Chapter 5

Composition of organic matter in source rocks

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Oil-production from Lower Palaeozoic sediments is relatively limited compared to that from sediments of Late Palaeozoic, Mesozoic and Tertiary age (Bois *et al.*, 1982). This raises a simple question: is the low potential of Lower Palaeozoic basins due to limited abundance and poor quality of source rocks, or is it the long, deep and often more complex subsidence and thermal history combined with possible later deformation which has reduced the potential compared to younger basins?

Knowledge of the composition of the organic matter in the source rocks is very important in this context. Previous studies of oils from producing basins and organic matter from organic-rich units of Early Palaeozoic age are still limited in number and in choice and combination of analytical methods. The few detailed examples include the Michigan basin (e.g. Powell *et al.*, 1984; Rullkötter *et al.*, 1986), the Baltic Alum shales (Buchardt *et al.*, 1986), various Australian basins (e.g. McKirdy *et al.*, 1983, 1984; Glickson *et al.*, 1985), and comparison of Ordovician oils and source rocks from several basins (e.g. Reed *et al.*, 1986; Hatch *et al.*, 1987). Little information is available from the largest producing Lower Palaeozoic basins in the world in Algeria and Sibiria.

In the following, systematically recorded information from microscope studies, either of palynological specimens or of algae observed in thin section, is combined with a number of organic geochemical parameters obtained by pyrolysis, gas chromatography (GC), gas chromatography/mass spectrometry (GS/MS), and carbon isotope studies. The presentation concentrates on the two major organic-rich units in North Greenland: the Lower to Middle Cambrian Henson Gletscher Formation and the Lower Silurian shales. The hydrocarbon potential, thermal maturity and geological relations of these two potential source rocks have previously been described on the basis of field and screening data (Christiansen *et al.*, 1987; Christiansen & Nøhr-Hansen, 1989). The organic matter in the two source rock units is here characterized geochemically. This is followed by a discussion of the possible control of source rock formation with emphasis on depositional environment, palaeogeography and climate, possible upwelling, regional sea level variation, and basin development.

Microscope studies

The results of studies under the microscope are presented in detail in the preceding chapter and by Larsen (1989). Palynologically, the source rocks are dominated by aggregated and finely disseminated amorphous kerogen with only minor amounts of palynomorphs and rare remains of filamenteous algae. Shelf carbonates with a considerably lower content of organic matter than the source rocks have a relatively higher abundance of palynomorphs.

Systematic studies of more than 400 thin sections provided an overview of a large number of algal groups in the Lower Palaeozoic sediments in North Greenland (Larsen, 1989). However, this study only recorded algae in shallow-water carbonate facies without any source rock potential. Visually well defined algal remains have not been reported from the source rocks, probably because of the small size or lack of resistant cell-walls of algae in this depositional setting. Furthermore, degradation and compaction are often intense in the shales compared to the carbonates, so that the original structure is unlikely to be preserved.

Pyrolysis

More than 600 samples were studied by Rock Eval pyrolysis (Christiansen *et al.*, 1985, 1987; Christiansen & Nøhr-Hansen, 1989; Chapters 3 and 6). In particular the Hydrogen Index (HI) and the Oxygen Index (OI), plotted in a modified van Krevelen diagram, provide information on the composition of the organic matter and its hydrocarbon potential. However, the majority of the analysed source rocks are postmature and display low HI values which makes it impossible to discern the

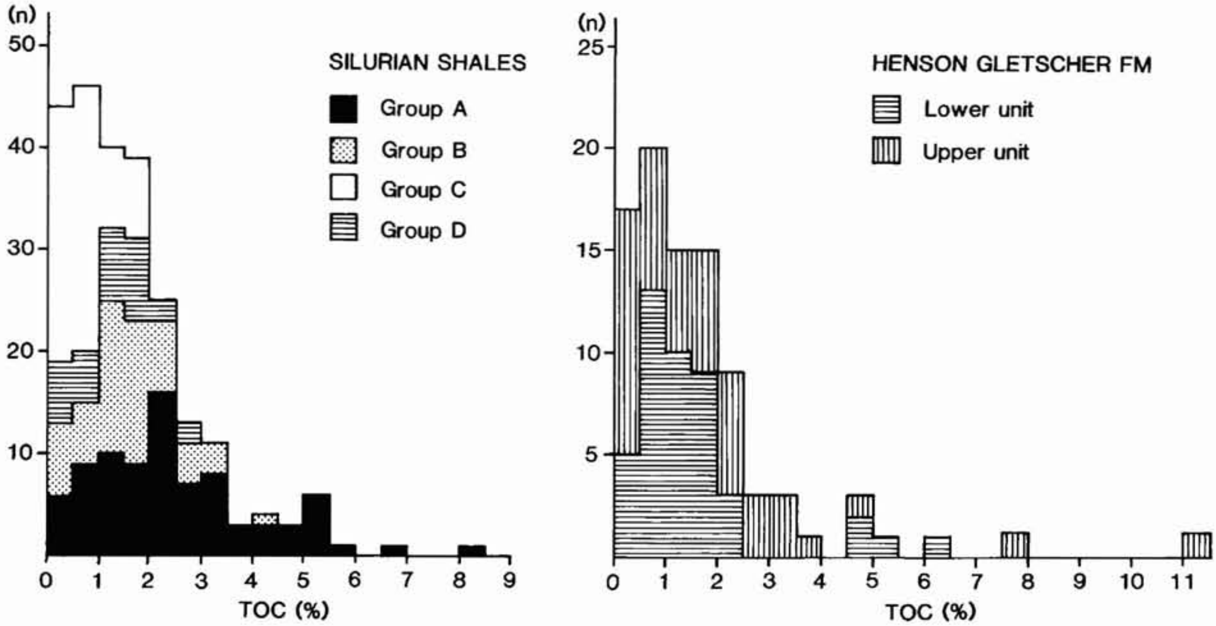

Fig. 16. Histograms showing the total organic carbon (TOC) distribution in the Cambrian Henson Gletscher Formation and in the Silurian shales. See details and subdivision in Christiansen *et al.* (1987) and Christiansen & Nøhr-Hansen (1989).

kerogen type. The kerogen from a minor number of early mature samples, mainly from Silurian shales in Washington Land and Nares Land, has been classified as typical Type II kerogen (Christiansen & Nøhr-Hansen, 1989, fig. 16), which is generally considered as derived from marine organisms, probably algae and bacteria.

The TOC distribution in the Silurian shales and the Henson Gletscher Formation is shown in fig. 16. Despite the high thermal maturity most of the shales and lime mudstones have relatively high TOC contents. In the Silurian shales, particularly group A (lower part of Thors Fjord Member and Lafayette Bugt Fm) which overlaps platform carbonates, is rich in organic carbon whereas the uppermost shales (group C) (upper part of Wulff Land and Lafayette Bugt Formations) and the back-reef shales display lower TOC contents (see details in Christiansen & Nøhr-Hansen, 1989). The Henson Gletscher Formation has a more uniform distribution with only a minor difference between the upper and lower part (fig. 16).

Gas chromatography and gas chromatography/mass spectrometry

A total of 31 potential source rock samples, 12 Cambrian and 19 Silurian, were analysed by gas chromatography (GC). In addition six of these samples, two Cambrian and four Silurian, were analysed by gas chromatography/mass spectrometry (GC/MS) (see analytical details in Chapter 3 and Østfeldt, 1987b). Additional geochemical data were obtained from the associated bitumen occurrences (see Chapter 7).

The extracts of the Cambrian and Silurian source rocks closely resemble each other in organic geochemical composition. They are dominated by saturated hydrocarbons which are strongly paraffinic with a smooth distribution without any odd to even predominance (figs 17 and 18). Most samples have a pronounced light-end bias in the paraffin distribution due to the high thermal maturity. The strong thermal alteration is also the reason for the limited preservation of cyclic biomarkers in the C_{27} to C_{33} range (see details in Chapter 6). The pristane to phytane ratios of the studied Cambrian samples display lower values (range: 1.0–1.5, average: 1.32, SD: 0.17) than the Silurian (range: 0.9–2.0, average: 1.62, SD: 0.33) (fig. 19).

The interpretation of source parameters from cyclic biomarkers is hampered by the small number of immature to early mature samples. Four of the Silurian source rocks and two associated bitumen samples display homogeneous biomarker distributions and are hence considered as representative of this succession. The Cambrian material is more complicated since only two source rock samples, and none of the associated bitumens, have preserved measurable biomarkers.

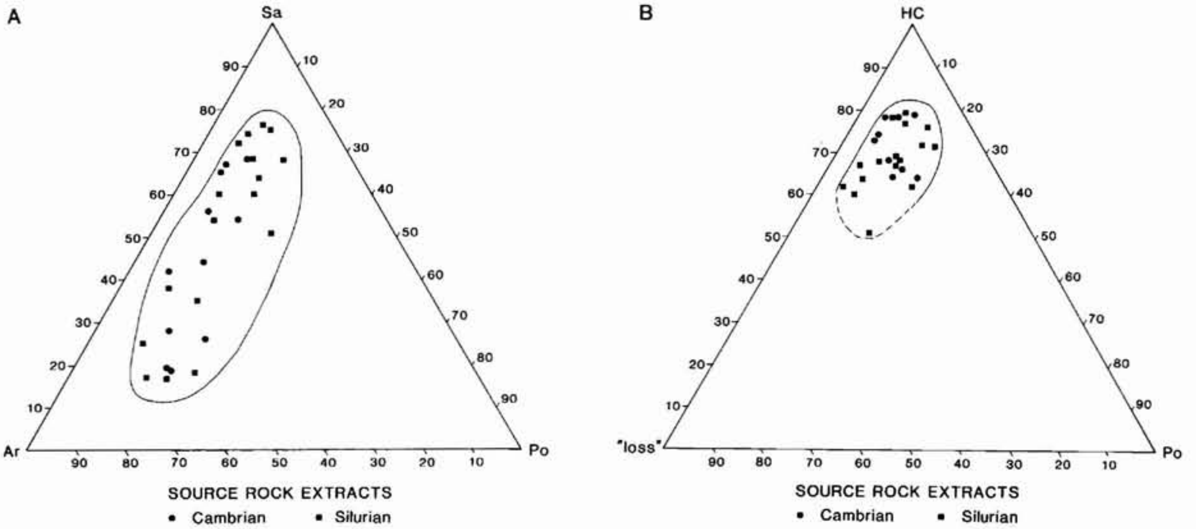

Fig. 17. Triangular diagrams showing the relative proportions in source rock extracts of (A) saturated, aromatic, and polar compounds and (B) hydrocarbons (saturates plus aromatics), polar compounds, and 'loss'. The 'loss' during column chromatography corresponds mostly to the asphaltene content.

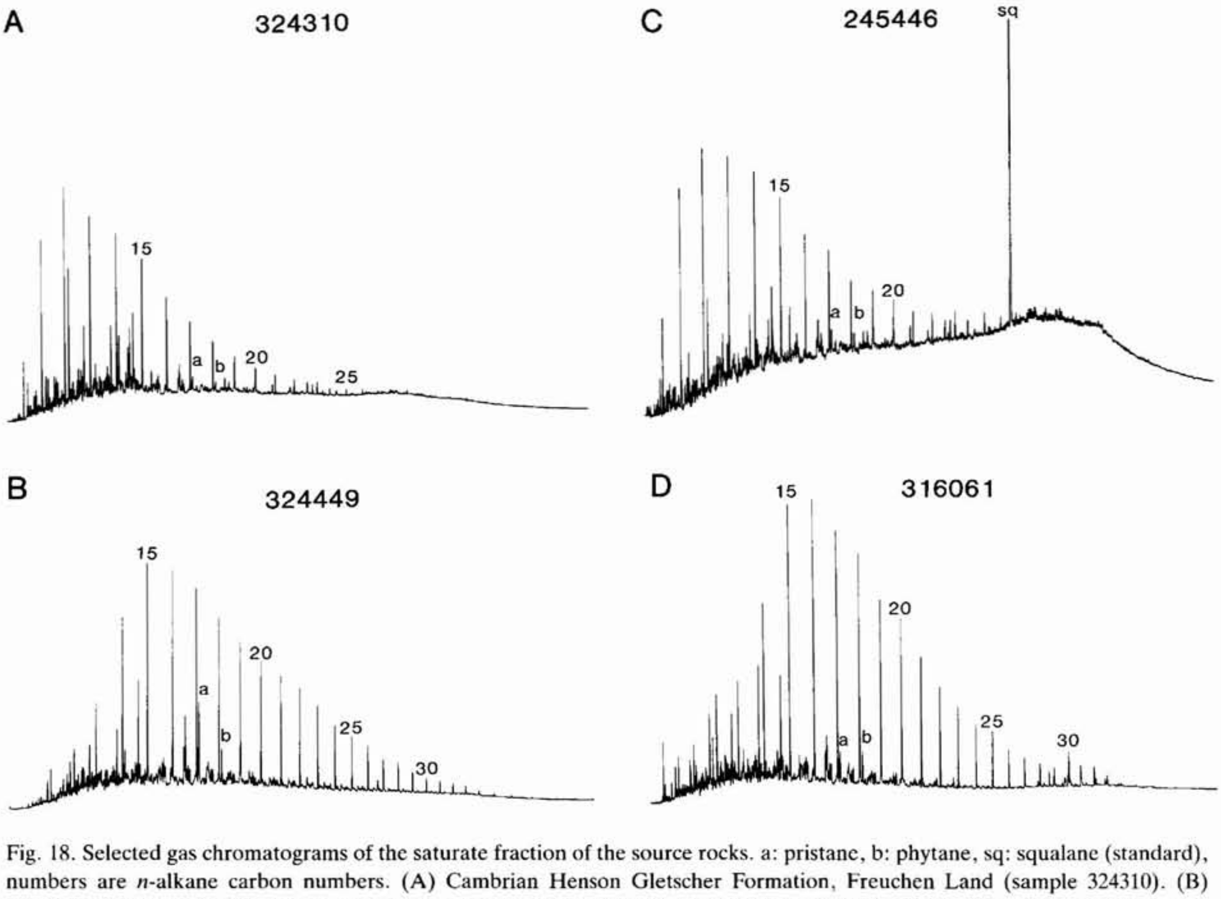

Fig. 18. Selected gas chromatograms of the saturate fraction of the source rocks. a: pristane, b: phytane, sq: squalane (standard), numbers are *n*-alkane carbon numbers. (A) Cambrian Henson Gletscher Formation, Freuchen Land (sample 324310). (B) Cambrian Henson Gletscher Formation, Peary Land (sample 245446). (C) Silurian Thors Fjord Member, Nares Land (sample 324449). (D) Silurian Lafayette Bugt Formation, Washington Land (sample 316061).

Many of the possible long distance migrated bitumens in the southern part of the region (see Chapter 7) have also preserved biomarkers.

The two Cambrian source rocks display a rather unusual, but uniform, biomarker distribution with relatively large amounts of tricyclic deterpenoid compounds, minor amounts of steroid biomarkers (mainly C_{29} steranes, fig. 21), and lack of cyclic triterpenoids (fig. 20 A). The Silurian source rocks (and bitumen samples) contain both steroid and treterpenoid biomarkers including hopanes (fig. 20 B). The sterane distribution is completely dominated by C_{29} steranes (figs 20 B and 21).

The long distance migrated bitumens (group C in Chapter 7) are moderately to severely biodegraded but contain detectable cyclic biomarkers such as steroids, triterpenoids and hopanes (fig. 20 C). It is remarkable that all eight analysed bitumen samples contain the triterpenoid biomarker gammacerane in relatively high amounts, since this compound has not been recorded from any of the two known source rock units.

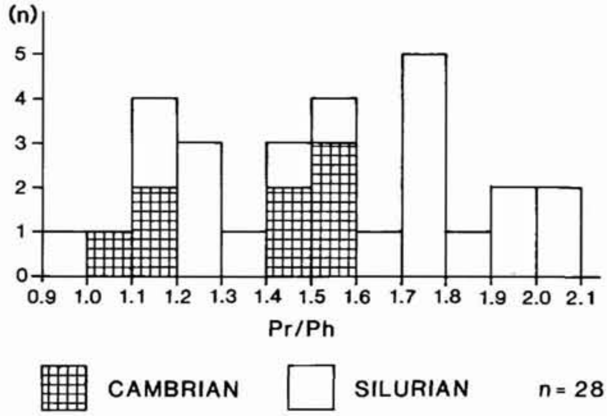

Fig. 19. Histogram showing the variation in pristane (Pr) to phytane (Ph) ratio in extracts of Cambrian and Silurian rocks.

Carbon isotopes

Carbon isotopic compositions were determined for 16 samples of Cambrian and Silurian organic-rich rocks. The data include both kerogen and soluble organic matter (extracts). δ^{13}C-values for both extracts and kerogens fall within a range from −26.5 to −32.0‰ (figs 22 and 23). Cambrian kerogens and extracts are depleted in the heavy carbon isotope compared to the Silurian samples (−29.7 to −31.2‰ for Cambrian, −26.9 to −30.5‰ for Silurian samples). The only exception is the Silurian sample 324446, which has a δ^{13}C-value comparable to that of the Cambrian material.

Extracts from Cambrian samples are slightly enriched in ^{13}C in relation to corresponding kerogens. Silurian extracts, on the other hand, are indistinguishable from the corresponding kerogens.

The carbon isotopic composition of kerogen of Early Palaeozoic age has been reported by Welte *et al.* (1975), Galimov (1980), Glickson *et al.* (1985), Lewan (1986), Buchardt *et al.* (1986), and Hatch *et al.* (1987). The values vary from −26 to −32‰ with a dominance in the range below −28‰. The North Greenland samples fall within this range.

Soluble organic matter is generally believed to be depleted in ^{13}C as compared to corresponding kerogen (Galimov, 1980; Schoell, 1984). In kerogen of predominantly amorphous composition, however, the difference seems to be insignificant (Buchardt & Cederberg, 1987; Buchardt & Lewan, unpublished data). The minor differences observed in the present material is therefore in accordance with other data.

Control of chemical composition

The variation in chemical composition of kerogen and soluble organic matter in source rocks is related to type of primary organic matter, the depositional environment and thermal maturation. The carbon isotopic composition is mainly dependent on the type of organic matter, environment and early diagenesis (Deines, 1980; Lewan, 1986) whereas thermal maturation has only minor influence on the composition (Lewan, 1983; Buchardt *et al.*, 1986). The pristane to phytane ratio also seems to be related to depositional conditions and it is generally accepted that high ratios reflect predominantly oxidizing environments whereas low ratios are found in organic matter deposited under reducing conditions (Tissot & Welte, 1984). The distribution of cyclic biomarkers has strong implications for the interpretation of the type of organic matter and the environment, especially from Mesozoic to Recent sediments, but most parameters are overprinted by maturity effects in thermally mature to postmature sediments.

In Mesozoic to Cenozoic deposits differences in composition are most commonly related to either a marine or a terrestrial origin of the kerogen. In North Greenland, however, few terrestrial palynomorphs and plant remains are reported (Larsen *et al.*, 1987; Nøhr-Hansen & Koppelhus, 1988), and the kerogen is presumed to be mainly of marine origin. This is in contrast to the Lower Palaeozoic source rocks formed in a fresh or brackish water environment in the Michigan, Chinese and Australian intracratonic basins. It should be noted that well-

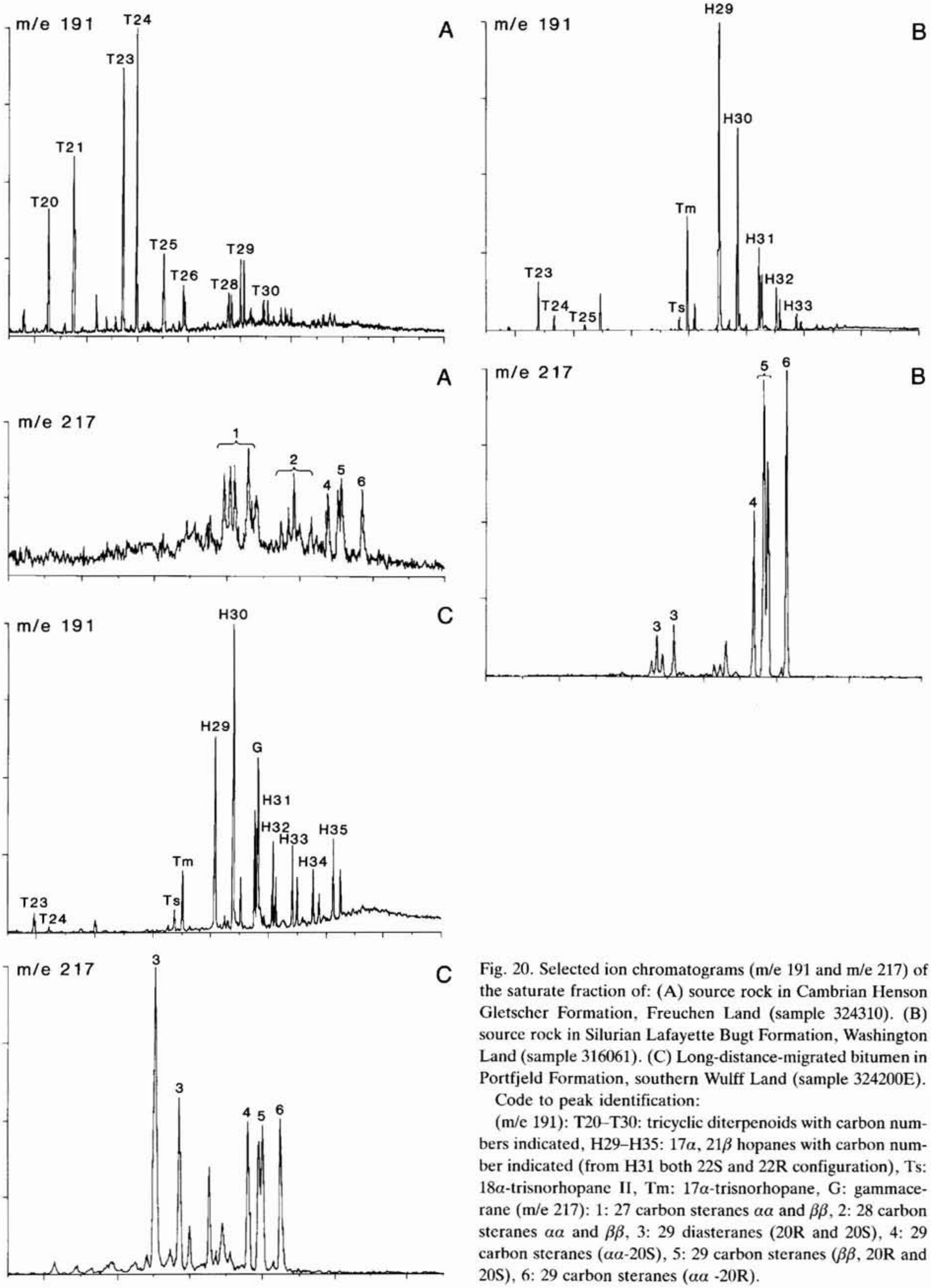

Fig. 20. Selected ion chromatograms (m/e 191 and m/e 217) of the saturate fraction of: (A) source rock in Cambrian Henson Gletscher Formation, Freuchen Land (sample 324310). (B) source rock in Silurian Lafayette Bugt Formation, Washington Land (sample 316061). (C) Long-distance-migrated bitumen in Portfjeld Formation, southern Wulff Land (sample 324200E).

Code to peak identification:

(m/e 191): T20–T30: tricyclic diterpenoids with carbon numbers indicated, H29–H35: 17α, 21β hopanes with carbon number indicated (from H31 both 22S and 22R configuration), Ts: 18α-trisnorhopane II, Tm: 17α-trisnorhopane, G: gammacerane (m/e 217): 1: 27 carbon steranes $\alpha\alpha$ and $\beta\beta$, 2: 28 carbon steranes $\alpha\alpha$ and $\beta\beta$, 3: 29 diasteranes (20R and 20S), 4: 29 carbon steranes ($\alpha\alpha$-20S), 5: 29 carbon steranes ($\beta\beta$, 20R and 20S), 6: 29 carbon steranes ($\alpha\alpha$ -20R).

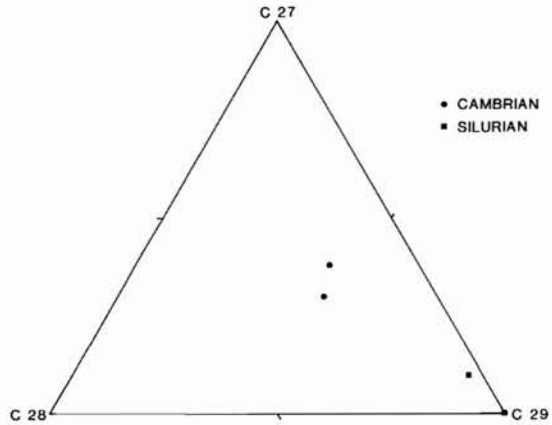

Fig. 21. Triangular diagram showing the relative proportion of the C_{27}, C_{28} and C_{29} steranes in Cambrian and Silurian source rocks.

defined remains of higher terrestrial plants are unknown from deposits older than Early Devonian (Glensel & Andrews, 1987).

Visually, only minor differences have been recorded between the organic matter in the Cambrian and Silurian source rocks (Chapter 4). It is completely dominated by apparently identical amorphous kerogen with only a minor content of palynomorphs. The amorphous kerogen probably derived from marine planktonic organisms. The observed differences in geochemical composition of Cambrian and Silurian kerogen are hence mainly ascribed to deviating environments or variation in early diagenetic modifications.

The higher pristane to phytane ratios in the Silurian rocks, as compared to the Cambrian, point to a more oxidizing environment at the time of deposition of Silurian source rocks. The ^{13}C-depleted kerogens are characterized by pristane/phytane ratios below 1.5 whereas ^{13}C-enriched samples have ratios between 1.5 and 2.1 (fig. 24). Similar relationships have been observed for Mesozoic deposits (Buchardt & Cederberg, 1987). The isotopic difference may be explained by preferential preservation of ^{13}C-depleted lipid-derivates in more reducing environments (Galimov, 1980).

Pristane and phytane are considered the primary derivates of the phytyl side-chain of the chlorophyll molecule (e.g. Illich, 1983). The presence in relatively high amounts in both the Cambrian and Silurian source rocks is taken as evidence of active photosynthesis in the precursors to the major part of the organic matter. In contrast, several world-wide distributed Ordovician source rocks have very low pristane and phytane contents and a kerogen composition dominated by *Gloeocapsamorpha prisca* Zalessky 1916 (Reed *et al.*, 1986). Geochemical evidence of this 'primitive' prokaryotic organism has not been recorded in the present study.

Selected biomarkers such as the steranes, hopanes and gammacerane may provide information on the possible precursors of the organic matter. Ourisson *et al.* (1979) claimed that prokaryotic organisms are the major source of hopanes in hydrocarbons whereas eukaryotic organisms and other higher organisms are the main sources of steranes. It is only the Silurian source rocks and the associated bitumens which contain hopanes. Since no major evolutionary steps in algae and bacteria are known to have taken place from Cambrian to Silurian times it would be expected that the Silurian source rocks were dominated by similar or less primitive organisms compared to the Cambrian, and hence have a lower hopane content. The hopane content is, however, easily changed during thermal maturation. Both the Cambrian and Silurian source rocks contain steranes. The C_{29} steranes, which in Mesozoic rocks are consid-

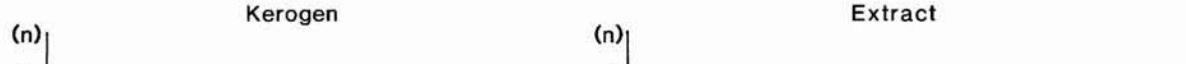

Fig. 22. Histogram showing the variation in $\delta^{13}C$ composition of kerogen and extracts in Cambrian and Silurian source rocks.

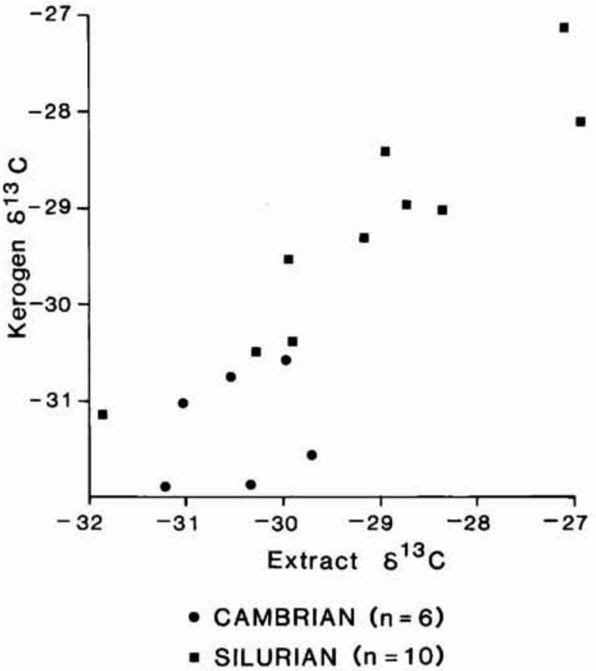

Fig. 23. Cross plot of isotopic composition in extracts versus kerogens.

ered to be terrestrial in origin (Huang & Meinschein, 1976), are dominant in the Silurian shales and occur in moderate amounts in the Cambrian source rocks (fig. 21). This dominance of C_{29} steranes is commonly observed in Lower Palaeozoic rocks (Waples, 1985 p. 162; Moldowan *et al.*, 1985; Grantham, 1986). The triterpenoid biomarker gammacerane, which has only been recorded from the long distance migrated bitumens, was also originally proposed as a component of non-marine origin (Hills *et al.*, 1966). This interpretation has since been questioned and although the origin is still unclear it should be noted that the compound is most abundant in Mesozoic sediments from hypersaline environments, especially lacustrine (e.g. Moldowan *et al.*, 1985; Philp & Lewis, 1987).

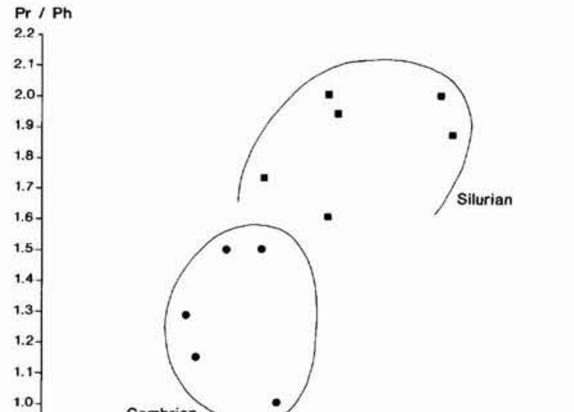

Fig. 24. Cross plot of isotopic composition versus pristane to phytane ratio of Cambrian and Silurian source rock extracts (only organic-rich units included).

The recorded combined parameters from GC, GC/MS and C-isotope analyses make it possible to distinguish geochemically between the Cambrian and Silurian source rocks. The difference in composition seems to be mainly controlled by variation in depositional environment rather than variation in precursors of the organic matter. It is suggested that the Cambrian source rocks formed under more reducing conditions than the Silurian.

Control of source rock deposition

Deposition of source rocks in the Early Palaeozoic, and black shales in general, was controlled in time and space by a large number of more or less interdependent factors (see e.g. Thickpenny & Leggett, 1987): organic production versus biochemical degradation, climate, sea level stand, palaeogeography, upwelling zones, sedimentation rate, water depth, etc.

Compared to younger sediments exact knowledge of some of these fundamental factors is often limited. In North Greenland the spatial and chronological relations of source rock deposition are controlled by a combination of local factors controlling basin development, and the global configuration (palaeogeography, climatic belts, global sea-level, evolution of organisms) at the time of deposition.

In Late Cambrian times North Greenland was situated approximately 10° south of the equator and the basin margin had an east–west orientation (Scotese *et al.*, 1979 fig. 9). During the Early Ordovician it drifted northwards to a position 15° north of the equator. The position of Laurentia (North America and Greenland) did not change much in the following period and in mid-Silurian time North Greenland was still at a position of 15° north with a northwest to southeast trend of the basin margin (Scotese *et al.*, 1979 fig. 18). The equatorial position of the Franklinian basin throughout most of its depositional history points towards a stable tropical climate with a possible variation caused by the crossing of the equator and the counterclockwise rotation. This climatic interpretation is further supported by the algae study which indicates a tropical or subtropical climate at the time of deposition (Larsen, 1989).

The palaeogeographic position with an east–west trend of the basin margin is not in accordance with a control of source rock deposition by 'classical coastal upwelling', a model which has been suggested for many basins (e.g. Parrish, 1982, 1987; Schopf, 1983). Berry & Wilde (1978) proposed a general model of black shale deposition controlled by progressively ventilated oceans; during glacial times with low sea levels, well-oxygenated conditions prevailed whereas extensive shelf areas were covered with anoxic water in the interglacial periods of high stands of sea level. This model implies generally anoxic waters, and very long periods of anoxic conditions, in Early Palaeozoic time. Black shale deposition in Europe was particularly concentrated in three intervals: Middle to Late Cambrian, Caradoc (in Late Ordovician), and Llandovery (Silurian), all characterized by periods of rising sea levels (McKerrow, 1979; Leggett *et al.*, 1981; Thickpenny & Leggett, 1987). Compared to this temporal pattern the situation in North Greenland seems different. The Early to Middle Cambrian Henson Gletscher Formation was deposited in a period of inferred falling global sea level whereas the most organic-rich parts of the Silurian shales formed during a major sea-level rise in the Llandovery (see Leggett *et al.*, 1981). Considered in detail it should be noted that the organic-rich Silurian shales in North Greenland are slightly younger than the maximum deposition of black shales in Europe. Furthermore, the onset of source rock deposition was diachronic; it started earlier towards the west (Washington Land) than in the central part of North Greenland (Christiansen & Nøhr-Hansen, 1989).

The Silurian source rock deposition was related to the foundering of the carbonate platform. This is a combined effect of sea-level rise due to the Gondwana deglaciation and possible downflexuring caused by loading of the thick turbidite sequence deposited to the north (Higgins *et al.*, in press; see also Chapter 2). The foundering platform was covered by up to 100 m of black shales deposited in an anoxic environment (the Thors Fjord Member). During continued high-rate subsidence this pattern changed to more oxygenated deposits of deep-water grey shales and sandstone turbidites.

In the Cambrian case, source rock deposition took place in a period with a wide outer shelf. The onset of the anoxic conditions followed a change from siliciclastic to dominating carbonate deposition and ended when platform carbonates prograded northwards over the muddy/siliciclastic outer shelf.

It is concluded that deposition of organic-rich sediments with a good primary hydrocarbon potential was widespread in Early Palaeozoic times in North Greenland. Two major organic-rich units were deposited, one in Early to Middle Cambrian time and one in Early Silurian time. The organic matter in both units seems to have been derived from the same types of precursors as those to the amorphous kerogen. Geochemically, the two units are discerned employing several, mainly environmentally controlled, parameters.

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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

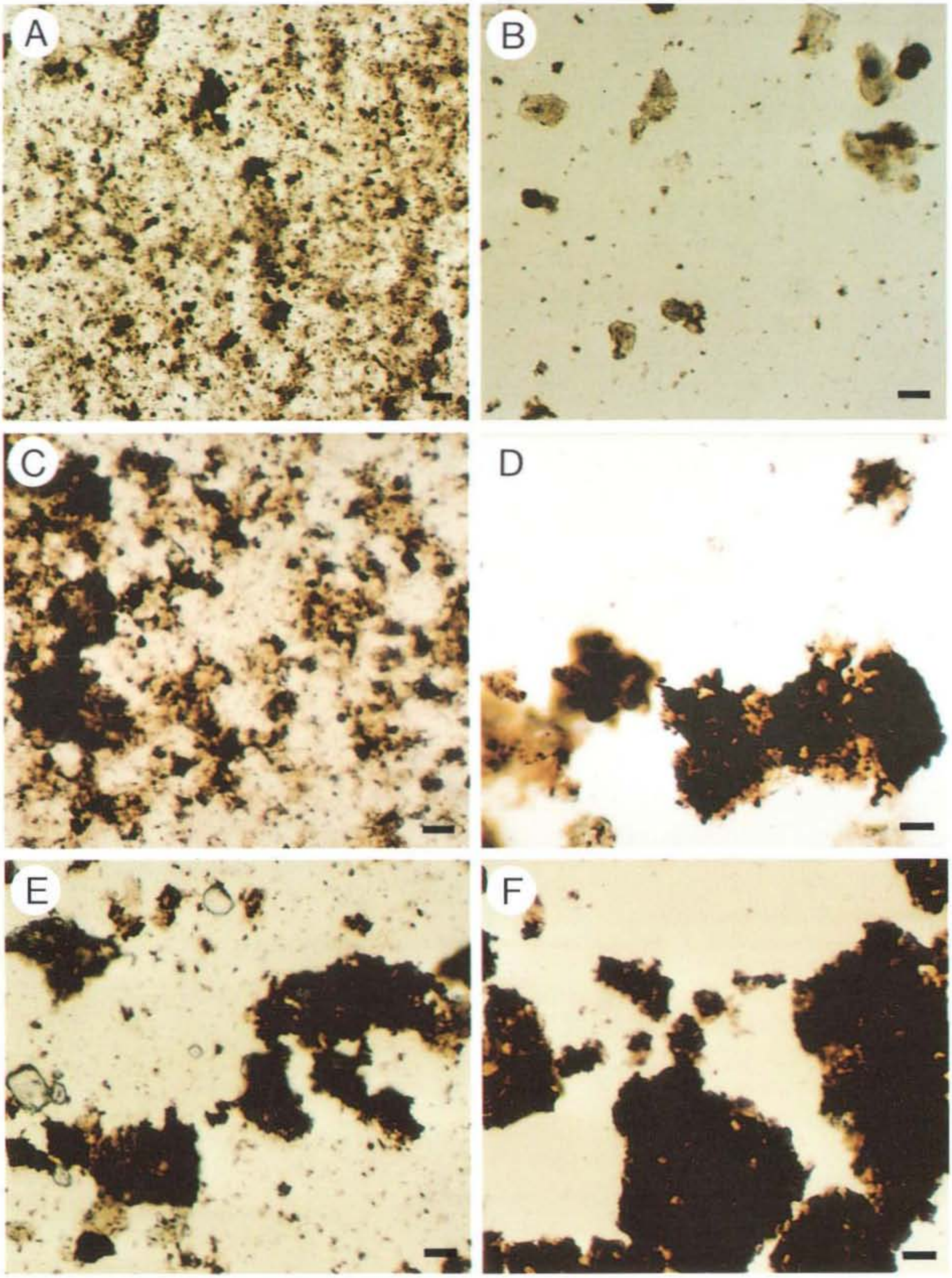

Plate 2. Cambrian palynomorphs

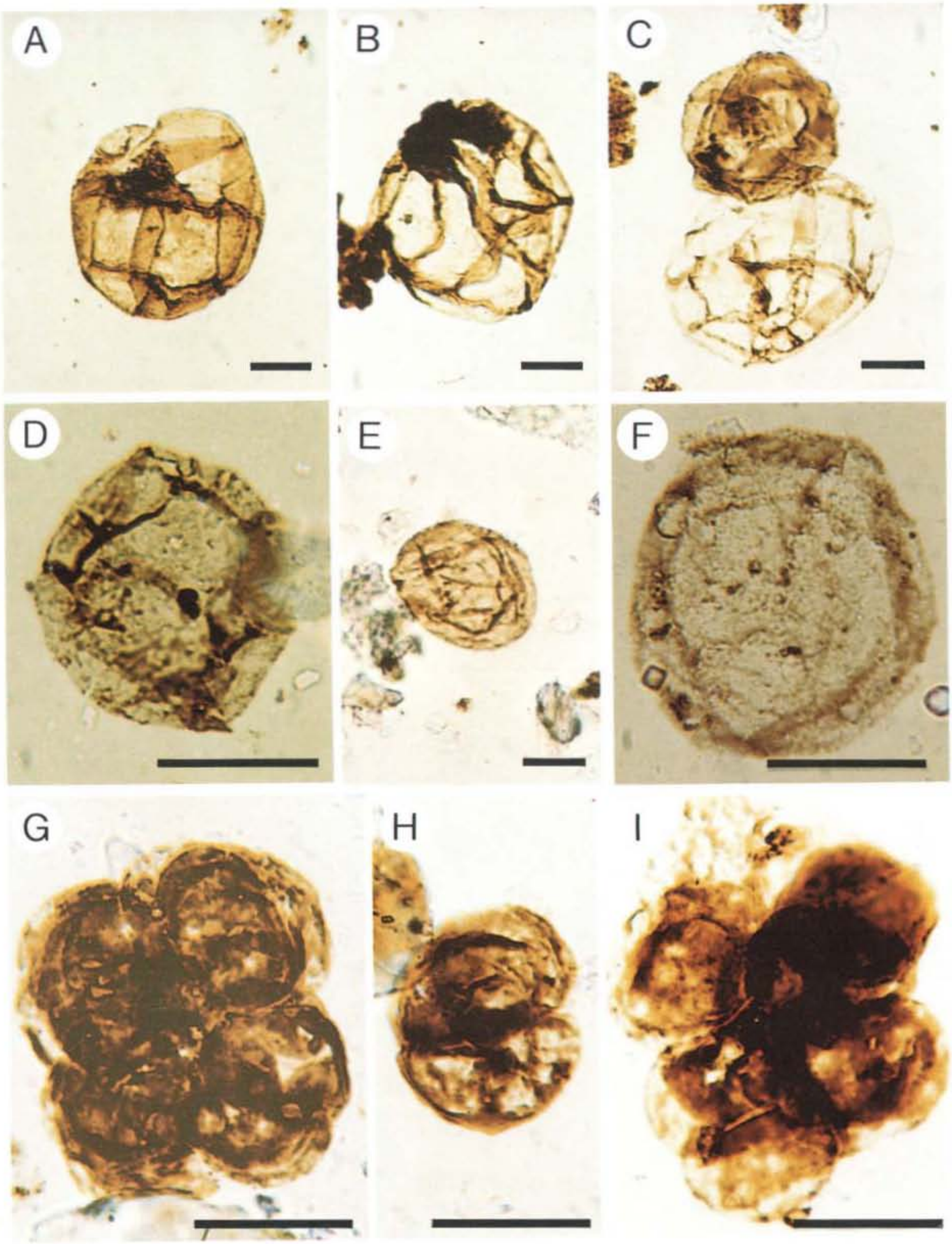

Plate 3. Ordovician palynomorphs

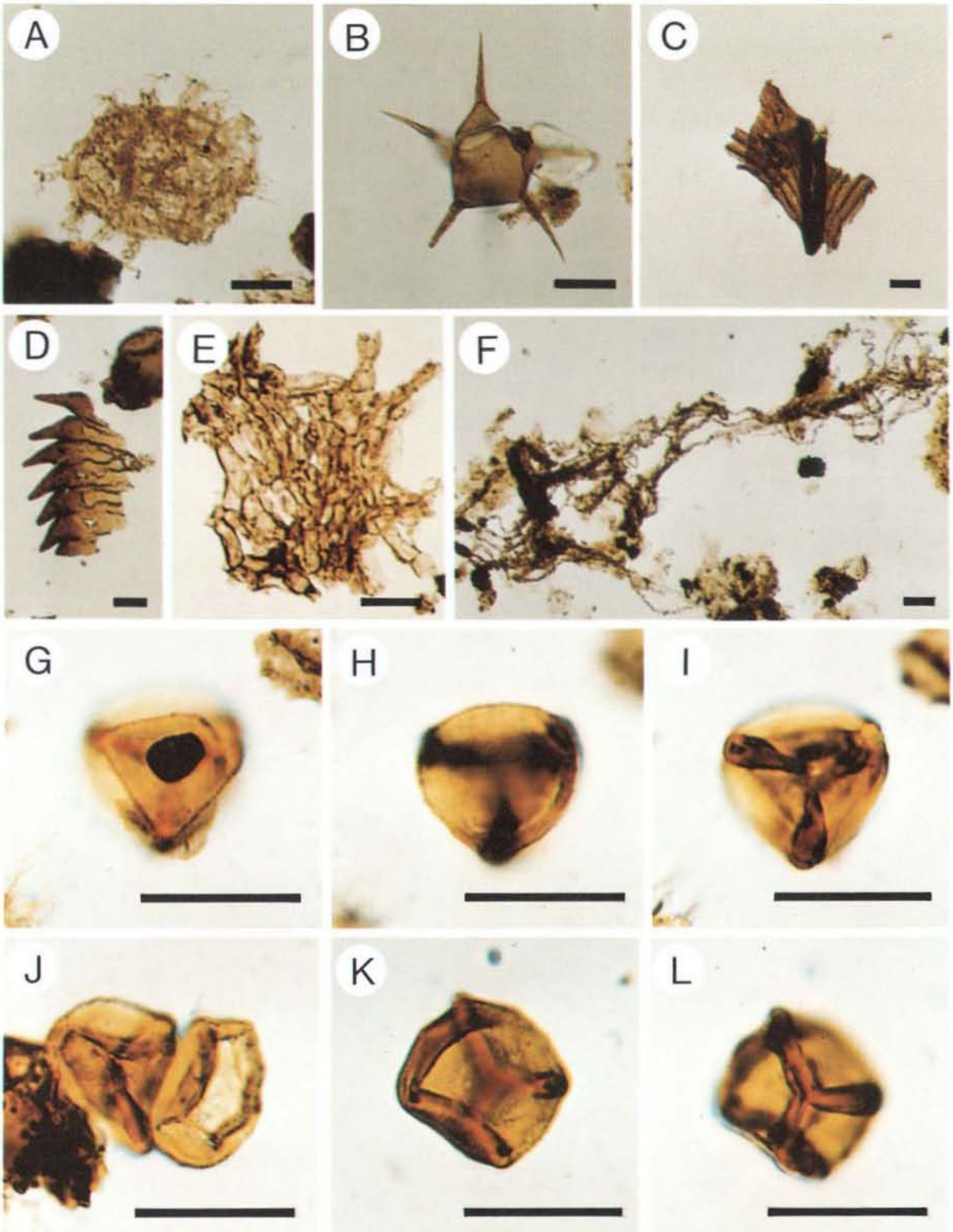

Plate 4. Silurian palynomorphs

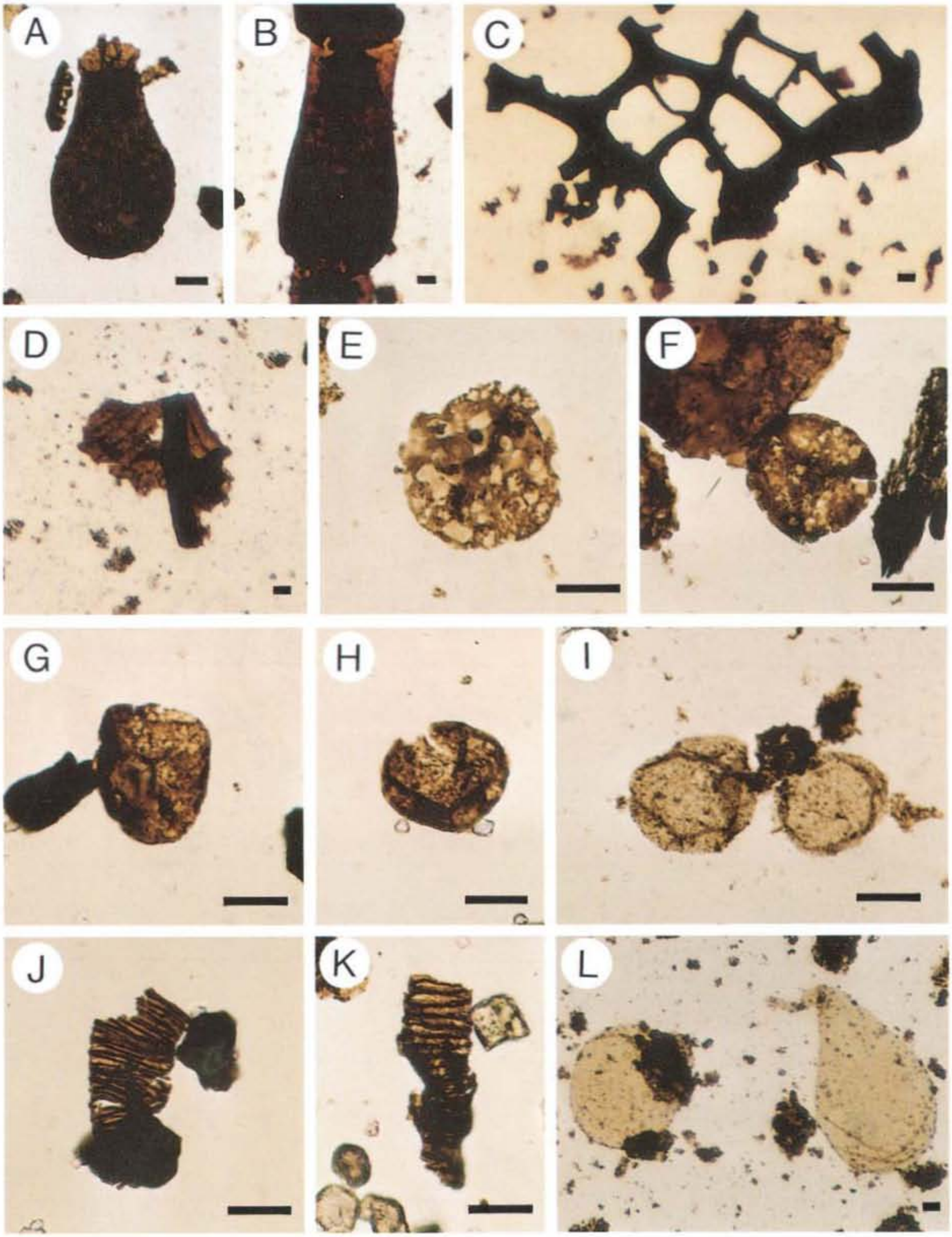

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

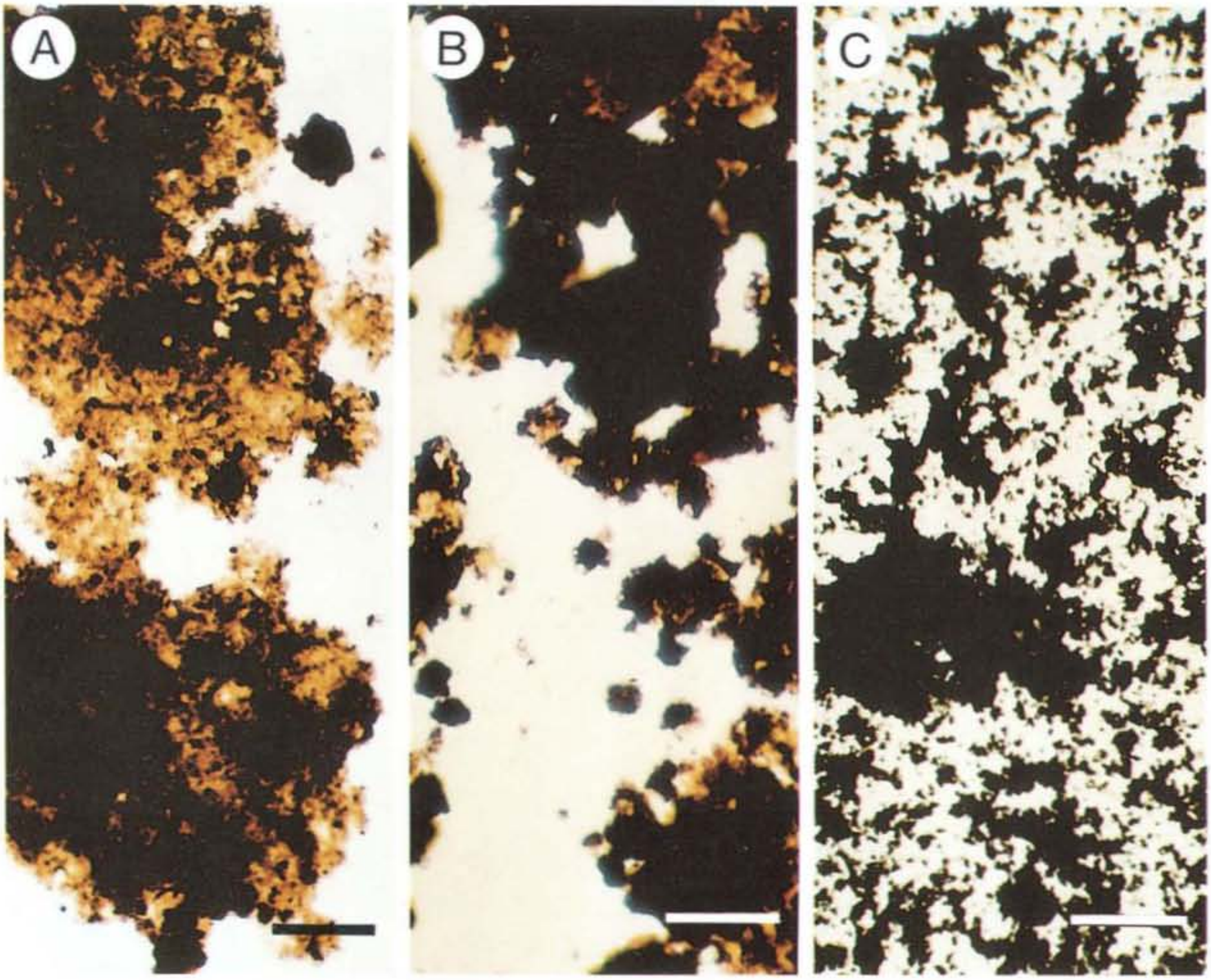

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

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

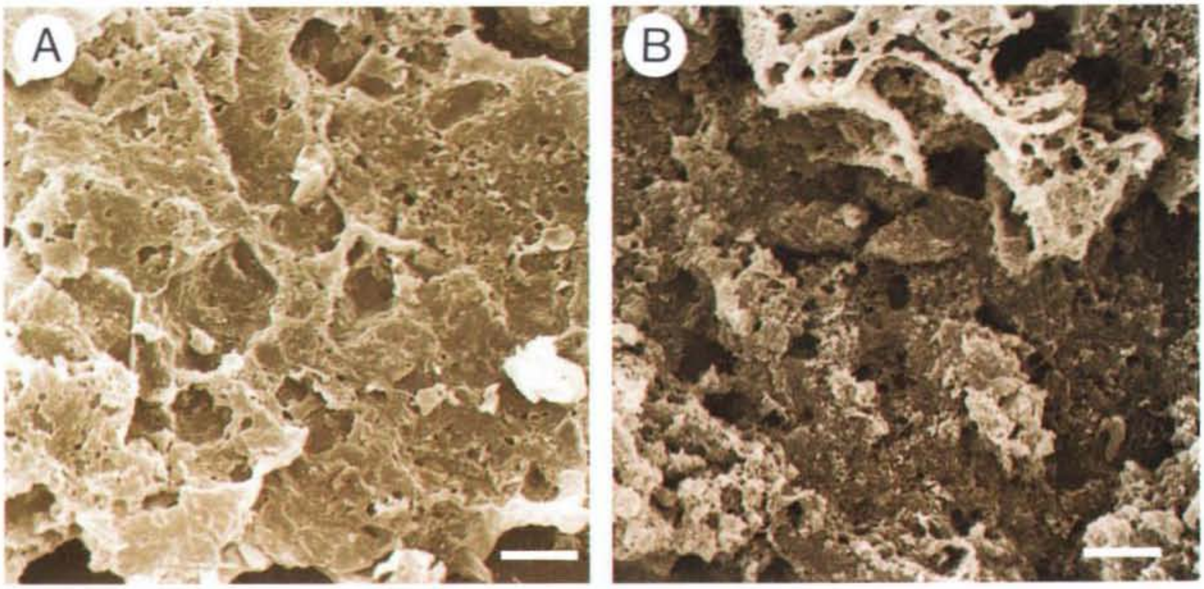

Plate 6. Change in structure of amorphous kerogen with increasing thermal alteration as observed in the scanning electron microscope

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

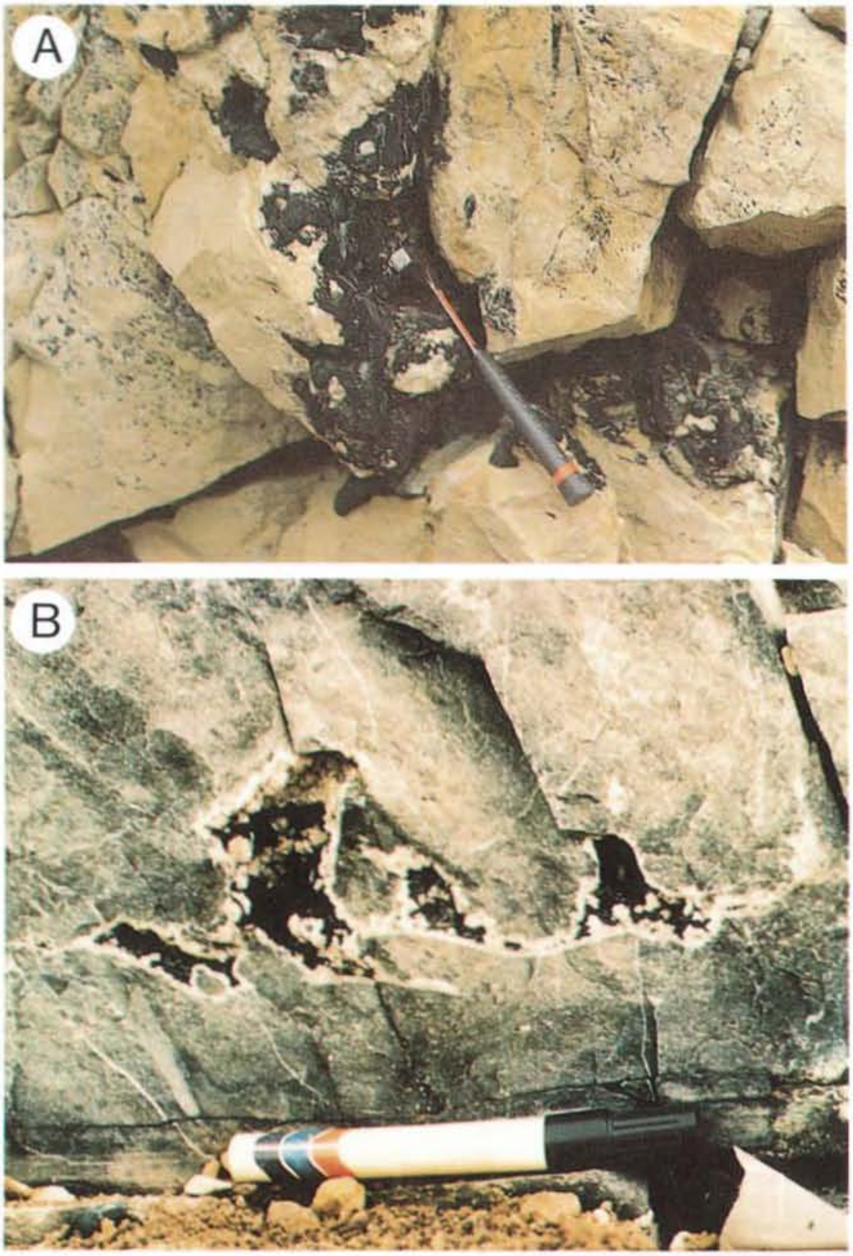

Plate 8. Macroscopic bitumen in slabs

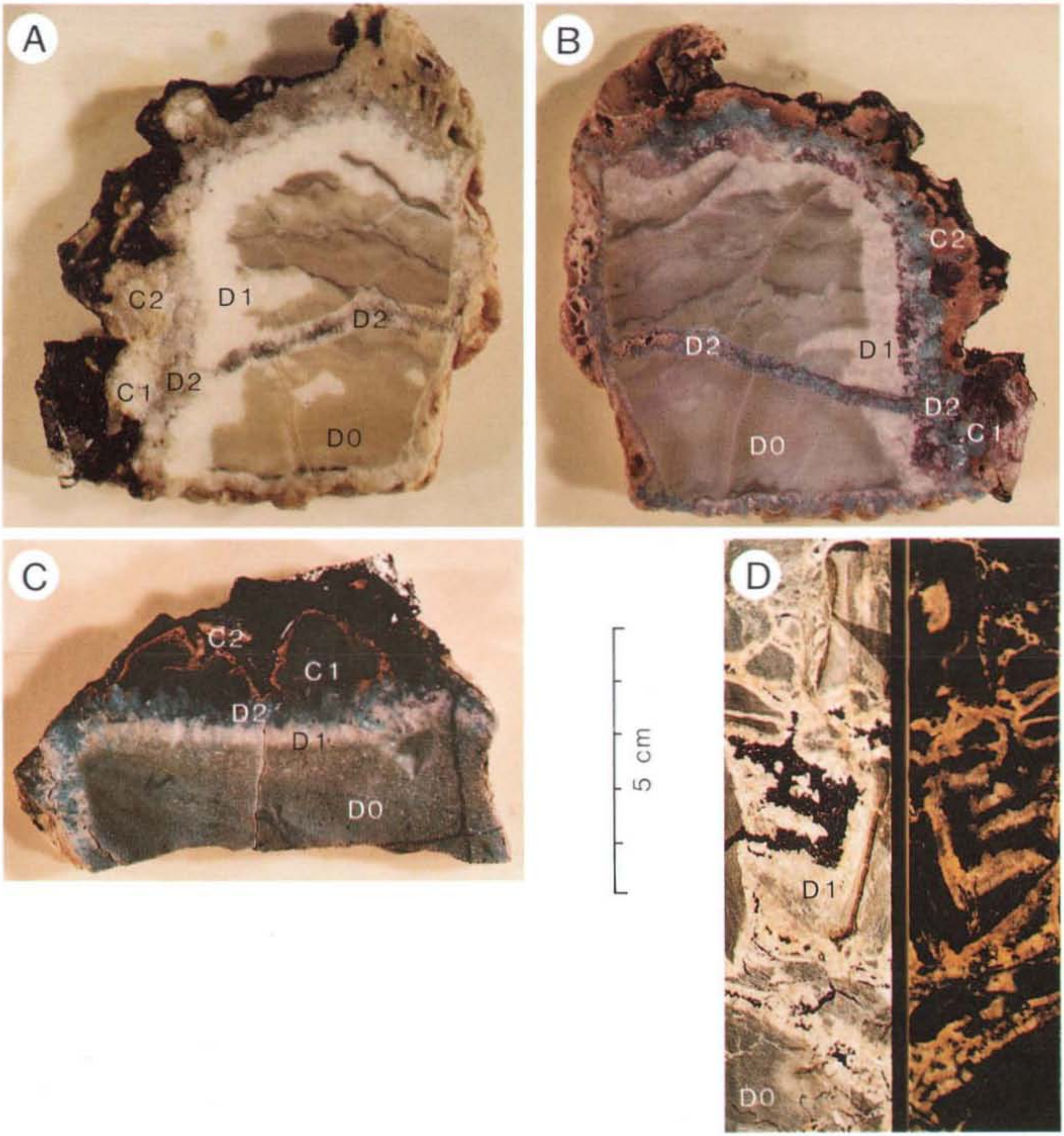

Plate 9. Bitumen in thin section

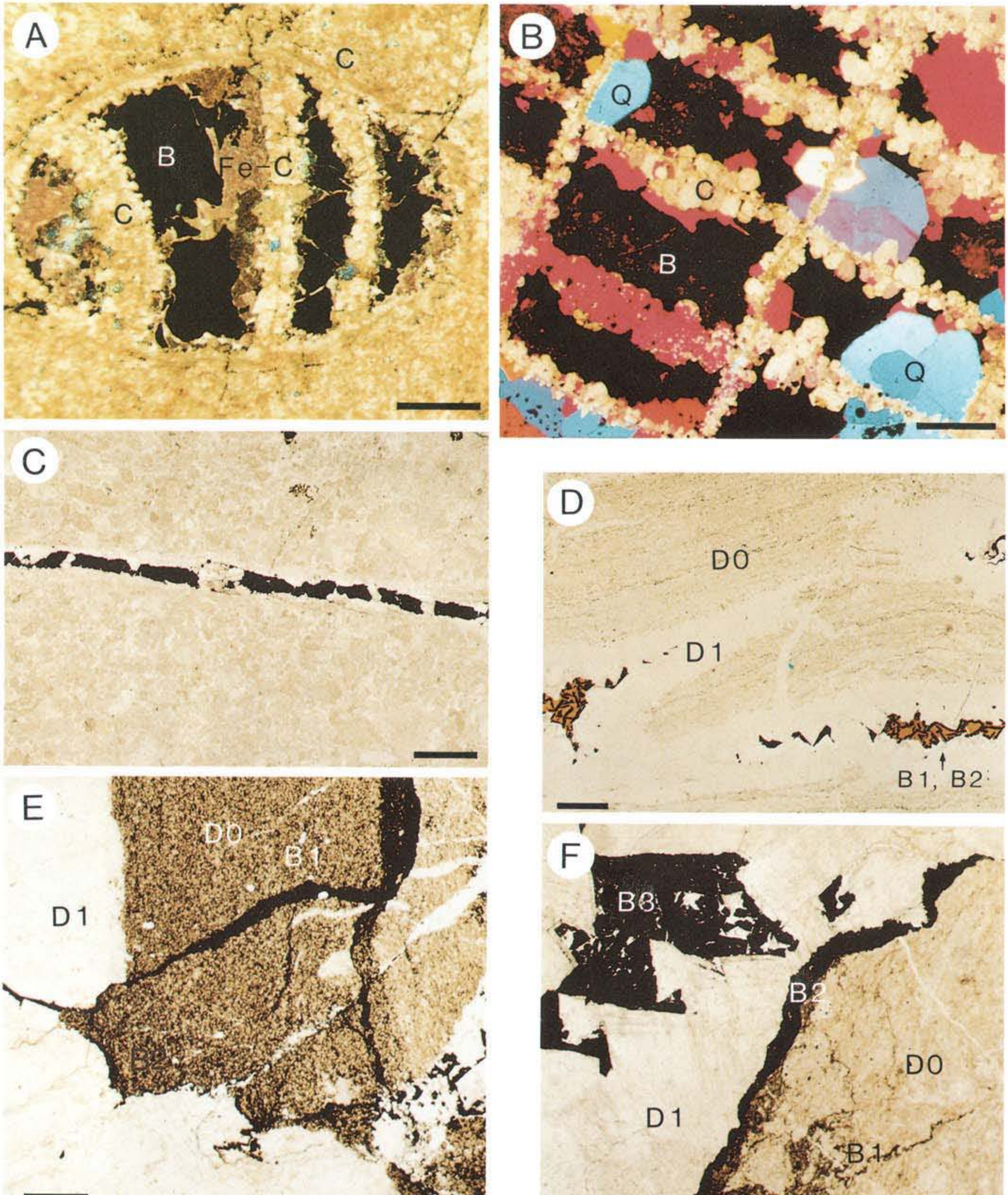

Plate 10. Bitumen in palynologically prepared samples observed in microscope or in SEM

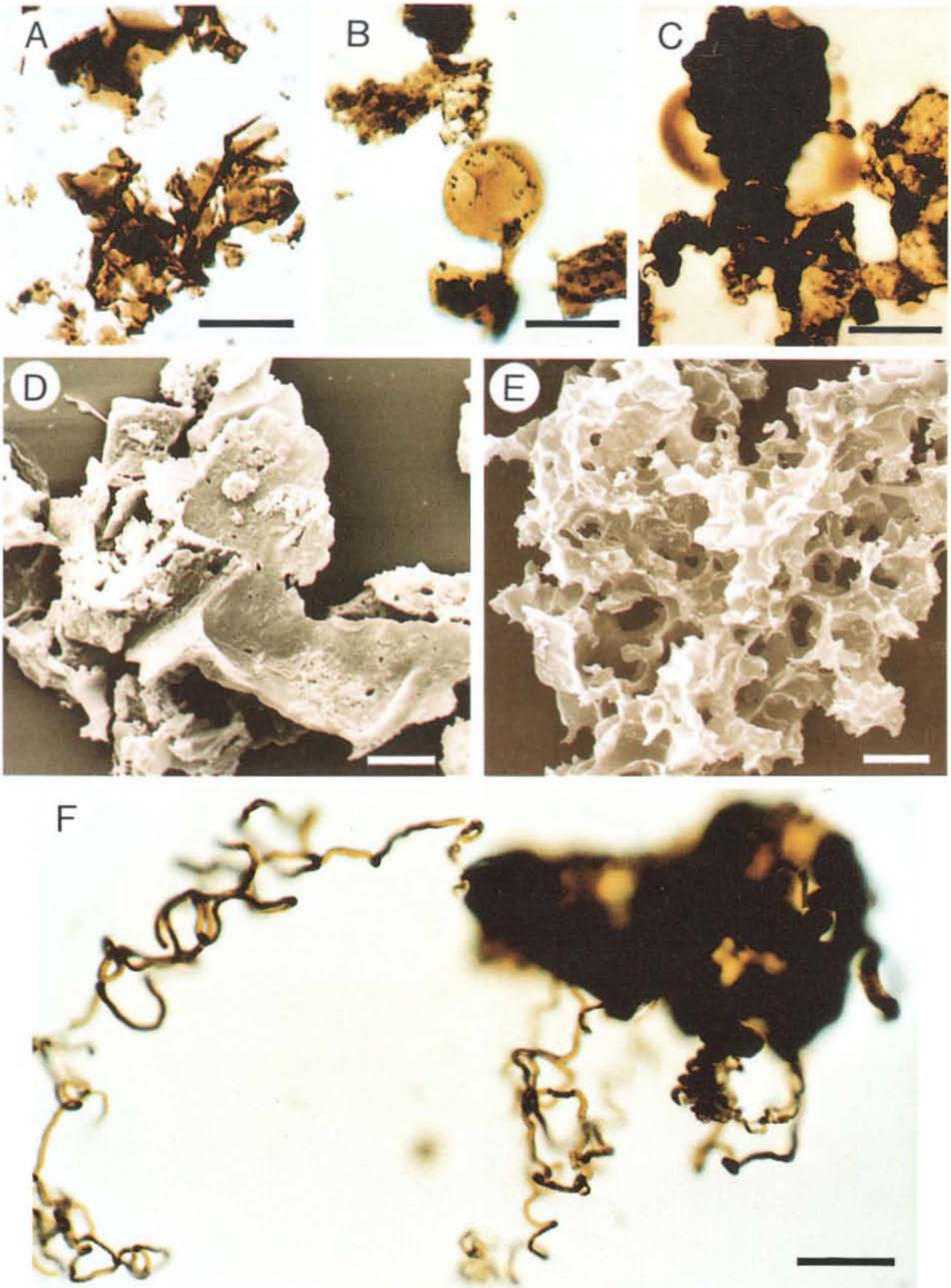

Plate 11. Bitumen in polished section

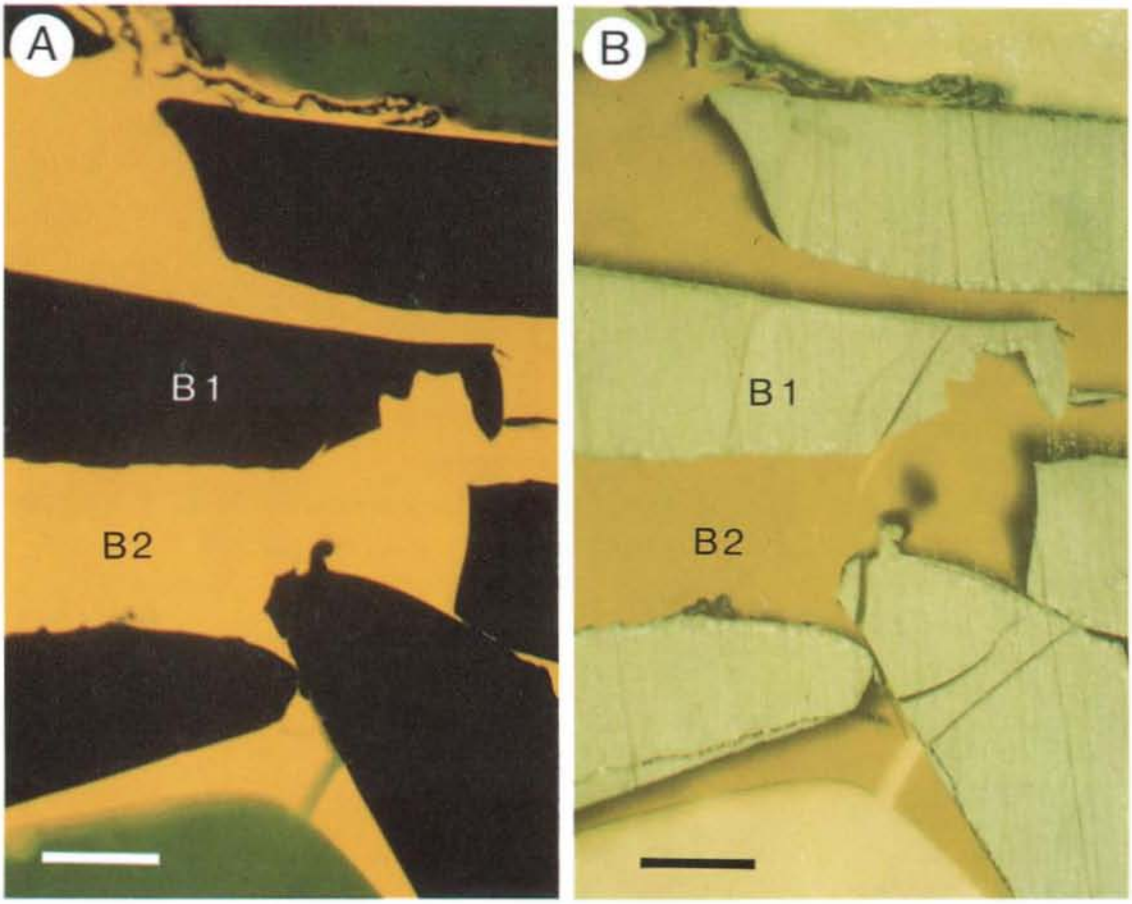

Plate 11. Bitumen in polished section

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.