Chapter 2

Review of the Lower Palaeozoic basin in North Greenland with special emphasis on petroleum geology

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The Lower Palaeozoic sediments of North Greenland were deposited in the eastward extension of the Franklinian basin of Ellesmere Island, and are exposed today in a broad E–W trending zone across North Greenland about 800 km long and up to 200 km wide (figs 4 and 5).

Numerous accounts on the geology of this region have appeared, particularly over the last decade following field work by GGU in 1978–1980 and 1984–1985 (*Rapp. Grønlands geol. Unders.* **88, 99, 106, 126, 133**). A number of reviews with quite different approaches summarize the geology with respect to the history of exploration (Dawes & Christie, 1982, Christie & Dawes, in press), general geology (Dawes, 1971, 1976; Dawes & Peel, 1981; Higgins, 1986), stratigraphy (Peel, 1982, 1985), deformation (Higgins *et al.,* 1985) and basin development (Surlyk & Hurst, 1984; Higgins *et al.,* in press). Reviews concerning the geological implications for future petroleum activities have, however,

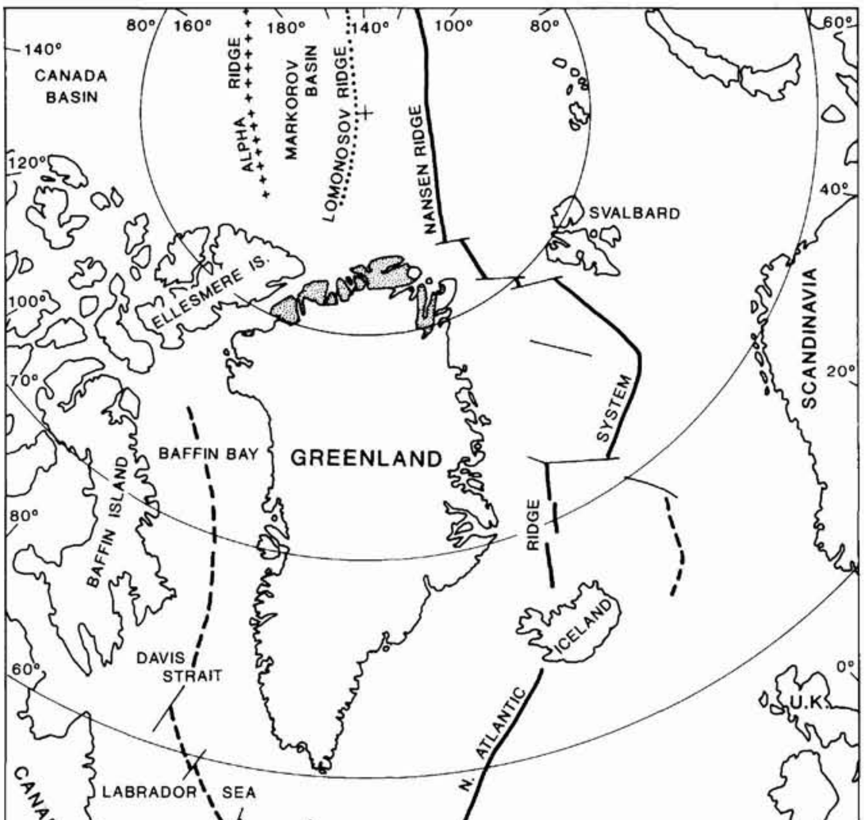

Fig. 4. Map showing the tectonic position of the Lower Palaeozoic sediments in North Greenland. Dark tone: exposures of the Lower Palaeozoic Franklinian basin in North Greenland, full lines: active spreading zones, thin lines: fracture zones, dash lines: extinct spreading zones (?), lines of crosses: ridge of uncertain origin, line of dots: ridge of continental origin.

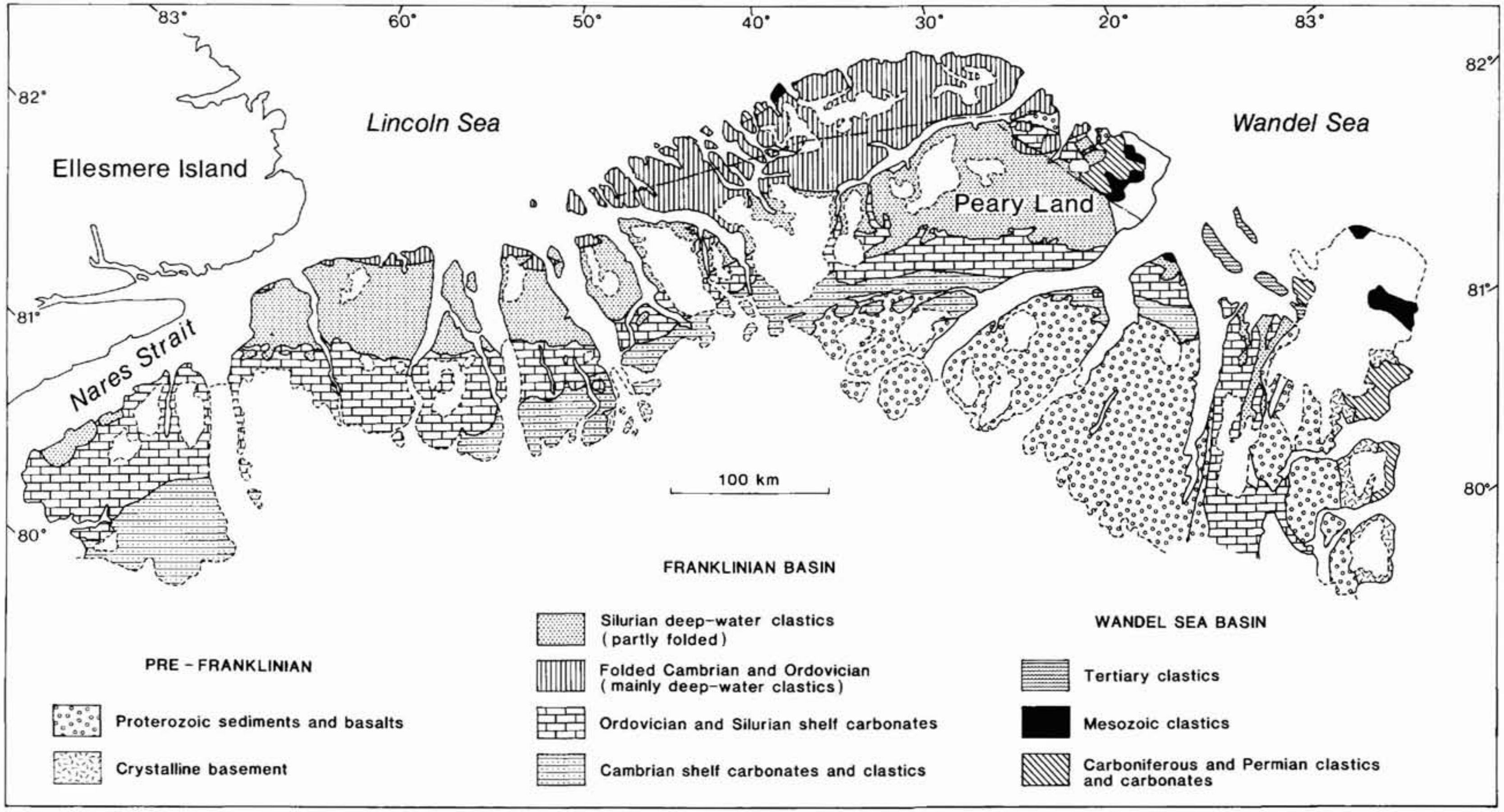

Fig. 5. Geological map of North Greenland. Simplified and modified after Dawes (1976), Higgins *et al.* (in press), and Christiansen *et al.* (in press).

been very limited (Henderson, 1976; Christiansen *et al.*, in press).

Tectonic setting

The segment of the Franklinian basin represented in North Greenland developed in Early Palaeozoic time and is now exposed along the northern margin of the Greenlandic Precambrian shield. Cratonic rocks (Archaean–Proterozoic crystalline basement and Middle to Late Proterozoic volcanics and sediments) underlie at least the southern part of the basin in North Greenland.

During the time of basin development, from latest Proterozoic or earliest Cambrian to Devonian time, the Greenland craton formed part of the Laurentia continent with a palaeogeographic position of the study area between latitudes 5°S and 15°N (Scotese *et al.*, 1979). On the basis of the east–west sediment transport direction, parallel to the continental margin, Surlyk & Hurst (1983) proposed that the basin took the form of a relatively narrow trough with a northern barrier. Two main hypotheses were proposed: the presence of a narrow ocean with the spreading axis ridge forming the barrier or an aulacogen model with rifting from the Iapetus Ocean extending deeply into the continent. Earlier, a back-arc model had been proposed with the Pearya Geanticline in northern Ellesmere Island and its intrusions and volcanic rocks forming in this setting (Frisch, 1974; Christie, 1979; Trettin & Balkwill, 1979; Trettin, 1987). However, there is no evidence in the Greenland part of the basin in support of this model.

The final closure of the Iapetus Ocean in the Late Silurian and the subsequent continental collision formed the East Greenland Caledonian fold belt. This episode also strongly affected the Greenland part of the Franklinian basin; most of the Silurian turbidites were derived from the rising Caledonide mountains (Surlyk, 1982; Hurst *et al.*, 1983), and the subsidence history was affected by loading and local uplift (causing for instance the unconformity below the Wandel Valley Formation) (Surlyk & Hurst, 1984).

The Ellesmerian orogeny brought deposition in the Franklinian basin to a close in Late Devonian to Early Carboniferous time (fig. 6) and gave rise to the North Greenland fold belt. The fold belt trends approximately east–west, as do the metamorphic zones, roughly parallel to the margin of the deep-water trough (Dawes & Soper, 1973; Dawes, 1976; Higgins *et al.*, 1985); this implies collision with a northern continental mass of either cratonic or arc affinity, probably the Siberian block.

Plate tectonic reconstructions are important in petroleum exploration because by extrapolation they shed light on the development of the least known parts of the tectonic and sedimentary history. Often this approach is applied to predict potential source and reservoir facies and prospect types. Various basin classifications have been proposed over the past 20 years (e.g. Klemme, 1971; Bally & Snelson, 1980; Stoneley, 1981; Bois *et al.*, 1982; St. John *et al.*, 1984; Kingston *et al.*, 1985). These

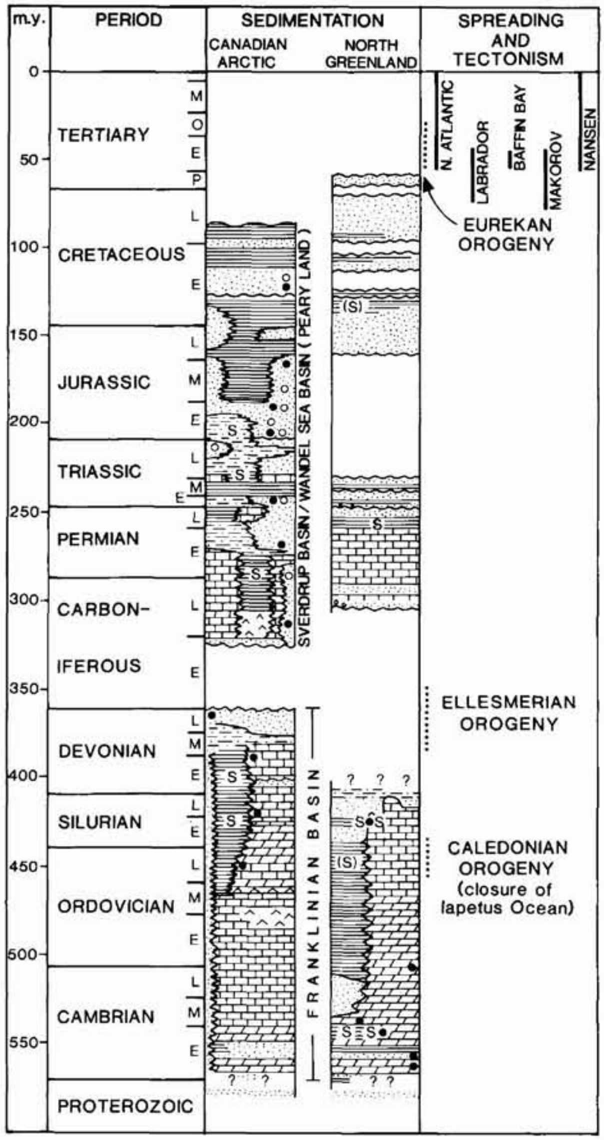

Fig. 6. Simplified diagram showing the relations between stratigraphy, sedimentation, source rock deposition(s), hydrocarbon occurrences (filled circles: oil and bitumen, open circles: gas), ocean spreading and tectonism in North Greenland and Canadian Arctic. Based on numerous sources mentioned in text, in particular Dawes & Kerr (1982 and papers herein), Kerr (1980), Rayer (1981).

classification systems are generally difficult to apply to North Greenland, particularly due to lack of data in respect to the northern border of the basin and the limited knowledge of the Late Palaeozoic and Mesozoic histories. It should, however, be noted that the Franklinian basin differs from many oil-producing Lower Palaeozoic basins; the latter are mainly of an intra-cratonic type with very long and slow subsidence histories (e.g. the Michigan basin and several basins in Australia, South America and northern Africa). An oil-producing basin with a strong resemblance to North Greenland in age and tectonic setting occurs in Alberta, Canada. Many other Lower Palaeozoic basins with similarities to North Greenland only have a very low petroleum potential, mainly because of very deep subsidence and later orogenesis caused by continental collision (e.g. the Lower Palaeozoic successions in the Caledonides in Europe and North America).

Basin evolution and source rock deposition

The tectonic/sedimentological evolution of the Lower Palaeozoic deep-water basin in North Greenland was described in terms of 9 development stages by Surlyk & Hurst (1983, 1984), an approach recently expanded to incorporate the shelf areas by Higgins *et al.* (in press).

Throughout the depositional period, the region was characterized by major generally east–west trending facies belts (fig. 5). In the southern shelf areas mainly carbonate shallow-water deposition took place, bordered to the north by outer shelf and slope mudstones (fig. 6). In the north mainly siliciclastic deep-water sedimentation prevailed in the trough. With time, the facies boundaries moved southwards during a stepwise basin expansion. The major facies boundaries were probably controlled by deep crustal faults, some of which have no surface expressions today, while others were reactivated during Ellesmerian deformation (see e.g. Soper & Higgins, 1987). Of particular importance to the present study is the Navarana Fjord escarpment (Hurst & Surlyk, 1983; Surlyk & Hurst, 1984; Escher & Larsen, 1987; Surlyk & Ineson, 1987a,b) which separated carbonate and turbidite deposition in Late Ordovician to Early Silurian time. The Permin Land flexure (Surlyk & Hurst, 1983, 1984), largely corresponding to the Early Silurian hinge line of Sønderholm *et al.* (1987), also has important implications for the petroleum geology. This lineament or flexure seems to have developed as a response to loading from the thick and rapidly deposited Lower Silurian turbidites. It is considered as a flexure line with increasing subsidence to the north and is not necessarily controlled in position by deeper crustal structures. The flexure controls the position of the Early to Late Silurian reef-belt, which developed as a series of large slope mounds along the northern margin of the platform (Sønderholm & Harland, 1989a).

Towards the south, shelf sedimentation was dominated by carbonates, with the exception of a single period of siliciclastic sedimentation in earliest Cambrian time. In the Early Cambrian, carbonate deposition extended to a position just north of the present northern coast of Nyeboe Land; in Late Ordovician to Early Silurian, the Navarana Fjord escarpment defined the boundary between the carbonate platform and the deep-water trough. Later during the Early Silurian (late Llandovery) the platform margin moved to a more southerly position controlled by the Permin Land flexure. The southern limit of carbonate deposition is not known due to cover by the Inland Ice but the platform was probably at least 200 km wide and may have been considerably wider as in the Canadian Arctic Interior Platform (fig. 3). The thickness of the shelf deposits suggests a slightly decreasing subsidence rate from the Early Cambrian to the earliest Silurian with a relatively uniform history along depositional strike and a much higher subsidence rate in the Early to Late Silurian (M. Sønderholm, personal communication, 1988). However, the eastern part of the shelf sequence in Peary Land was uplifted and partially eroded in the earliest Ordovician, corresponding to the strata underlying the unconformity at the base of the Wandel Valley Formation, probably in response to Caledonian tectonism to the east (Hurst & Surlyk, 1983; Surlyk & Hurst, 1984).

Trough sedimentation was dominated by turbiditic sandstones with minor siltstones and conglomerates. The Ordovician succession is relatively thin compared to the Cambrian and Silurian part reflecting considerable variation in subsidence rate. The trough may be traced for more than 800 km along strike in North Greenland and continues into Ellesmere Island. The width is not known but was probably between 100 and 200 km throughout much of the depositional period with the exception of the Early Silurian to Late Silurian (earliest Devonian?) when the deep-water basin expanded strongly towards the south.

The outer shelf and slope deposits, which are particularly interesting in the present study due to their source potential, comprise a mixture of mainly black shales, lime mudstones and conglomerates. The configuration of the outer shelf and slope varied considerably with time and therefore has strong implications for the source potential. In earliest Cambrian time this zone was very wide but apparently without source rock deposition due to well oxygenated conditions. In the Early to Middle Cambrian, outer shelf deposition took place in a wide belt under mainly anoxic conditions, and good source rocks formed. This pattern changed from the Middle Cambrian throughout most of the Ordovician when outer shelf-slope sedimentation occurred in a narrower zone. During Late Ordovician to Early Silurian time the Navarana Fjord escarpment defined a narrow by-pass margin between shallow-water carbonate deposition and deep-water siliciclastic sedimentation, and the formation of organic-rich units was very restricted. A wide outer shelf prevailed in mid-Silurian time when black shales overlapped the shallow-water carbonates. This was a period of major source rock deposition.

Stratigraphy, reservoir and source rock studies

The lithostratigraphic nomenclature applied in the present study to the Lower Palaeozoic shelf sequence and slope and trough sequence is shown in figs 7 and 8. Information on the different units is summarized below, either at formation or group level and includes data on: main lithology, distribution and thickness, reference to general descriptions and to information of reservoir and source rock quality.

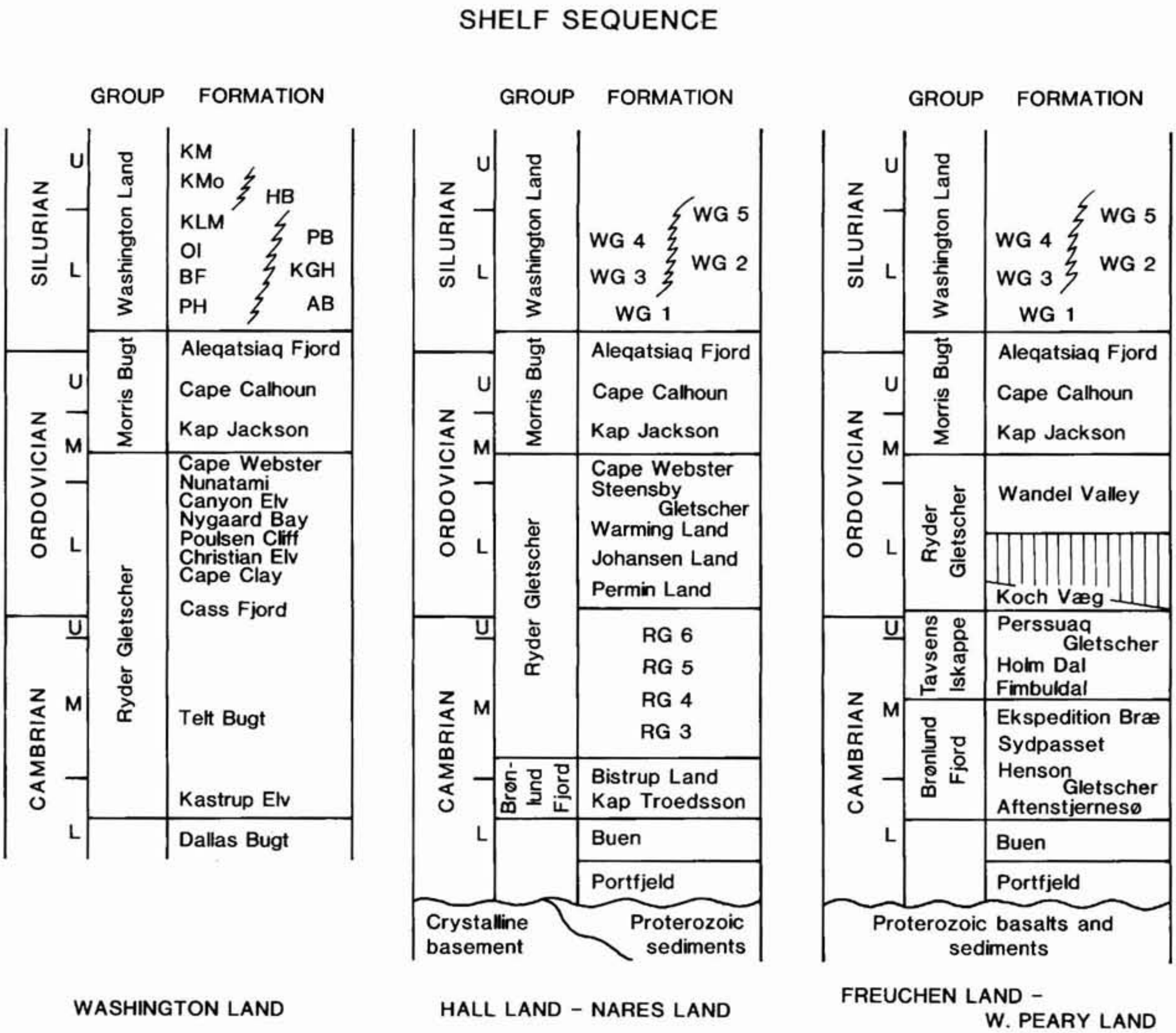

Fig. 7. Stratigraphic nomenclature of the shelf sequence in central and western North Greenland. Modified after Henriksen (1987) and Higgins *et al.* (in press). AB: Adams Bjerg, BF; Bessels Fjord, HB: Hauge Bjerg, KGH: Kap Godfred Hansen, KLM: Kap Lucie Marie, KM: Kap Maynard, KMo: Kap Morton, OI: Offley Island, PB: Pentamerus Bjerge, PH: Petermann Halvø, RG: Ryder Gletscher Group; WG: Washington Land Group.

Crystalline basement

Lithology: gneisses with minor amphibolite and supracrustals.

Distribution: only exposed at the head of Victoria Fjord and in Inglefield Land.

References: Henriksen & Jepsen (1985), Hansen *et al.* (1987).

Reservoir rocks: not likely.

Proterozoic sediments

Lithology: sandstones and volcanics.

Distribution: Inglefield Land and Peary Land, probably thin in central North Greenland.

Thickness: 25 m in Wulff Land to more than 2 km in Peary Land.

References: Jepsen (1971), Christie & Ineson (1979), Clemmensen (1979), Collinson (1979, 1980), Dawes *et al.* (1982), Peel *et al.* (1982).

Reservoir rocks: possible?, most sandstones are altered by dykes and volcanics.

Source rocks: not likely.

Lower Palaeozoic shelf sequence

Lower Cambrian shelf siliciclastics and carbonates

Lithostratigraphy: Skagen Group.

Lithology: siltstones and sandstones in lower part, dolomites in upper part.

Distribution: known in northern Wulff Land and easternmost Peary Land.

Thickness: 500–600 m in northern Wulff Land.

References: Christie & Ineson (1979), Friderichsen *et al.* (1982), Higgins & Soper (1985), Surlyk & Ineson (1987a).

Reservoir rocks: oolitic and pisolitic grainstones possible.

Source rocks: none, shales contain less than 1% TOC (Christiansen *et al.*, 1985).

Lower Cambrian shelf carbonates

Lithostratigraphy: Portfjeld Formation.

Lithology: dolomites.

Distribution: throughout North Greenland.

Thickness: 200–800 m, generally increasing northwards towards the shelf edge.

References: Jepsen (1971), Christie & Ineson (1979), O'Connor (1979), Surlyk & Ineson (1987a), Higgins *et al.* (in press).

Reservoir rocks: ?, asphalt seepage in Wulff Land, bitumen in upper part of the formation in Freuchen Land and Peary Land.

Source rocks: none, very low TOC contents with the exception of a 10–15 m thick interval of dark cherty dolomite near the base of the formation in Peary Land (O'Connor, 1979; Rolle & Wrang, 1981).

Lower Cambrian shelf siliciclastics

Lithostratigraphy: Buen and Dallas Bugt Formations.

Lithology: mainly sandstones in the lower part, mainly shales in the upper part.

Distribution: throughout North Greenland.

Thickness: 250–500 m, generally decreasing towards the north.

References: Jepsen (1971), Christie & Ineson (1979), Hurst & Peel (1979), Peel & Christie (1982), Davis & Higgins (1987), Higgins *et al.* (in press).

Reservoir rocks: poor to good, porosities in strongly cemented sandstones are up to 10% (see Chapter 7), hydrocarbon staining common in the southern part of Wulff Land.

Source rocks: none, very low content of TOC in shales, all 21 recorded values are below 0.2% (Rolle & Wrang, 1981; Christiansen *et al.*, 1985).

Lower Cambrian – Middle Ordovician shelf carbonates

Lithostratigraphy: Brønlund Fjord, Tavsens Iskappe and Ryder Gletscher Groups.

Lithology: dolomites, limestones with some shales and sandstones (Brønlund Fjord and Tavsens Iskappe Groups), dolomites with minor sandstones (Ryder Gletscher Group).

Distribution: throughout North Greenland.

Thickness: 900–1500 m, decreasing towards the north and east.

References: Henriksen & Peel (1976), Christie & Peel (1977), Ineson & Peel (1980, 1987, in press), Ineson (1985), Peel & Wright (1985), Sønderholm & Due (1985), Christiansen *et al.* (1987), Higgins *et al.* (in press).

Reservoir rocks: several possibilities, sandstones in Henson Gletscher and Sæterdal Formations of the Brønlund Fjord Group, vuggy carbonates in the Aftenstjernesø and Henson Gletscher Formations of the Brønlund Fjord Group. Macroscopic bitumen and hydrocarbon staining are common in these units (see Chapter 7).

Source rocks: The Henson Gletscher Formation contains good to excellent source rocks and has consequently been one of the main targets of the present study (Christiansen & Rolle, 1985; Christiansen *et al.*, 1985, 1986, 1987; see further details in later chapters).

Middle Ordovician to Lower Silurian shelf carbonates

Lithostratigraphy: Morris Bugt Group.
Lithology: limestones.
Distribution: throughout North Greenland.
Thickness: 620–760 m.

SLOPE AND TROUGH SEQUENCE

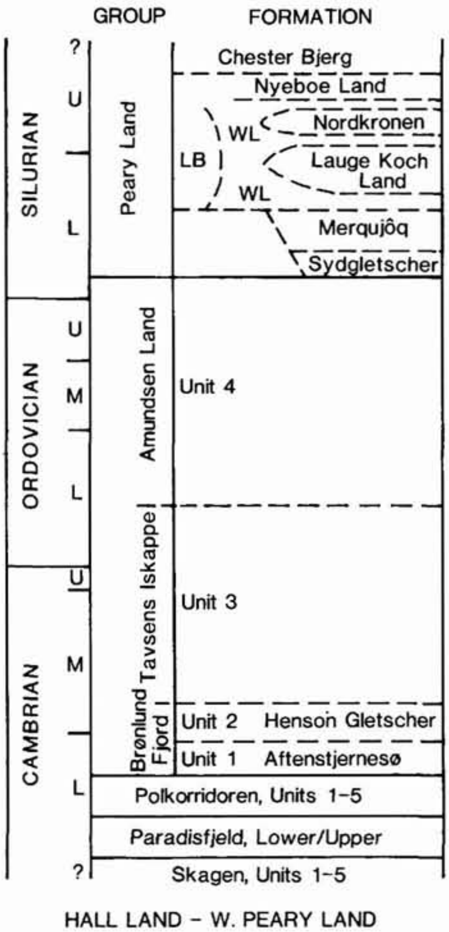

Fig. 8. Stratigraphic nomenclature of the slope and trough sequence in central and western North Greenland. Modified after Henriksen (1987) and Higgins *et al.* (in press). LB: Lafayette Bugt, WL: Wulff Land.

References: Peel & Hurst (1980), Sønderholm *et al.* (1987), Higgins *et al.* (in press), Smith *et al.* (1989), Sønderholm & Harland (1989a,b).
Reservoir rocks: ?, some bitumen in Aleqatsiaq Fjord Formation.
Source rocks: none, a few intervals in Aleqatsiaq Fjord Formation contain more than 1% TOC (Christiansen *et al.*, 1985).

Silurian shelf carbonates

Lithostratigraphy: Washington Land Group.
Lithology: limestones and dolomites, both as platform and reef facies.
Distribution: throughout North Greenland.
Thickness: 200–1500 m.
References: Hurst (1980a,b, 1981, 1984), Sønderholm *et al.* (1987), Sønderholm & Harland (1989a,b).
Reservoir rocks: likely, especially some of the reef complexes which are juxtaposed with shales of source rock and seal quality. Bitumen is common in debris from the reefs.
Source rocks: none, some of the back and inter-reef lime mudstones contain 1–2% TOC but display a poor hydrocarbon potential (Christiansen & Nøhr-Hansen, 1989).

Lower Palaeozoic slope and trough sequence

Lower Cambrian deep-water carbonates

Lithostratigraphy: Paradisfjeld Group.
Lithology: carbonate mudstones and conglomerates.
Distribution: widely exposed in north Peary Land and Nansen Land.
Thickness: at least 1 km.
References: Dawes & Soper (1973), Friderichsen *et al.* (1982), Friderichsen & Bengaard (1985).
Reservoir rocks: none, possible reservoirs only occur in postmature areas.
Source rocks: not likely.

Lower Cambrian deep-water siliciclastics

Lithostratigraphy: Polkorridoren Group.
Lithology: sandstones and shales.
Distribution: widely exposed in north Peary Land and Nansen Land.
Thickness: at least 2 km.
References: Dawes & Soper (1973), Friderichsen *et al.* (1982), Higgins *et al.* (1985).

Reservoir rocks: none, possible reservoirs only occur in postmature areas.

Source rocks: not likely.

Middle Cambrian to Lower Silurian slope and trough sediments

Lithostratigraphy: Vølvedal and Amundsen Land Groups (Brønlund Fjord and Tavsens Iskappe Groups).

Lithology: sandstones, shales, chert, carbonate mudstones and conglomerates.

Distribution: throughout North Greenland from Nyeboe Land to Amundsen Land.

Thickness: 60–450 m in the area studied (mainly slope facies), about 1 km in Amundsen Land (trough facies).

References: Friderichsen *et al.* (1982), Surlyk & Hurst (1984), Higgins & Soper (1985), Davis & Higgins (1987), Ineson & Peel (in press), Higgins *et al.* (in press).

Source rocks: The recognition of the correlation between the Henson Gletscher Formation and unit 2 of Higgins & Soper (1985) considerably increases the known source potential of the Cambrian succession. In addition the black shales of unit 4 of Soper & Higgins (Amundsen Land Group) are organic-rich. Analyses from Nyeboe Land and Freuchen Land show several TOC values in excess of 5%, despite the high thermal maturity (Christiansen *et al.*, 1985; U. H. Jacobsen, personal communication 1988).

Silurian sandstone turbidites and shales

Lithostratigraphy: Peary Land Group.

Lithology: sandstones, shales and conglomerates.

Distribution: throughout North Greenland.

Thickness: from less than 1 km in the southernmost exposures to more than 5 km in the northernmost areas.

References: Hurst (1980a), Hurst & Surlyk (1982), Surlyk & Hurst (1984), Larsen & Escher (1985, 1987), Surlyk & Ineson (1987a,b).

Reservoir rocks: ?, the sandstone turbidites of the Merqujôq, Lauge Koch Land and Nyeboe Land Formations are fine-grained and the porosity/permeability values are low.

Source rocks: The Silurian shales contain good to excellent source rocks and have been considered in detail in the present study (Christiansen *et al.*, 1985, 1986; Christiansen & Nøhr-Hansen, 1989; see further details in later chapters). The lower part of the Lafayette Bugt and Wulff Land Formations (Thors Fjord Member) are particularly rich in organic matter.

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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

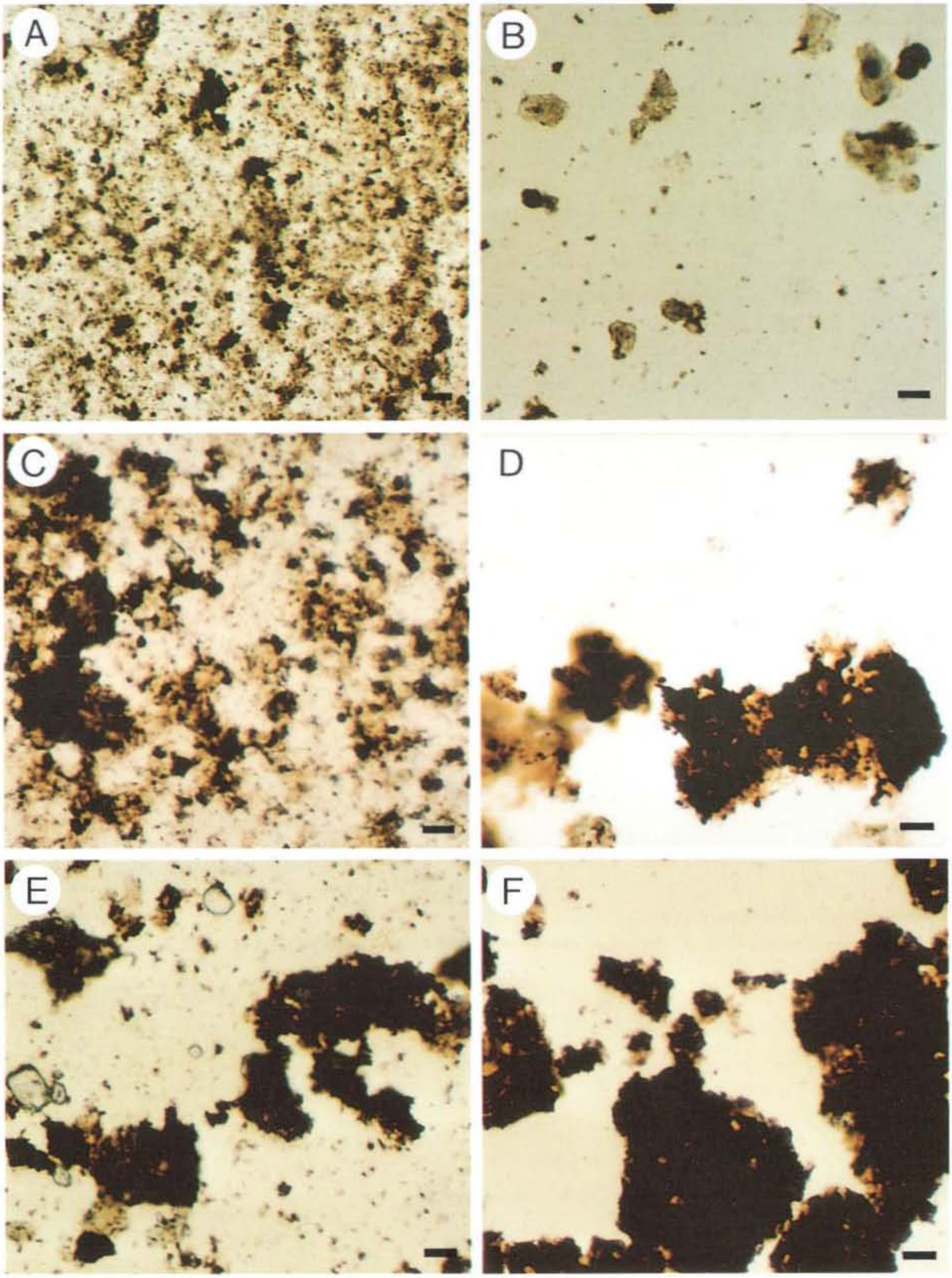

Plate 2. Cambrian palynomorphs

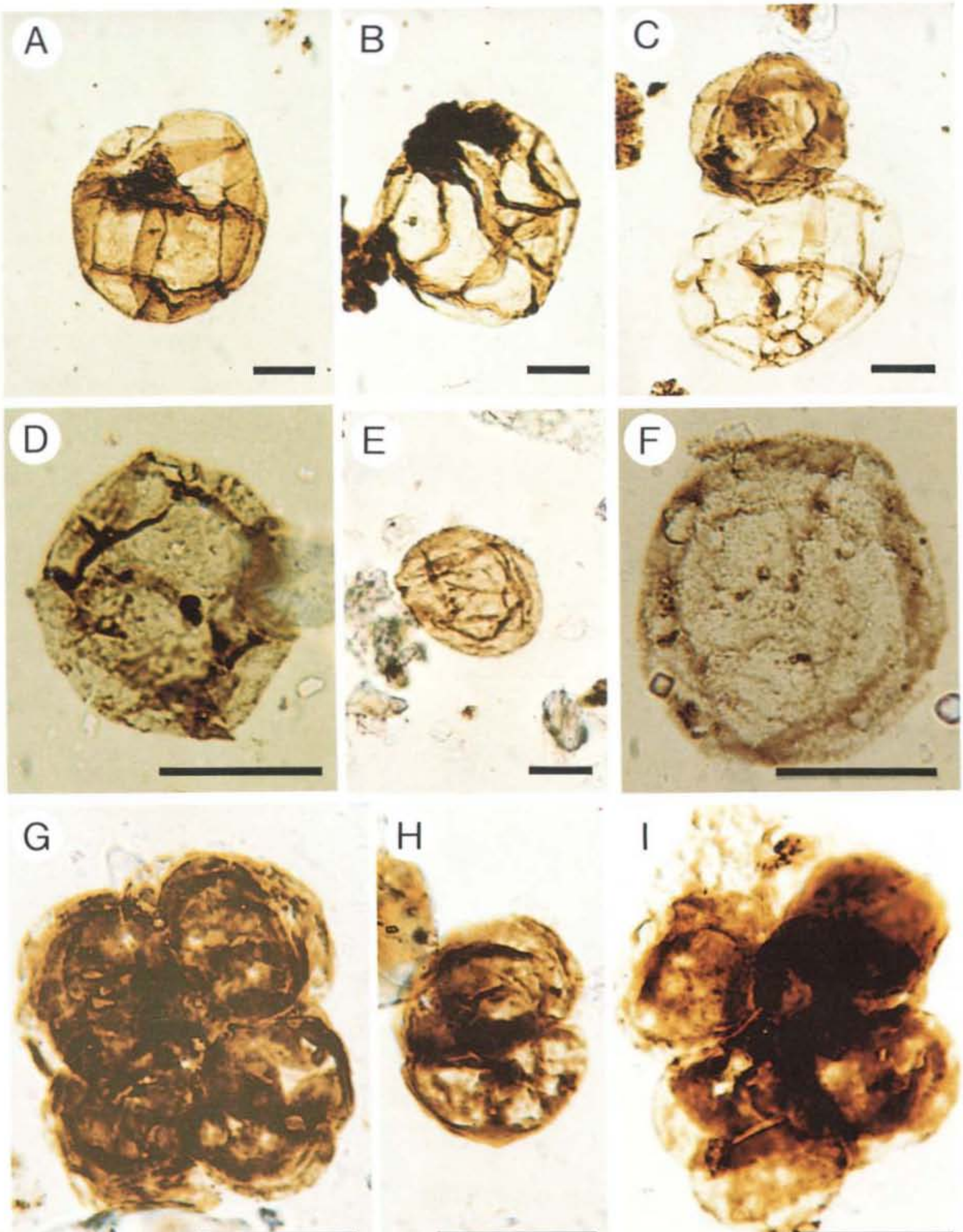

Plate 3. Ordovician palynomorphs

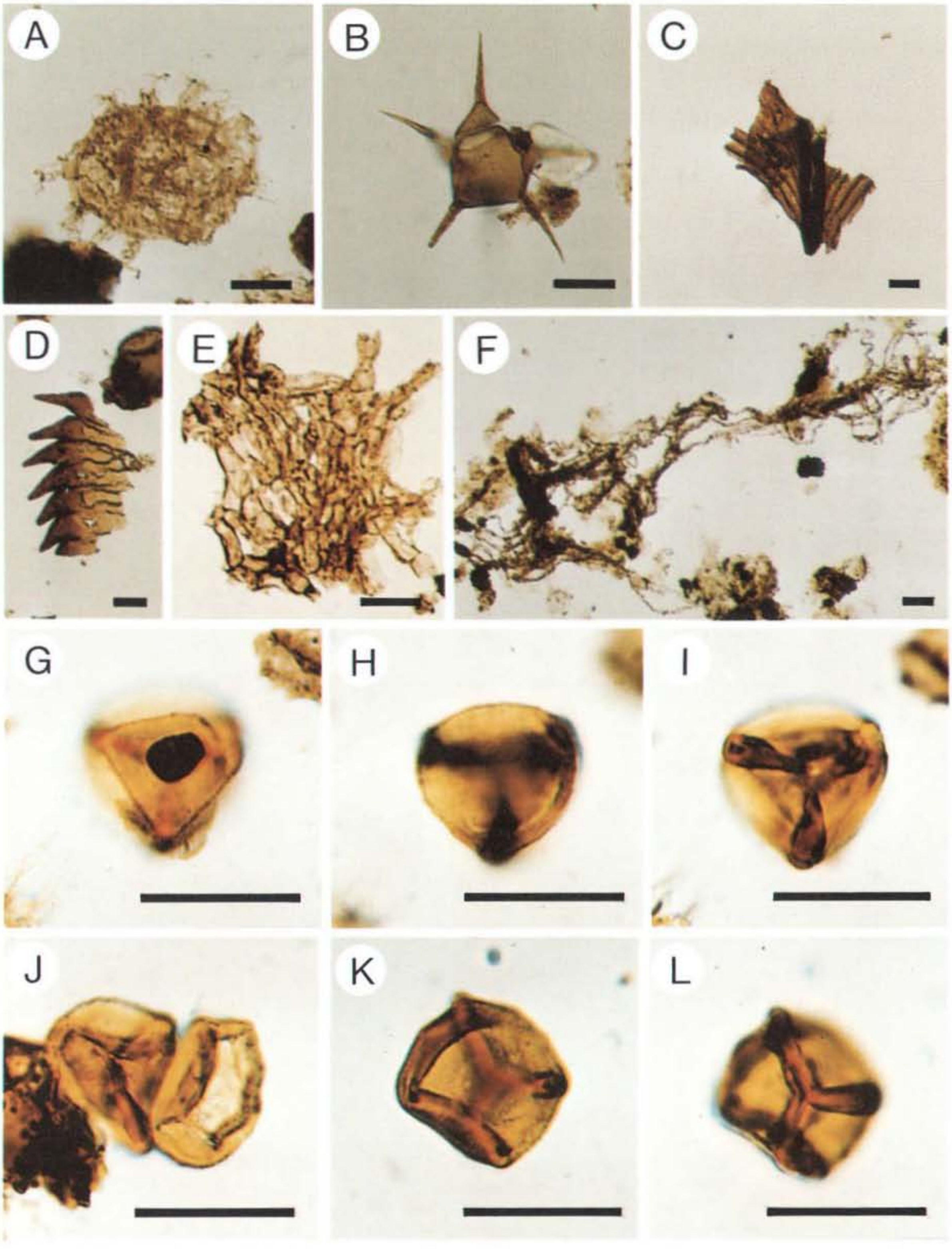

Plate 4. Silurian palynomorphs

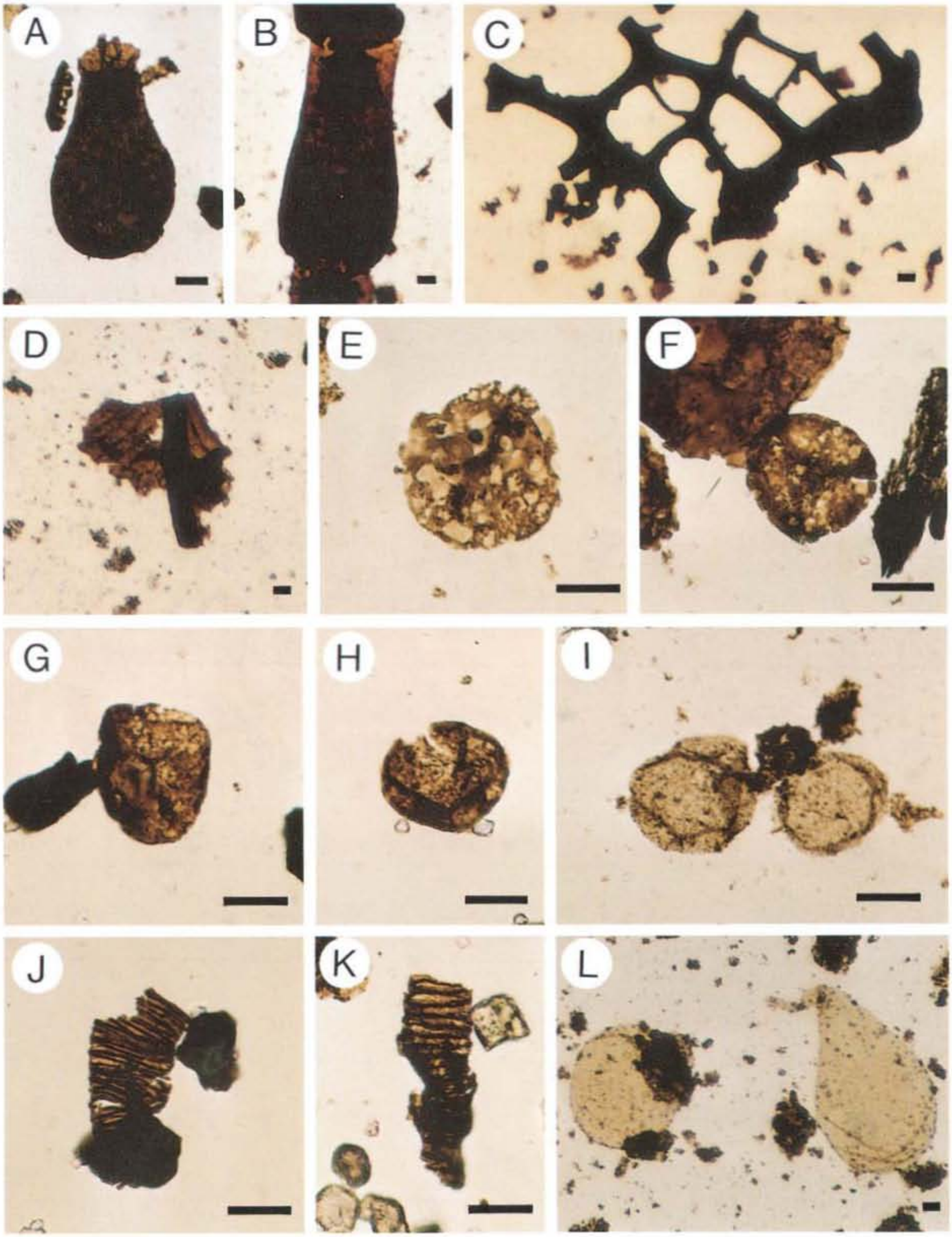

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

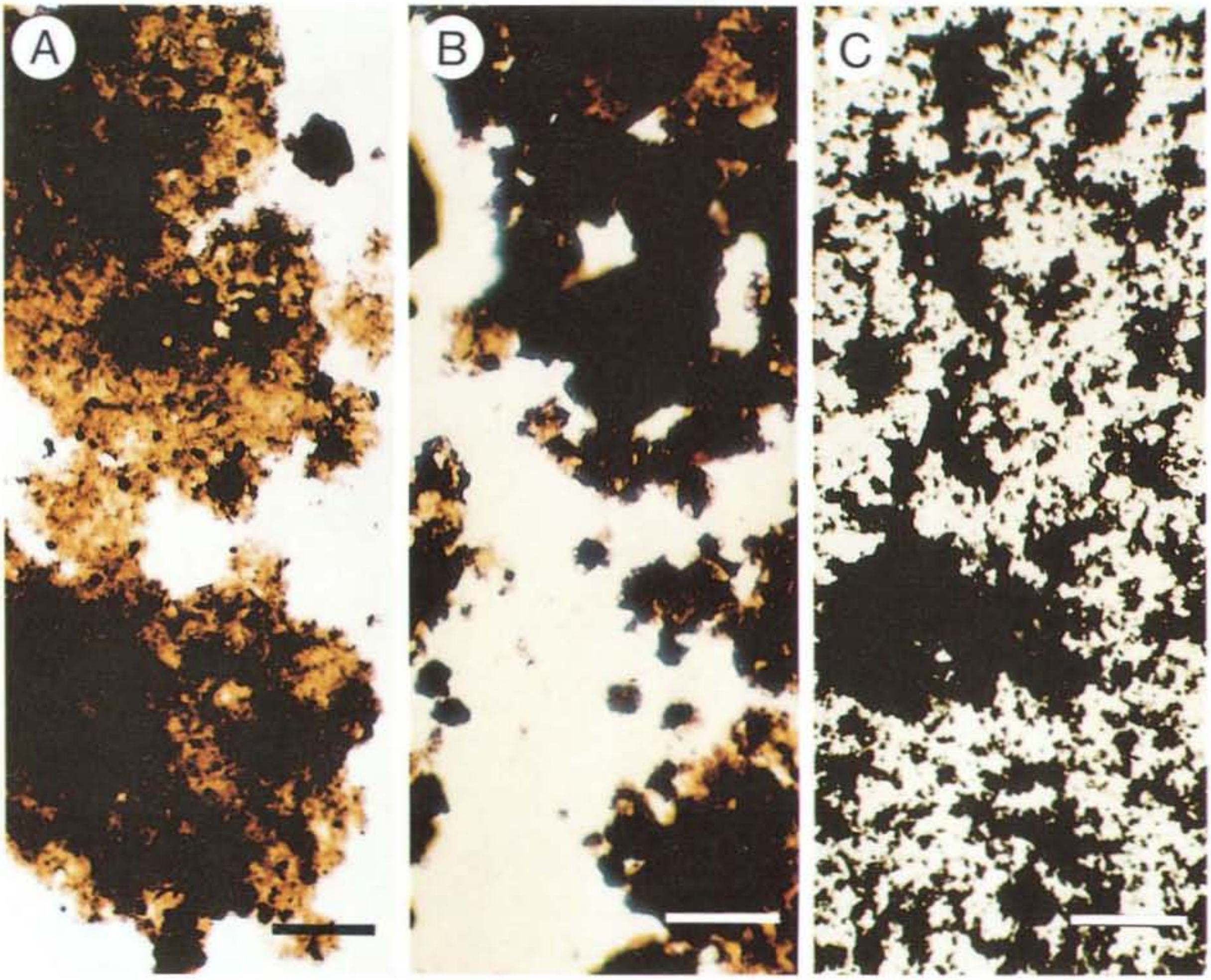

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

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

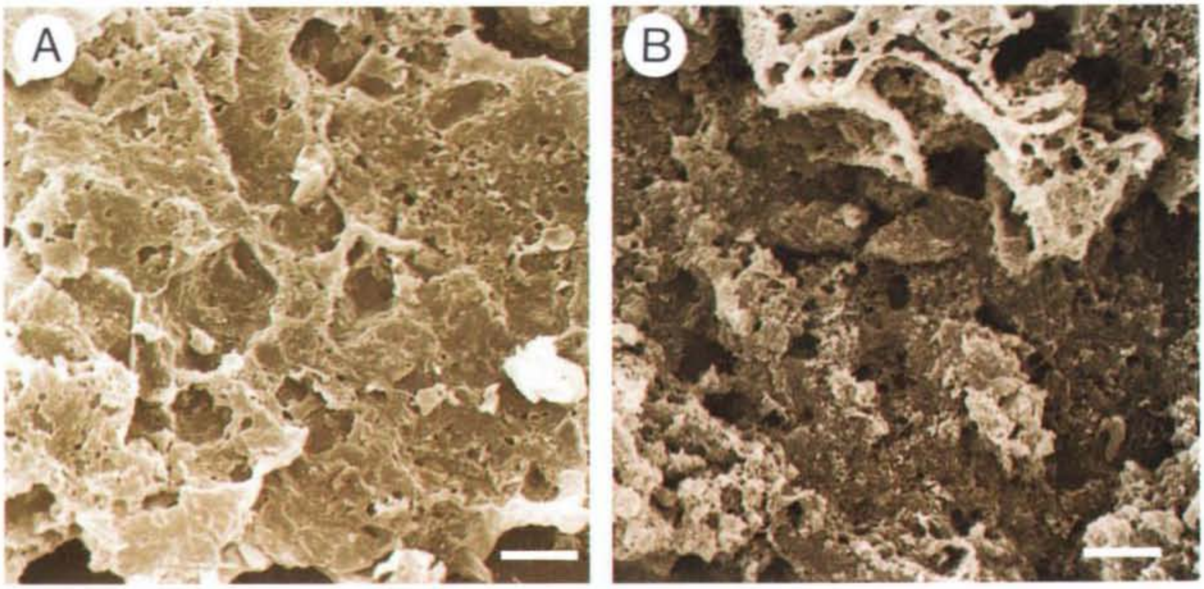

Plate 6. Change in structure of amorphous kerogen with increasing thermal alteration as observed in the scanning electron microscope

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 iŋ 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

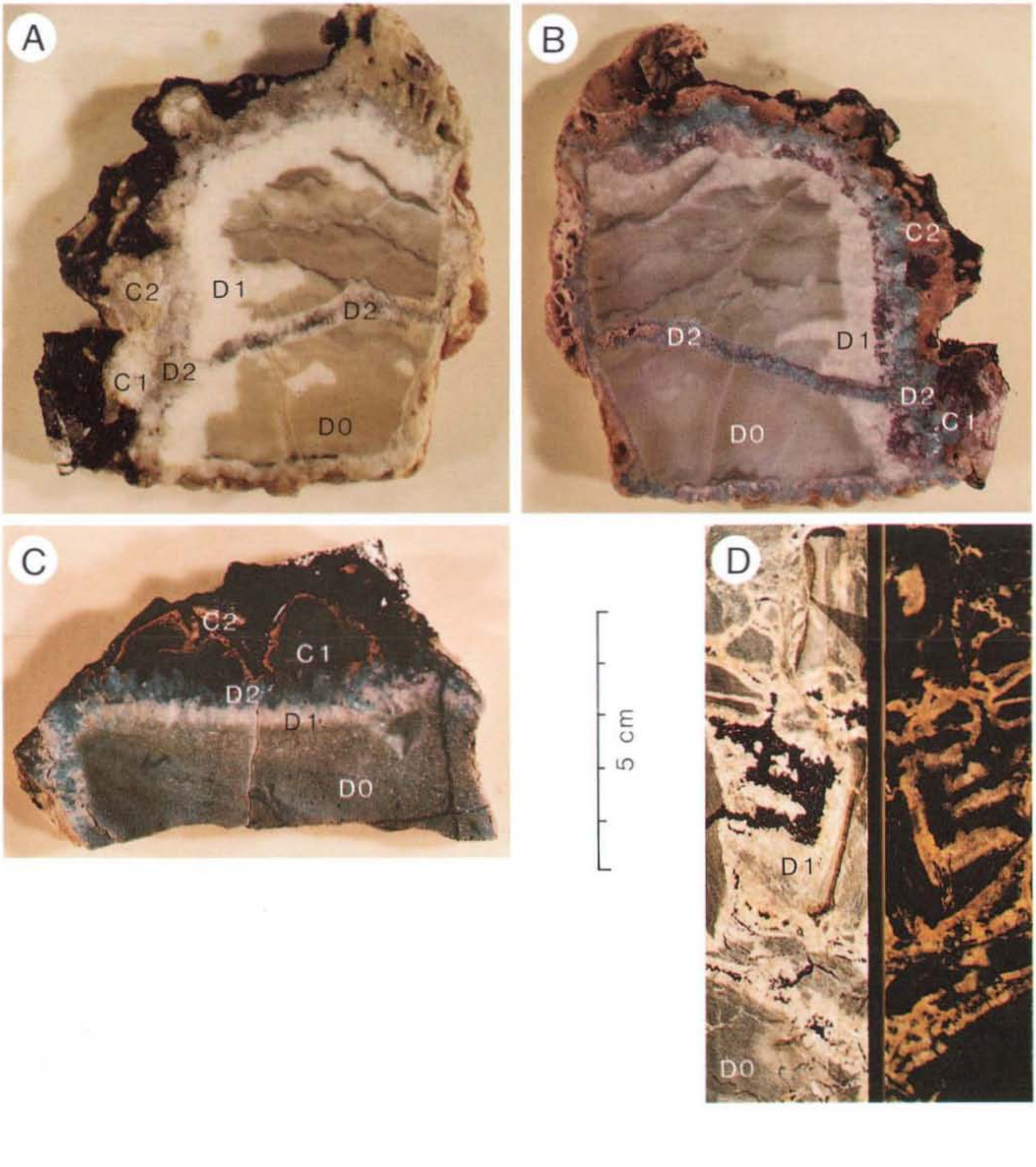

Plate 9. Bitumen in thin section

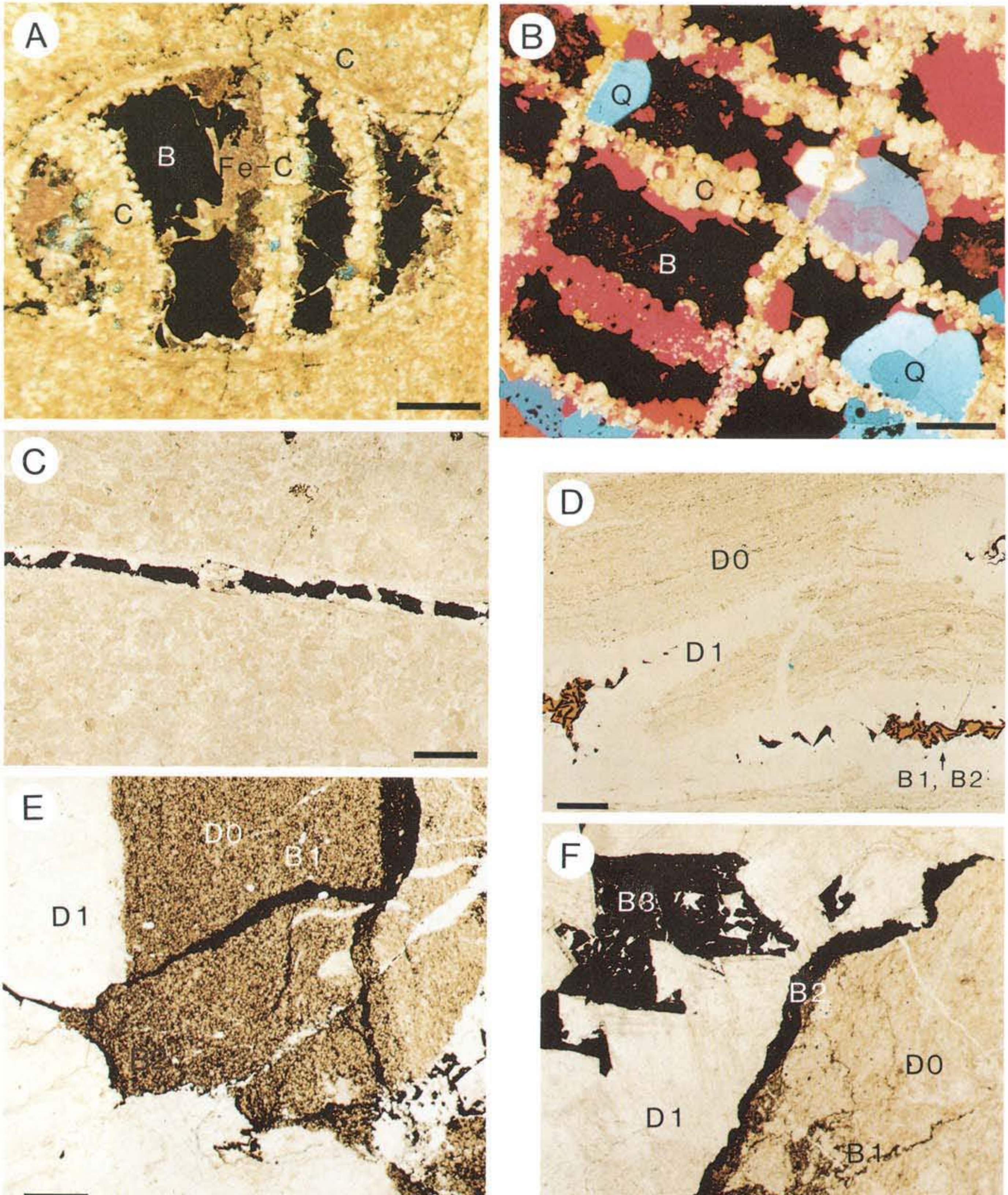

Plate 10. Bitumen in palynologically prepared samples observed in microscope or in SEM

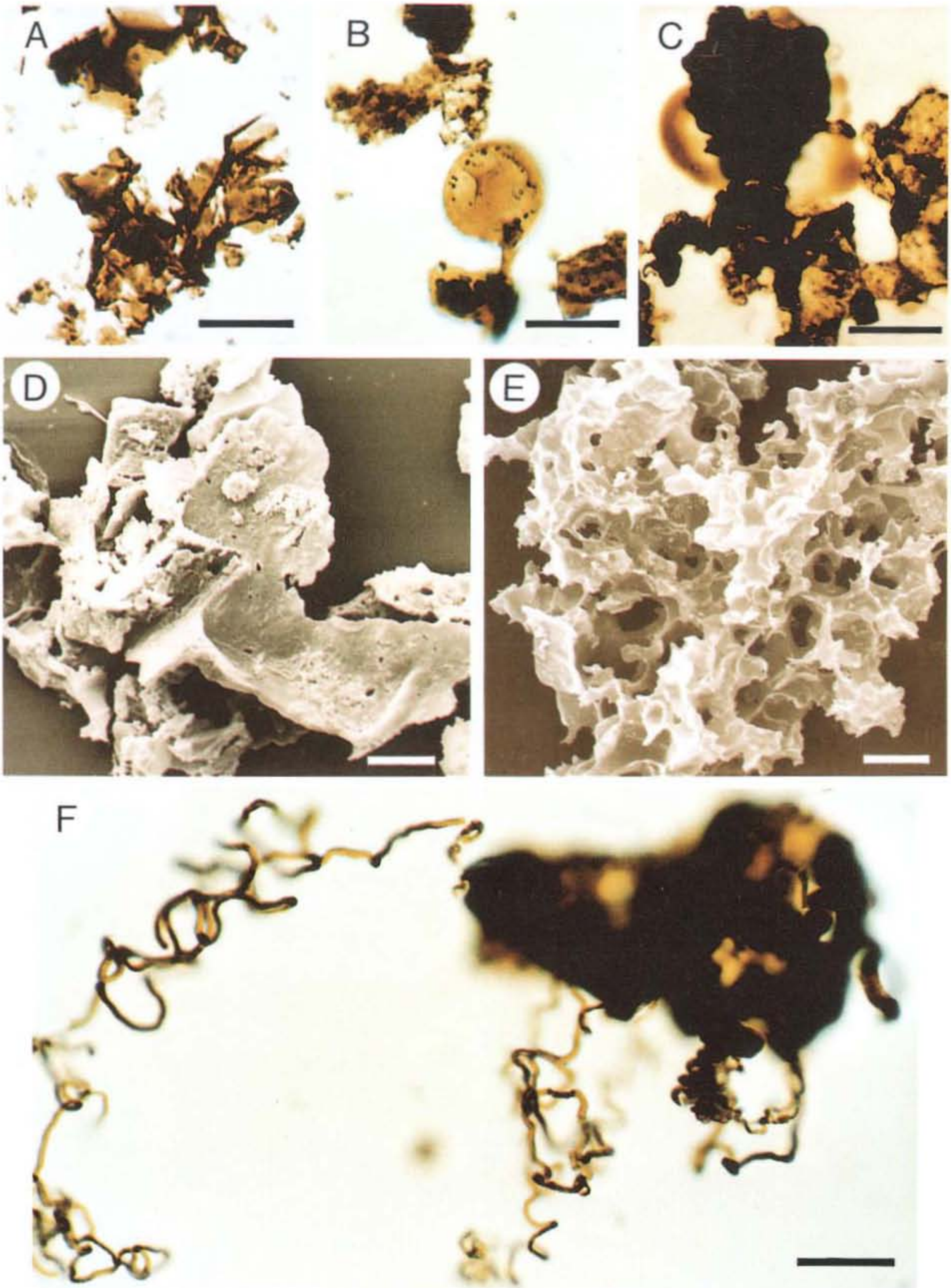

Plate 11. Bitumen in polished section

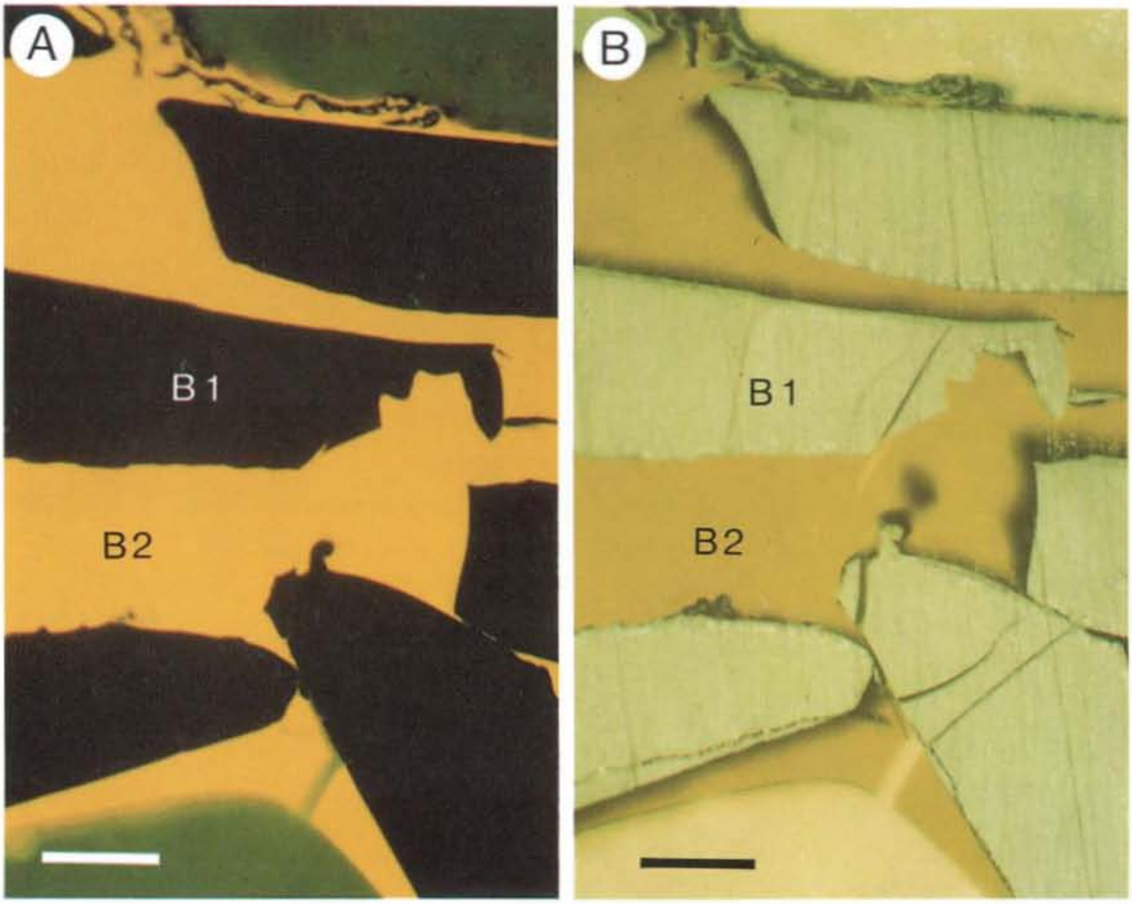

Plate 11. Bitumen in polished section

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.