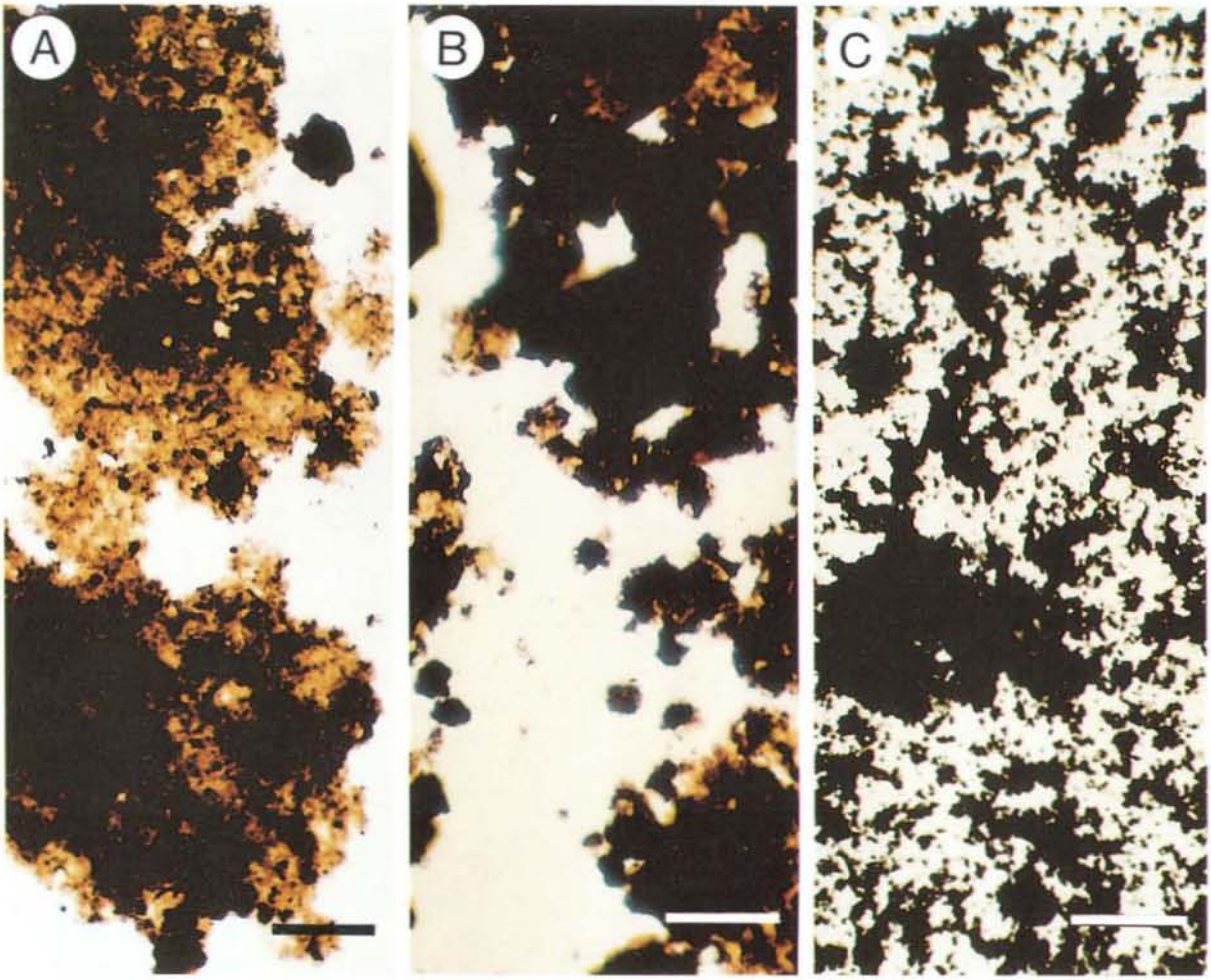
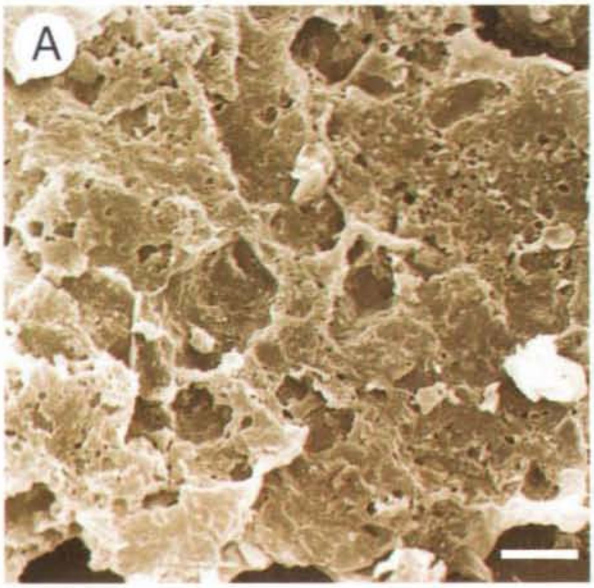


Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

Scale bar: 50 μm

A. TAI: (2)–2^+, GGU 211759–2. B. TAI: 2^+–(3^-), GGU 324405–2. C. TAI: 4^+, GGU 316475–1.

Plate 6. Change in structure of amorphous kerogen with increasing thermal alteration as observed in the scanning electron microscope



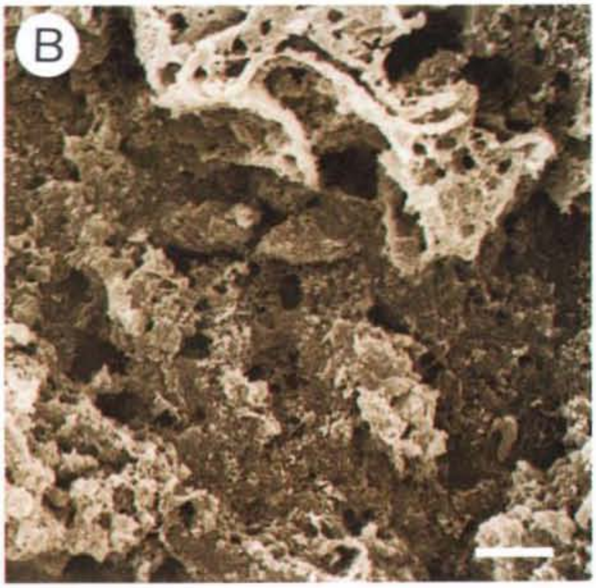


Plate 6. Change in structure of amorphous kerogen with increasing thermal alteration as observed in the scanning electron microscope

A. TAI: 2^{+}–(3^{-}), T_{max}: 446, GGU 324405–2, scale bar: 10 μm.

B. TAI: 4^{+}, T_{max}: n.d., GGU 316475–2, scale bar: 10 μm.

Plate 7. Field appearance of bitumen

A. Seeping asphalt from southern Wulff Land (equivalent to GGU 324200).

B. Hard solid bitumen in dolomite vug in the Sydpasset Formation (equivalent to GGU 324287–324299, core GGU 318003).

Plate 8. Macroscopic bitumen in slabs

A. Asphalt from seep in dolomite breccia. GGU 324200A.
B. Like A. Stained. D0, D1, D2, C1, C2 correspond to generations of dolomite and calcite.
C. Asphalt from seep in dolomite breccia. Stained. Same generations of carbonates as A and B. GGU 324200E.
D. Hard solid bitumen in vugs and veins in dolomite grainstone. DO: dolomite grainstone, D1: saddle dolomite. Core GGU 318003.

Plate 9. Bitumen in thin section

A. Bitumen in coral. GGU 324130B, Lafayette Bugt Formation, Nyeboe Land. Plane light, stained, C: calcite, Fe-C: Fe-rich calcite, B: bitumen, scale bar: 1 mm.
B. Bitumen in coral. GGU 316067, Lafayette Bugt Formation, Washington Land. Crossed nicols + gypsum plate. Q: quartz, C: calcite, B: bitumen, scale bar: 1 mm.
C. Bitumen-filled fracture in calcarenite. GGU 318013–09, Lafayette Bugt Formation, Nyeboe Land. Plane light, scale bar: 2 mm.
D. Two-phased bitumen (black and yellow) (B1, B2) in saddle dolomite veins (D1) cross-cutting dolomite grainstone (D0). See close-up (arrow) in Plate 11. GGU 318003–53, Henson Gletscher Formation, Freuchen Land. Plane light, scale bar: 2 mm.
E.-F. Saddle dolomite vein (D1) in dolomite grainstone (D0). Bitumen occurs as impregnation in DO (B1), as residual matter in the contact between D0 and D1 (B2, R_o: 0.92%) and in the centre of the vein (B3, R_o: 1.21%). GGU 318003–21, Sydpasset Formation, Freuchen Land. Plane light, scale bars: 1 mm.

Plate 10. Bitumen in palynologically prepared samples observed in microscope or in SEM

A. Bitumen with flaky appearance (note crystal impressions). GGU 315172–1. Ryder Gletscher Group Fm 6, Wulff Land. Scale bar: 25 μm.
B. Globular bitumen. GGU 315865–2, Aftenstjernesø Formation, Nares Land, scale bar: 50 μm.
C. Globular bitumen which has been extruded during and after sample preparation by the xylene-containing mounting medium. GGU 315199, Ryder Gletscher Group Fm 6, Warming Land. Scale bar: 12.5 μm.
D. Bitumen with flaky appearance (note crystal impressions). GGU 315172–1, Ryder Gletscher Group Fm 6, Wulff Land. Scale bar: 10 μm.
E. Bitumen mirroring imprints of crystals from coral space. GGU 316067–2, Lafayette Bugt Formation, Washington Land. Scale bar: 10 μm.
F. Thread-like bitumen. GGU 324453, Buen Formation, Wulff Land. Scale bar: 25 μm.

Plate 7. Field appearance of bitumen

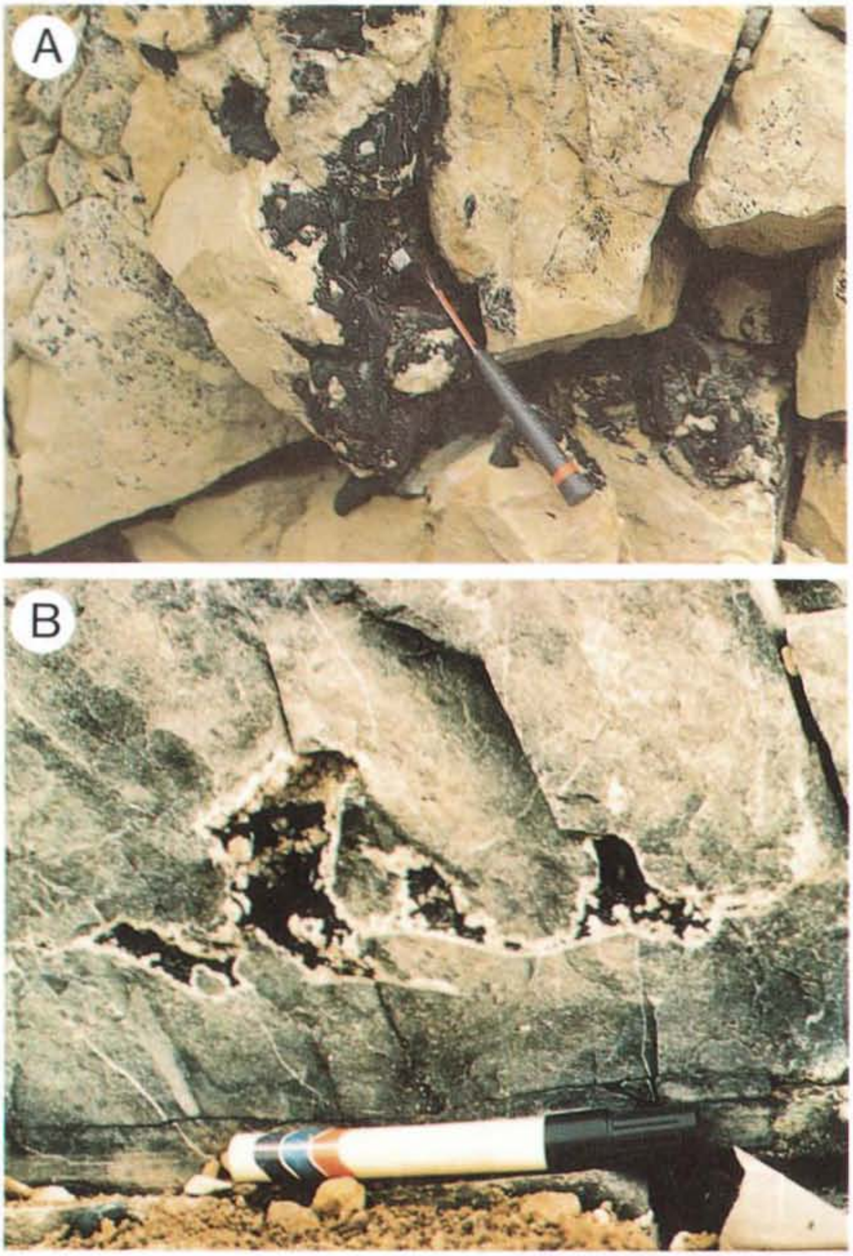


Plate 8. Macroscopic bitumen in slabs

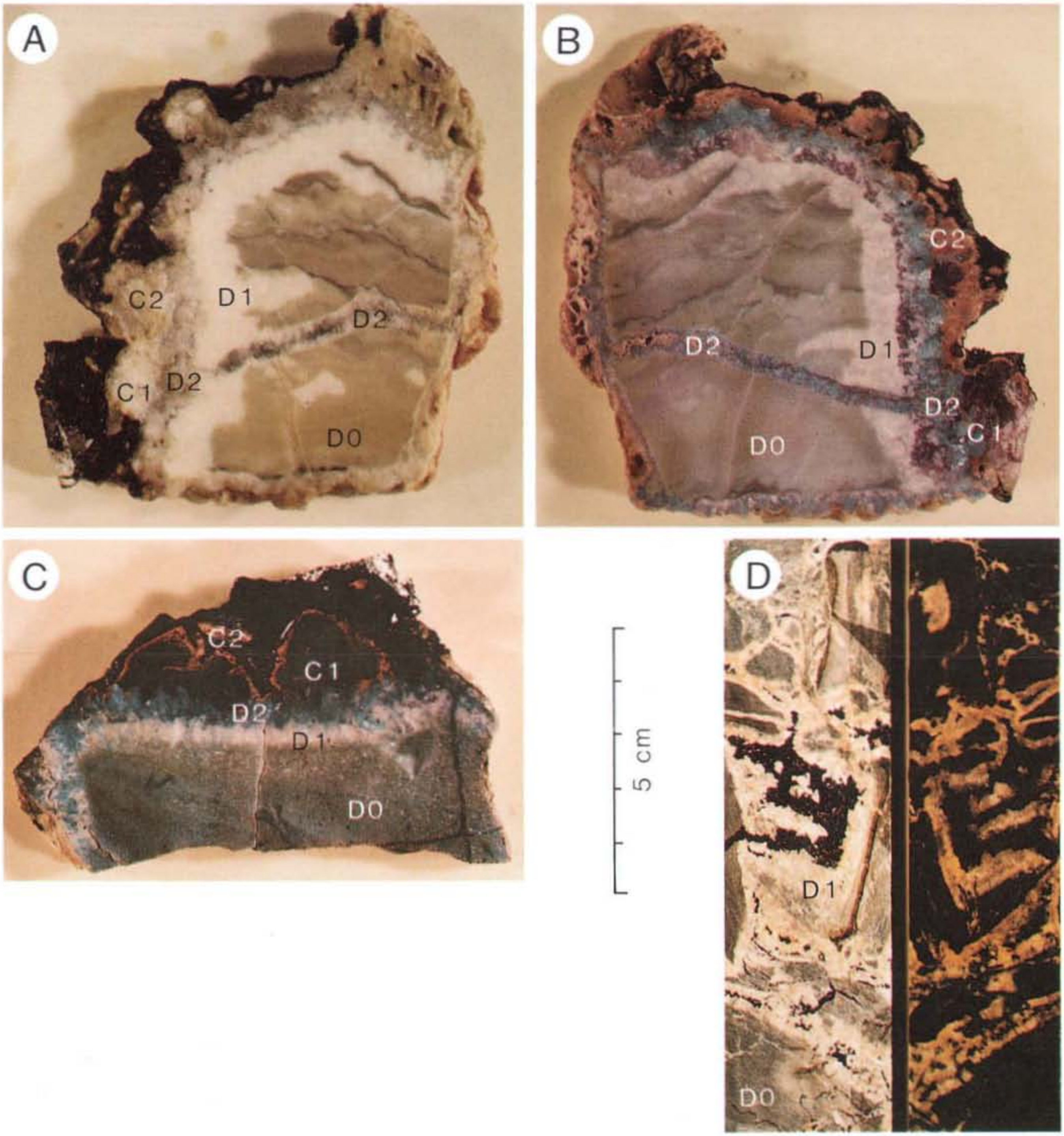


Plate 9. Bitumen in thin section

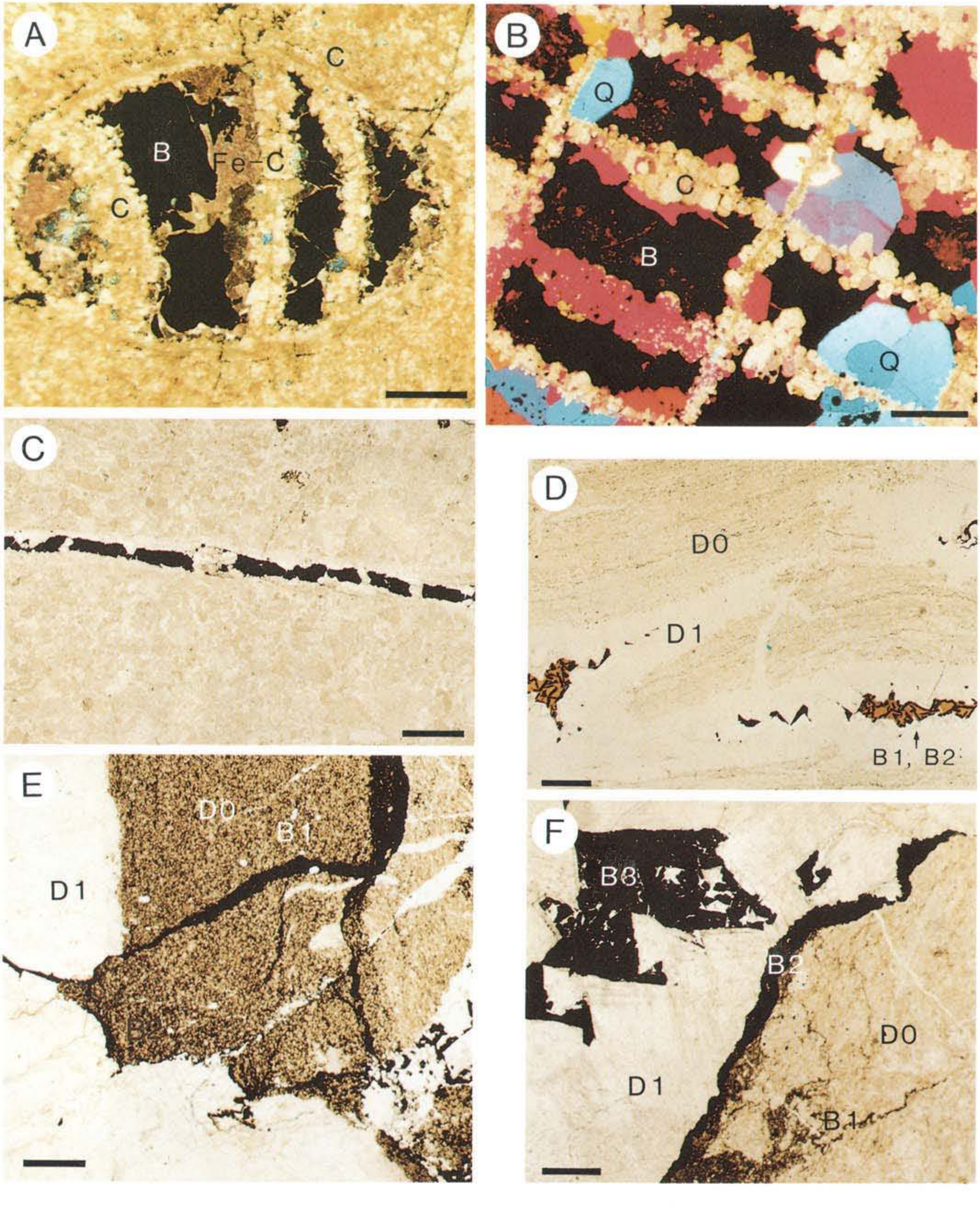


Plate 10. Bitumen in palynologically prepared samples observed in microscope or in SEM

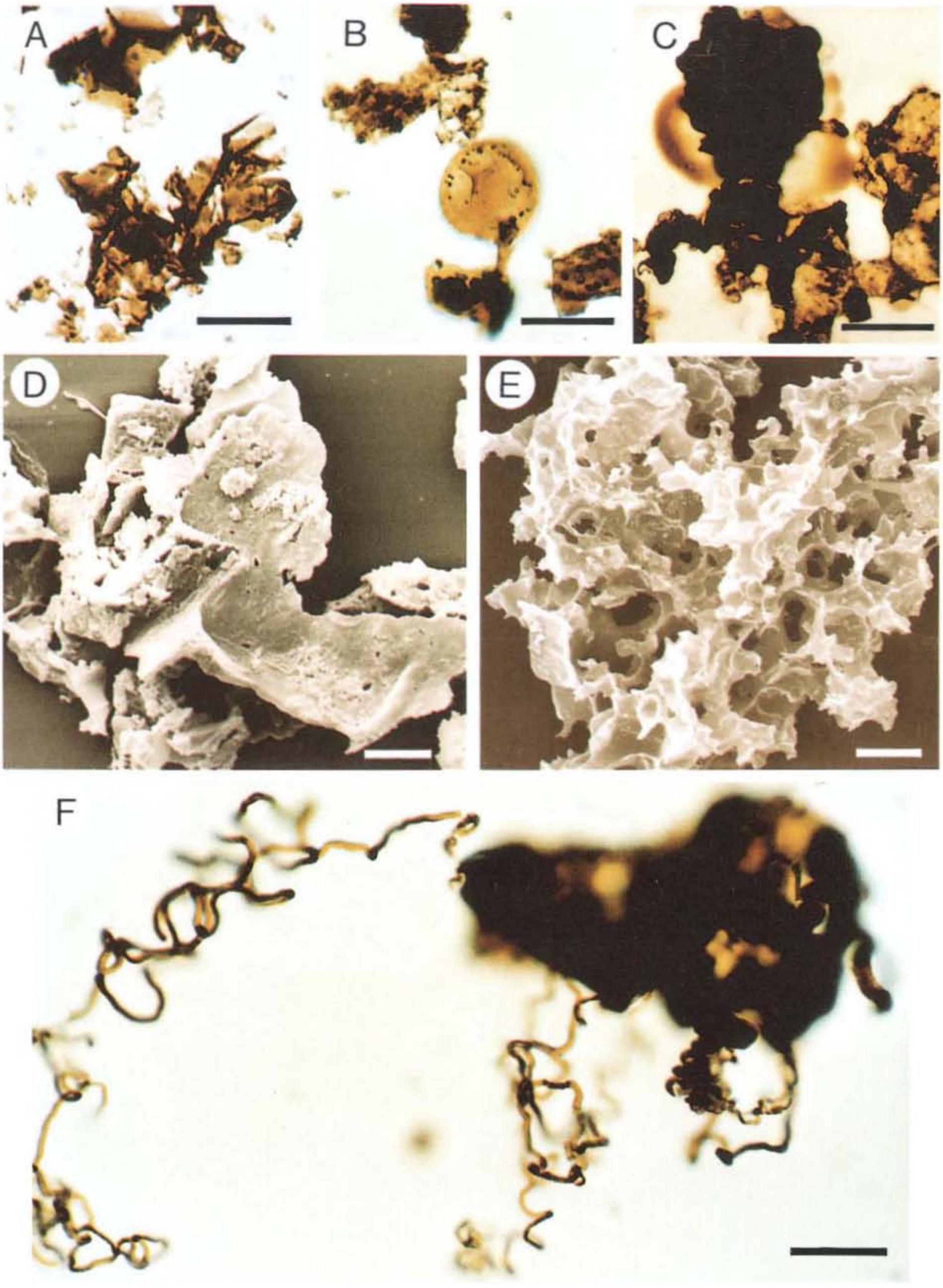


Plate 11. Bitumen in polished section

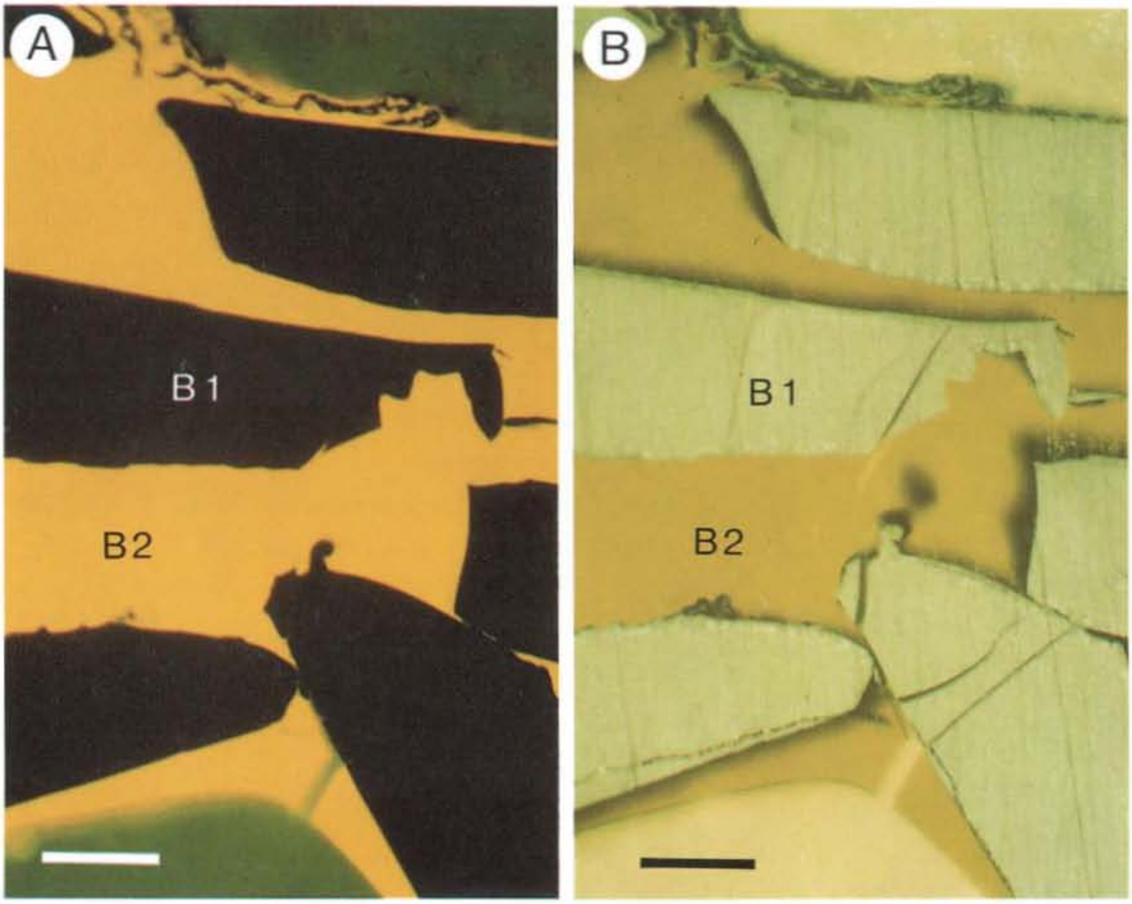


Plate 11. Bitumen in polished section

GGU 318003–53, Henson Gletscher Formation, Freuchen Land.
Scale bar: 50 μm

A. Fluorescent light photograph of two-phase bitumen.

B. Normal reflected light photograph of same field. The yellow-fluorescent low-reflecting bitumen (B2) has a R_o of 0.08% and the dark non-fluorescent high-reflecting bitumen (B1) a R_o of 1.17%.

Cover picture
Cambrian and Ordovician strata at Blue Cliffs, Wulff Land, North Greenland. Photo: J. Lautrup, GGU.