Chapter 7

Bitumen occurrences

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The previous chapters have demonstrated the existence of two potential source rock units in North Greenland and a thermal history which suggests that significant amounts of hydrocarbons were once generated.

For any future exploration in the region the direct evidence of generation and migration, namely bitumen occurrences, provides important additional information for the source rock study. Although highly sophisticated geophysical methods dominate petroleum exploration today, the importance of oil seeps and visual bitumen must not be underrated. Many of the important oil-producing regions of the world were first discovered through surface seeps, and in an undrilled sedimentary basin the existence of seeps is the first and only indication that petroleum is present. In the late 1800s and early 1900s seeps were the main factor in localizing drill sites (Moore, 1984). Since that time structural analyses, firstly on the basis of surface and well data and secondly from geophysical data, have played an ever increasing role. Surface indications are, however, particularly common in folded, faulted and deeply eroded sediments and consequently still important in areas with these characteristics (Link, 1952; Hunt, 1979) like most onshore basins in Greenland.

Terminology

The terminology of solid bitumen and similar substances is complicated, confusing and dependent on the mode of information. The traditional classification scheme is based on solubility, fusibility and H/C ratio (see Rogers *et al.*, 1974; Hunt, 1979). More recent classifications are based on either detailed geochemistry (Curiale, 1986) or fluorescence/reflectance values (Jacob, 1983, 1985).

In the present study the term bitumen is used for products of once-liquid oil (more or less thermally altered and/or biodegraded) which was generated and migrated from a source rock. Most bitumens are due to the generally high thermal maturity of the source rocks (see Chapter 6) considered as the 'allochthonous' post-oil type (Curiale, 1986).

In the field, a distinction was made between bitumen-stained samples (dark sandstones or carbonates, often with a petroliferous odour), macroscopic hard solid bitumen, and macroscopic soft to seeping asphalt. Geochemically, bitumen is considered as the soluble extractable organic matter from any of the three above distinct types and is described by conventional analytical parameters. Microscopically, bitumen is defined as the dark porous-filling organic matter of migrational origin. In polished sections the bitumen is classified using reflectance and fluorescence values (Jacob, 1985). With increasing thermal alteration (and biodegradation?) the reflectance increases and the fluorescence decreases giving the following rank in classification: asphalt, gilsonite, glance pitch, albertite, grahamite, epi-impsonite, cata-impsonite.

Stratigraphic and geographic distribution

Migrated hydrocarbons and their altered remains, observed as black asphalt and solid bitumen or as oil-stained limestone and sandstone, have been reported from numerous localities in central and western North Greenland. Stratigraphically and geographically three main relations of appearance are distinguished (fig. 49).

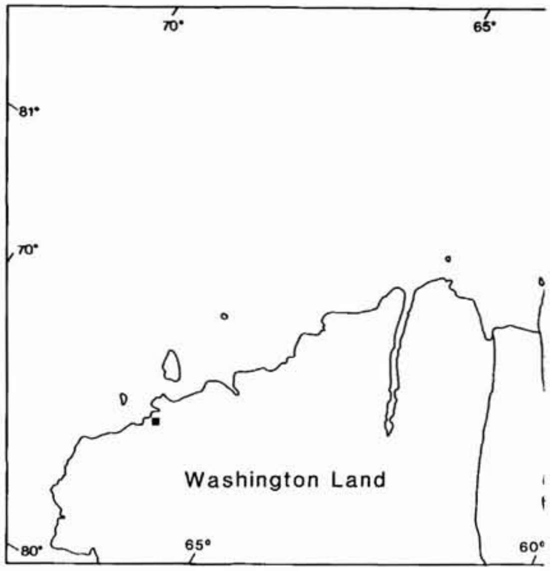
Group I: Migrated hydrocarbons associated with source rocks in the Cambrian Henson Gletscher Formation.

Group II: Migrated hydrocarbons associated with source rocks in the Silurian shales.

Group III: Migrated hydrocarbons which are not closely associated with any known source rocks. Restricted to Cambrian sediments in the southern part of the region.

The bitumens of *group I* are closely associated with the known source rocks in the Henson Gletscher Formation (Chapter 2; Christiansen *et al.,* 1987). Most

Fig. 49. Bitumen occurrences in North Greenland. Group I (circles), group II (squares), group III (triangles).



samples are situated within distances of less than 100 m vertically from the source rocks, in many places less than 10 m. The most commonly observed type is solid black bitumen occurring in vuggy and veined dolomite, either in the upper part of the Henson Gletscher Formation or in the enclosing Sydpasset and Aftenstjernesø Formations. Bitumen-stained sandstone is also common in the middle siliciclastic unit of the Henson Gletscher Formation (Christiansen *et al.,* 1987). A few examples have been recorded at a distance of several hundred metres from the source rocks, both stratigraphically above (Tavsens Iskappe Group) and below (Portfjeld Formation).

The bitumen of *group II* occurs within a few metres' or even centimetres' distance of Silurian shales, mainly in veins, vugs or corals in debris flow conglomerates of the Lafayette Bugt Formation. Relatively few occurrences are reported compared to group I, probably due to the high thermal maturity of most Silurian shales (Christiansen & Nøhr-Hansen, 1989; Chapter 6).

The bitumen samples of *group III* all come from the southern part of Warming Land and Wulff Land (fig. 49), an area without any known source rock. Asphalt seepage and asphalt filled vugs and veins occur in brecciated Portfjeld Formation less than 100 metres above the underlying Precambrian basement. The Buen Formation sandstones are dark and bitumen-stained at a number of localities. The upper part of the Ryder Gletscher Group contains both bitumen-stained sandstone and vuggy carbonates with black solid bitumen.

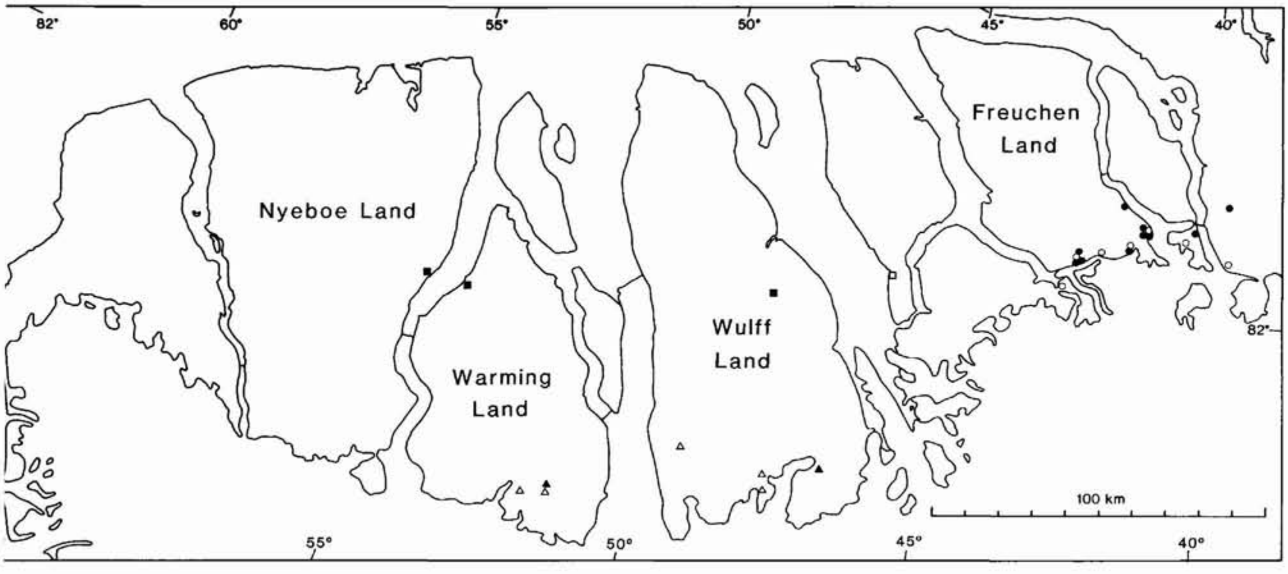
Composition and properties of bitumen

The bulk chemical composition and physical properties of the bitumen have been studied by GC (n = 26), GC/MS (n = 10), carbon isotope analyses of whole extracts (n = 25) and reflectance/fluorescence methods (n = 25) (see Chapter 3 for analytical details).

Most of the analytical results are consistent with the stratigraphic and geographic distribution of the bitumen and hence presented within this framework.

Group I (associated with Cambrian source rocks). The bitumens of group I are from a relatively mature area with few early mature and many mature and postmature samples. This high regional thermal maturity also affects the composition and properties of the bitumen. The reflectance of the bitumen is high (fig. 30); with the exception of few albertite/grahamite samples and some two-phased bitumens, most of the material is classified as epi-impsonite according to the terminology of Jacob (1985).

The extractability is low to moderate (30–200 mg SOM/g TOC) compared to other migrated hydrocarbons. This is probably due to the high maturity and is further supported by the lack of cyclic biomarkers and a strong light-end bias of the generally paraffinic saturates (fig. 52 A; Østfeldt, 1987). The effect of biodegradation ranges from low to moderate as expressed by the low to moderate content of polars (NSO-components) and asphaltenes (figs 50 and 51) and the Pr/nC_{17} relation (fig. 53).



Pristane/phytane ratios are consistent and low (mean: 1.11 (SD: 0.35), range: 0.70 to 1.81). The carbon isotopic composition is also relatively constant and very depleted in ^{13}C (mean $\delta^{13}C$: −30.93‰ (SD: 0.80), range: −29.69‰ to −32.19‰) (fig. 54).

Group II (associated with Silurian source rocks). The small number of group II samples ranges considerably in regional thermal maturity with few early mature and a number of postmature samples. This variation in maturity of associated source rocks is also observed in the bitumen parameters. The bitumen reflectance varies in accordance with the regional maturity, the least mature samples contain glance pitch and albertite/grahamite, all the postmature samples epi-impsonite.

The two early mature samples have a high extractability (700–800 mg SOM/g TOC) and cyclic biomarkers are retained in the extracts. The biomarkers exhibit a ste-

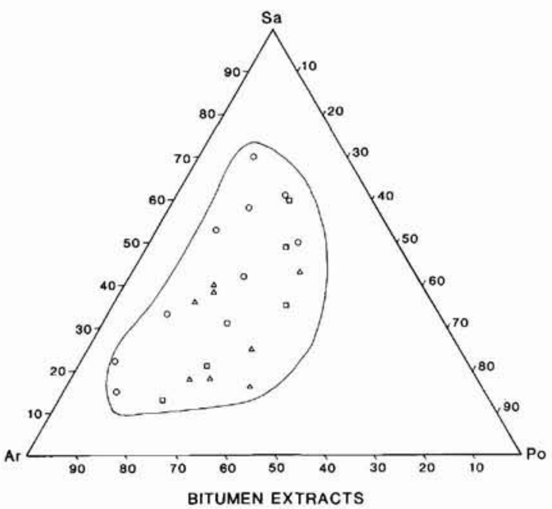


Fig. 50. Triangular diagram of the relative proportion of saturated, aromatic and polar compounds in extracts of bitumens.

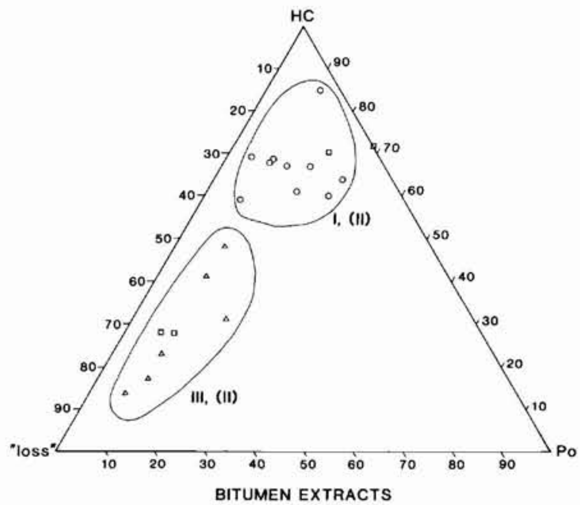


Fig. 51. Triangular diagram of the relative proportions of hydrocarbons (saturates + aromatics), polar compounds, and 'loss' in extracts of bitumens. The 'loss' during column chromatography corresponds mostly to the asphaltene content.

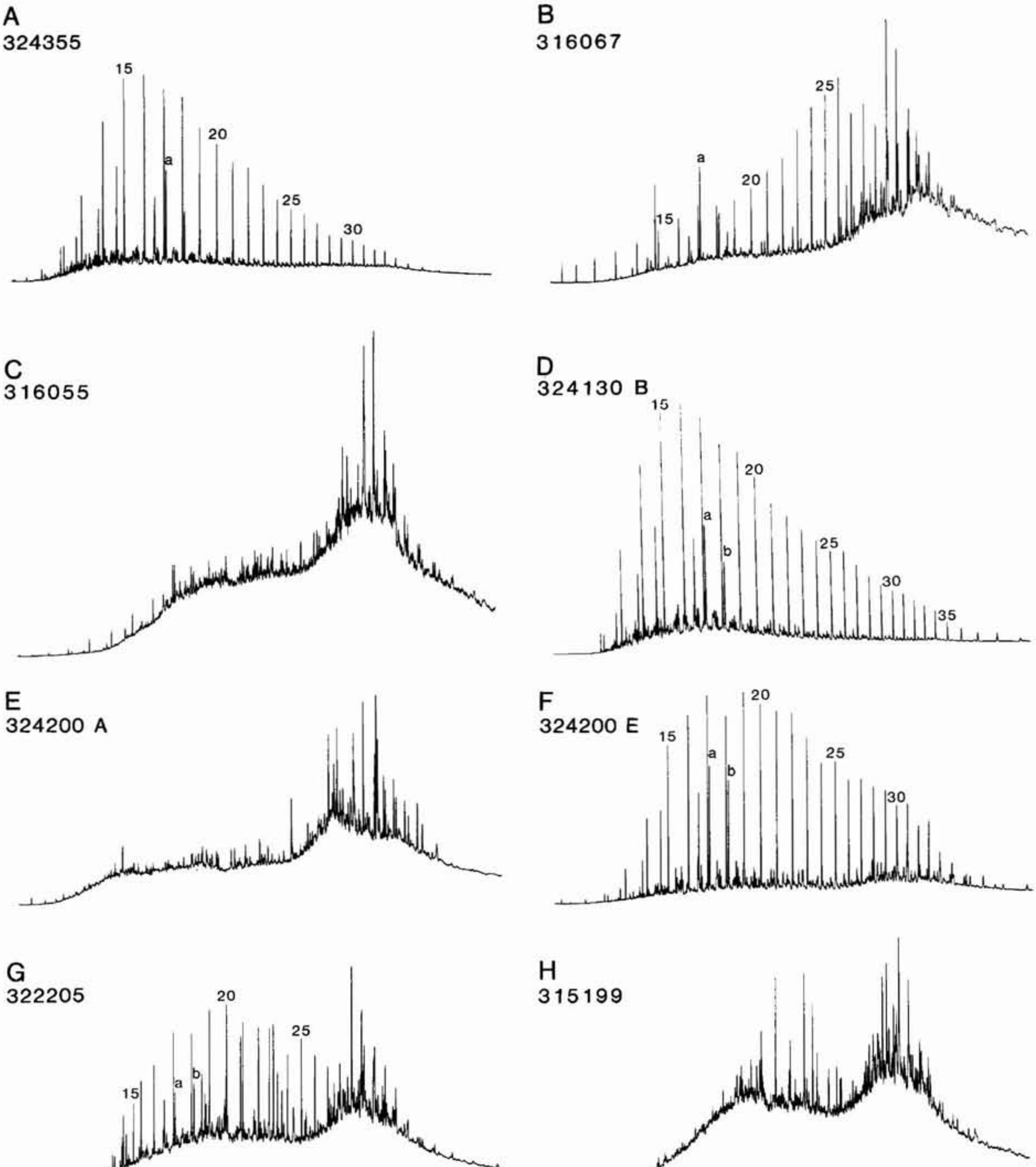


Fig. 52. Selected gas chromatograms of the saturated hydrocarbons from bitumen extracts. a: pristane, b: phytane, numbers are *n*-alkane carbon numbers. (A) Thermally mature, little biodegraded group I bitumen from sandstone (sample 324355). (B) Thermally early mature, mildly biodegraded group II bitumen from coral in conglomerate (sample 316067). (C) Thermally early mature, strongly biodegraded group II bitumen from coral in conglomerate (sample 316055). (D) Thermally postmature, little biodegraded group II bitumen from coral in conglomerate (sample 324130B). (E) Thermally early mature, strongly biodegraded group III bitumen from seeping asphalt (sample 324200A). (F) Thermally early mature, little biodegraded group III bitumen from asphalt filled vug (sample 324200E). (G) Thermally early mature, little biodegraded group III bitumen from sandstone (sample 322205). (H) Thermally early mature, strongly biodegraded group III bitumen from limestone (sample 315199).

rane distribution completely dominated by C_{29} steranes, relatively high Ts/Tm ratios and lack of gammacerane, all consistent with the interbedded source rocks (Østfeldt, 1987b; see also Chapter 5). The biodegradation of these two samples is moderate to high, evaluated from the relatively high content of polars and asphaltenes (figs 50 and 51), gas chromatograms (figs 52 B and C) and Pr/nC_{17} ratio (fig. 53).

The bitumen from the postmature areas has a very low extractability (5–30 mg SOM/g TOC) and the saturates are paraffinic with a strong light-end bias. This material seems only slightly biodegraded (figs 50, 51, 52 D, 53).

The pristane/phytane ratios of group II are considerably higher than those of group I (mean: 1.83 (SD: 0.27), range: 1.61 to 2.22). Also the carbon isotope composition is different from group I and considerably ^{13}C-enriched (mean δ^{13}C: −26.50‰ (SD: 0.80), range: −25.16‰ to −27.12‰).

Group III (not closely associated with any source rock). All the samples from group III are from a thermally immature to early mature area and the bitumens do not show evidence of thermal alteration. The reflectance values are low with the material classified as gilsonite, glance pitch and albertite/grahamite.

The extractability is high to very high (most values ≥ 1000 mg SOM/g TOC). The extracts have a dominance of asphaltenes over hydrocarbons (fig. 51). Cyclic biomarkers are preserved in all samples with a sterane distribution entirely dominated by C_{29} steranes. The triterpenoid biomarker gammacerane is systematically detected in all samples, both in the slightly and the severely degraded (Østfeldt, 1987b).

The degree of biodegradation ranges from moderate to severe, evaluated from Pr/nC_{17} and relatively high contents of polars and asphaltenes (figs 50, 51 and 53). Many samples have no preserved normal alkanes, in some cases no isoprenoids either (figs 52 E and H). This biodegradation seems to be related to surface processes, since a clear difference is observed between seeping asphalt and asphalt from nearby closed spaces (figs 52 E and F).

The few samples with well defined pristane/phytane ratios show constant and low values similar to group I (mean: 1.03 (SD: 0.20), range 0.76 to 1.2) (fig. 54). The carbon isotopic composition is also comparable to group I, although slightly ^{13}C-enriched. If sample 324200A (strongly biodegraded and altered by surface evaporation) is omitted, the mean δ^{13}C is −29.48‰ (SD: 0.69) with a range between −28.59‰ and −30.82‰.

Correlation to source rocks

The composition and properties of the studied bitumen samples generally support a thermal history which is in accordance with the regional thermal maturity pattern. The group III samples reflect immature to early mature regional conditions, group I and II show a range

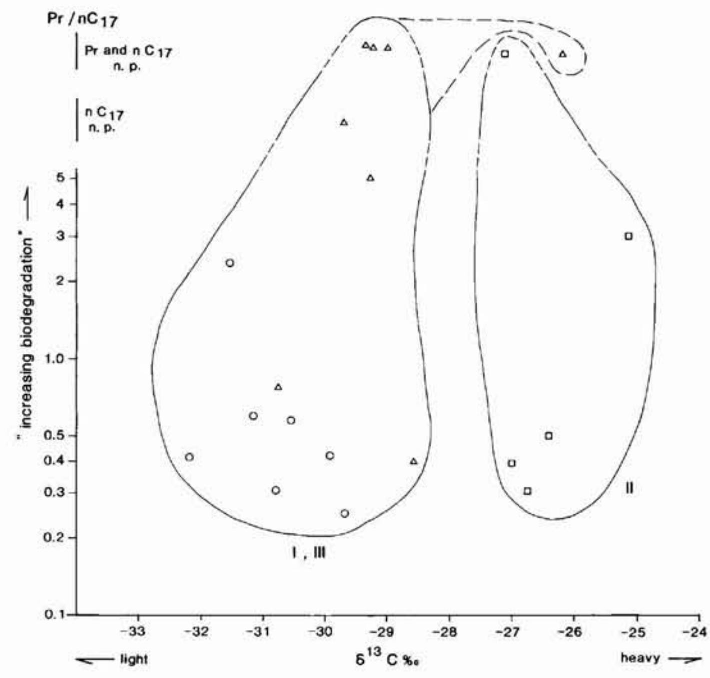


Fig. 53. Relation between carbon isotopic composition of total extracts and Pristane/nC_{17} alkane ratio of the three bitumen groups (I: open circles, II: open squares, III: open triangles). The Pr/nC_{17} value is, under the assumption of a common source, mainly dependent of the degree of biodegradation. The uppermost part of the figure show samples where nC_{17} and both pristane and nC_{17}, respectively, have been completely lost during degradation.

from early mature to postmature. Biodegradation seems to be most severe in the richest extracts from early mature areas; this is particularly so in the group III samples.

Two of the parameters, the pristane/phytane ratio and the carbonate isotope composition (Lewan, 1983), are only little affected by thermal alteration and biodegradation and are hence applicable for correlation purposes. Furthermore, these data are recorded from most bitumen samples and from a number of samples of two of the possible sources of the bitumen (see also Chapter 5), the Cambrian Henson Gletscher Formation and the Silurian shales.

The bitumens associated with Cambrian (group I) and Silurian (group II) source rocks are easily discerned in cross plots of Pr/Ph versus $\delta^{13}C$ (fig. 54) with only little variation within the groups. The associated source rock groups show a similar pattern but with more scattered values with some overlap inhibiting a clear distinction (fig. 24).

The extracts of the Silurian shales and the associated bitumens reveal a similar range in Pr/Ph values whereas the extracts are depleted in ^{13}C compared to the bitumen. In the Cambrian samples the bitumen and source rocks have a similar range in isotopic composition whereas the Pr/Ph values are slightly higher in the source rock extracts. The similar biomarker distribution of the Silurian shales and the Silurian bitumen should be

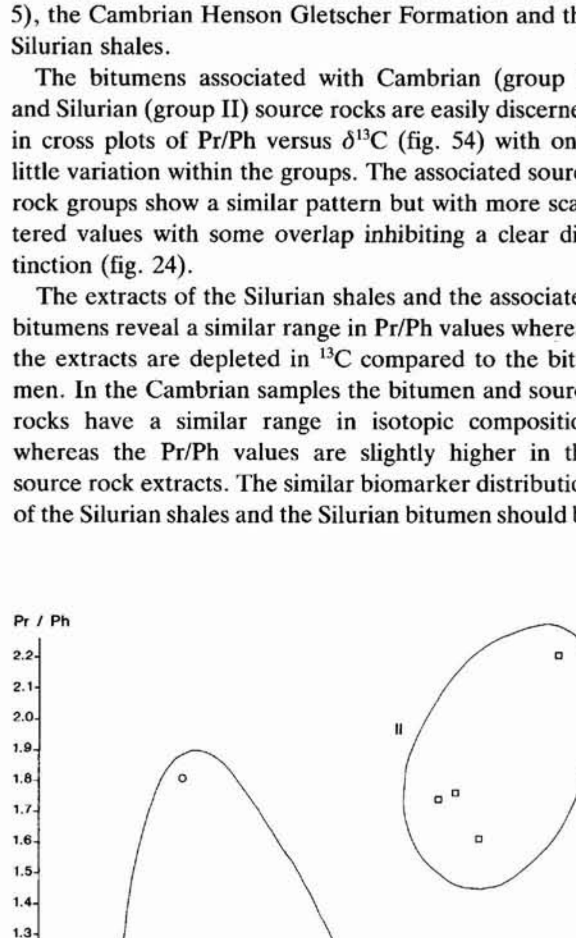


Fig. 54. Relation between carbon isotopic composition of total extracts and the pristane/phytane ratio of the three bitumen groups.

noted (Østfeldt, 1987b; see also Chapter 5). Unfortunately these compounds are not preserved in the Cambrian group I bitumen due to the high thermal maturity. Only two Cambrian source rocks contain cyclic biomarkers (see Chapter 5).

The group III samples have Pr/Ph ratios in the same range as the group I bitumen and the isotopic composition is slightly different (enriched in ^{13}C) compared to group I (fig. 54). This suggests that the source rocks of the two bitumen groups are geochemically similar. Assuming a common source, the difference in isotopic composition can be explained from the fact that only total extracts have been analysed. In normal oils saturated and aromatic hydrocarbons (which dominate in group I) are depleted in ^{13}C when compared to asphaltenes (which dominate in group III) (e.g. Schoell, 1984).

The hypothesis of a common source of the group I and III bitumens is, however, questionable when the few available cyclic biomarker distributions are considered. None of the group I bitumens, eight of the group III bitumens and two Cambrian source rocks contain preserved and detectable cyclic biomarkers. The group III bitumen and the Cambrian source rocks display distinct, but different distributions indicating a non-source relation. Particularly the ever present component gammacerane in the group III bitumens restricts the possible models since it points towards a source, or mixing with bitumen from a source, which was deposited in a hypersaline environment (see details in Chapter 5). In North Greenland such possibilities include unrecognized source rock within the Cambrian to Ordovician shallow-water carbonates or, more likely, a possible local variation in depositional environment of the Henson Gletscher Formation or its lateral equivalents (see fig. 66). Especially the transition from outer shelf Henson Gletscher Formation to contemporaneously deposited inner shelf or embayment carbonates is interesting in this context.

Host rocks

The observed migrated bitumens are hosted by a number of different rock types (Plates 7 to 9). Some of these are considered potential reservoir rocks (e.g. the Cambrian sandstones) whereas others, such as the vuggy and veined dolomites, probably do not qualify as potential reservoirs since the bitumen filled spaces are disconnected.

A detailed analysis of the diagenetic history of the potential reservoirs in North Greenland is beyond the scope of the present study. A general microscope investigation of bitumen-bearing samples, compared to reference samples without bitumen, provides some evidence of the conditions before, during and after hydrocarbon migration.

Sandstones. Bitumen-stained sandstones are restricted to the Cambrian (Lower Ordovician?) sequence with the most common examples in the Buen Formation, the Henson Gletscher Formation and Formation RG6. Other possibilities of the same type include the Morænesø, Sæterdal and Permin Land Formations (see Chapter 2).

The reservoir properties of the three most important sandstone units are summarized in fig. 55 and Table 3. The recorded values of porosity and permeability are not promising for any of the three reservoir targets. The relatively low values are due to intense quartz overgrowth leaving only minor inter-particle porosity. In some cases evidence of pressure solution or early signs of grain boundary migration are found, especially in samples from Peary Land. Early carbonate cement, predating hydrocarbon migration, is observed in several samples.

The hydrocarbon saturation in the pores has been calculated in several samples from the Buen and Henson Gletscher Formations based on Rock Eval and/or extraction data (Table 4). The Henson Gletscher Formation displays consistent saturation values below 12%, the Buen Formation a range between 36 and 63%. Considering the loss of hydrocarbons during surface evaporation and biodegradation (and loss during handling and preparation), the latter values seem high and indicate that the Buen Formation might have been oil-saturated or near-saturated at depth. This bitumen and its dark relicts are observed along grain boundaries, often associated with opaque minerals.

Carbonates. Carbonate rocks with bitumen-staining or black macroscopic bitumen in either primary or secondary spaces are common in both the Cambrian shelf succession and in the Silurian shelf and slope units. Three main types of appearance are distinguished: (a) dispersed bitumen in limestone or dolomite, (b) macroscopic discrete bitumen in primary intra- or interparticle spaces, and (c) macroscopic discrete bitumen in secondary spaces such as fractures, veins and vugs.

The three types are often closely associated within the same host rock unit but in several cases are related to different episodes (see e.g. Plate 9 with at least three 'generations' of bitumen).

The *dispersed bitumen* mainly occurs in graded limestones or dolomite grainstones in the Henson Gletscher Formation. The bitumen is observed along grain boundaries. Some of the dark dolomites are clearly postdated and partly dissolved by veins filled with saddle dolomite which is associated with another generation of bitumen (Plates 8 and 9).

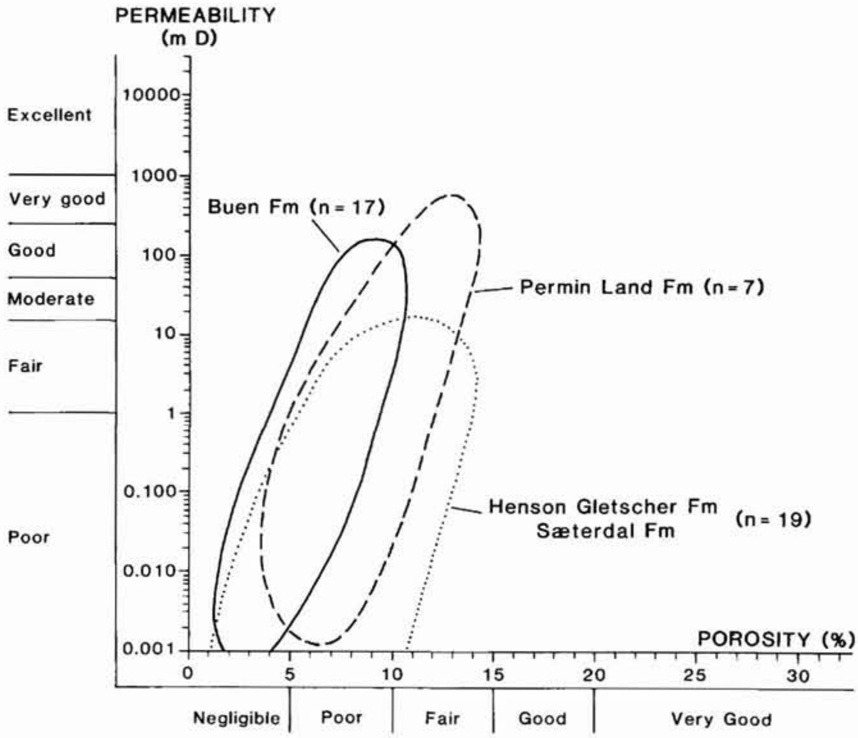


Fig. 55. Porosity/permeability variation of potential sandstone reservoirs.

Table 3. Summarized reservoir properties of

Lithostratigraphy	Outcrop pattern	Thickness	Composition[4]
Buen Fm[1]	Wulff Land– E. Peary Land	125–550 m	Quartz arenites (few subarkoses)
Henson Gl. Fm/ Sæterdal Fm[2]	Freuchen Land– C. Peary Land	<10–125 m	Subarkoses (with 15–30% dolomite)
Permin Land Fm[3]	Washington Land– Nares Land	12–53 m	Quartz arenites

1. *see* Jepsen (1971), Hurst & Peel (1979)

2. *see* Ineson (1985), Christiansen et al. (1987)

Macroscopic discrete bitumen in primary spaces is particularly common in Silurian limestones and conglomerates and especially the examples with intraparticle porosity (corals, crinoids) are impressive (Plate 9). The bitumen postdates growth of minerals with well defined crystal faces, mainly Fe-rich calcite, occasionally also Fe-rich dolomite, calcite or quartz (Plate 9). In contrast, reference samples without bitumen are dominated by calcite in similar, cemented primary pores.

Table 4. Oil saturation of Cambrian sandstones

Sample	$(S_1 + S_2)$ mg HC/g rock	SOM ppm	Porosity	Grain density	Saturation
Buen Formation					
322102	(2.72+6.09)		5.68	2.65	48%
		8560	5.68	2.65	47%
322205	(3.09+4.43)		5.46	2.62	42%
		11070	5.46	2.62	63%
324453	(3.40+4.72)		7.05	2.66	36%
Henson Gletscher Formation					
324256	(0.01+0.16)		2.95	2.69	2%
324269	(0.27+0.55)		6.30	2.69	4%
324309	(1.23+1.52)		7.51	2.67	12%
		1600	7.51	2.67	7%
324332	(0.05+0.22)		8.06	2.65	1%
324343	(0.08+0.26)		5.50	2.66	2%
324347	(1.31+1.41)		8.44	2.63	10%
324355	(0.40+0.80)		6.56	2.67	6%
		1710	6.56	2.67	8%

Density of HC ~ 0.85

Two Silurian samples, 316067 from the early mature areas in Washington Land and 324166 from the postmature areas in western Wulff Land were studied with fluid inclusion microthermometry (Jensenius, 1987). The calcite in 324166 contains abundant hydrocarbon inclusions and few one-phased aqueous inclusions. In sample 316067 the calcite inclusions are two-phased aqueous with homogenisation temperatures between 90°C and 150°C (fig. 56).

Macroscopic, discrete bitumen in secondary spaces is commonly reported in association with both source rocks and reservoir rocks of the previously mentioned types. Stylolites often contain organic-rich residues, and

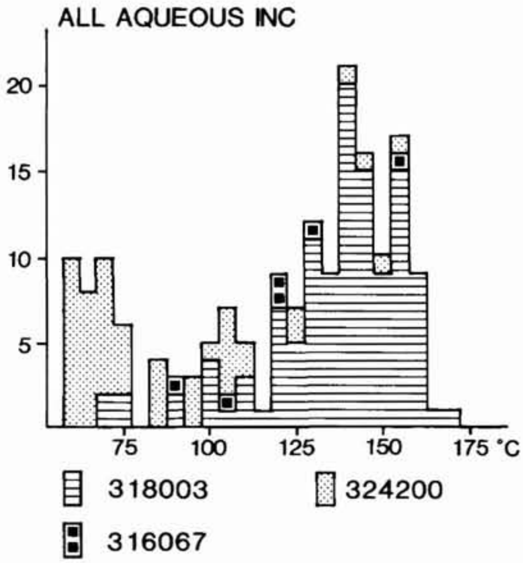


Fig. 56. Inclusion homogenisation temperaturs (Th) for all aqueous inclusions in the three samples 318003, 316067 and 324200. The low and high modes of 324200 correspond to calcite (C1) and dolomite (D2) hosted inclusions, respectively (see Jensenius, 1987, for details).

Typical grain size		Porosity	Diagenetic features
range:	0.1–1 mm	minor inter-particle	intense quartz overgrowth,
median:	0.2–0.4 mm	2–10%	occasionally early carbonate cement
range:	0.03–0.6 mm	minor inter-particle	intense quartz overgrowth
median:	0.05–0.1 mm	1.5–14%	
range:	0.05–0.4 mm	minor inter-particle	intense quartz overgrowth,
median:	0.1–0.15 mm	4–13%	occasionally early carbonate cement

3. *see* Peel (1980), Bryant & Smith (1985)

4. classification based on Folk (1968)

bitumen coating is commonly observed on fracture surfaces. The most common occurrence of secondary bitumen-filled spaces is in Cambrian dolomites, either in completely recrystallized sucrosic dolomites or in vugs and veins which are partly filled with crystalline material. Large saddle dolomite grains (Radke & Mathis, 1980) dominate, but examples of clear calcite, quartz, Fe-rich dolomite and calcite have also been reported (Plates 8 and 9).

Two examples were studied in detail combining petrographic, fluid inclusion and stable isotope techniques, namely the C1 core (samples 318003) from the mature to late mature part of Freuchen Land and the dolomite breccia which hosts an impressive asphalt seep in the thermally immature southern Wulff Land (sample 324200) (Plates 7 and 8).

The 318003 sections consist of dark grey, often bitumen-stained, dolomite grainstone, which are crosscut by numerous fracture zones. Most of these are subhorizontal, some are diagonal to the core and a few (especially the thinner ones) are vertical. Large saddle dolomite grains often replace the dolostone and are also present in the centre of partly open veins in association with bitumen (Plates 7, 8 and 9). Four main appearances are distinguished: (1) dispersed dark bitumen in the pores of the dolomite grainstone, (2) dark bitumen in stylolitic contacts between dolomite grainstone and saddle dolomite veins, (3) large black, often fractured, bitumen particles in the central part of the saddle dolomite veins, (4) yellow bitumen enclosing the large black bitumen particles (Plates 9 and 11). The two first types have similar reflectance values of about 0.9%, the third group somewhat higher (1.2%), whereas the yellow fluorescent bitumen has a very low reflectance (0.08%). The dolomite contains many green–yellow fluorescent hydrocarbon inclusions and some aqueous inclusions. The latter have homogenisation temperatures between 65°C and 170°C with a mode of 140°C (fig. 56), which after pressure corrections suggest a formation temperature of about 160–170°C (Jensenius, 1987). A minor variation in stable isotope composition between the dolomite grainstone (D0) and the saddle dolomite (D1) is shown (fig. 57).

Sample 324200 with the impressive asphalt-filled fractures exhibits a number of generations of carbonate minerals (Plate 8). The primary dolomite grainstone (D0), which typically contains stylolites, is postdated by replacive saddle dolomite (D1). A new generation of

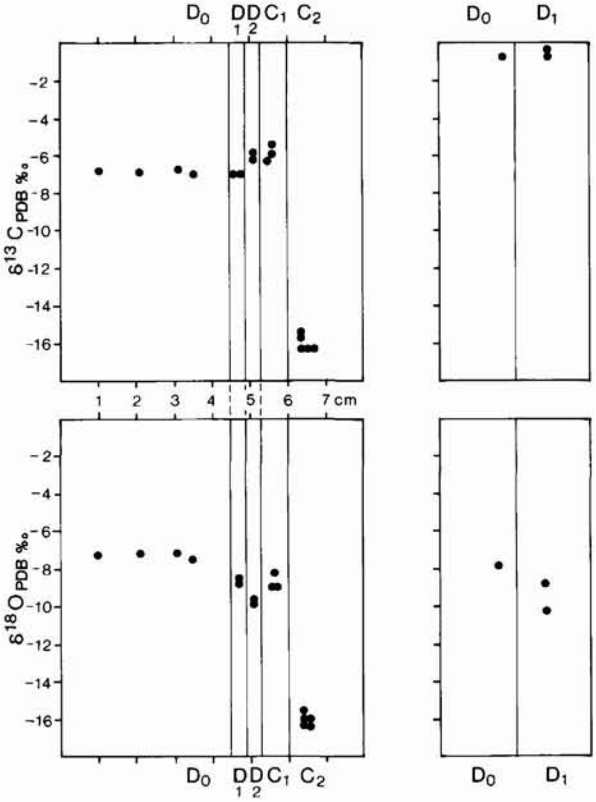


Fig. 57. Carbon and oxygen isotope values obtained in samples 318003 and 324200 showing the variations for the different generations of carbonate minerals (Plate 8).

fractures formed with subsequent precipitation of coarse-grained Fe-rich saddle dolomite (D2) and Fe-rich calcite (C1). The remaining voids are filled with asphalt, occasionally with a thin zone or crust of calcite (C2). Fluid inclusions (both hydrocarbon and aqueous types) were reported from the D2 and C1 zones. The homogenisation temperatures range between 34°C and 154°C with a mode around 60°C in the Fe-rich calcite and a considerably higher mode of about 100°C in the Fe-rich dolomite (fig. 56). These values correspond, after pressure correction, to precipitation temperatures of about 80–90°C and 115–125°C, respectively (Jensenius, 1987). The carbon and oxygen isotope values obtained display significant differences between the various generations of carbonate minerals (fig. 57).

Diagenetic history and hydrocarbon migration

The siliciclastic host rocks, which constitute several potential reservoirs, only express a limited part of the history. A general feature is the occurrence of early carbonate cement formed prior to hydrocarbon migration and an intense quartz overgrowth and pressure solution which is partly contemporaneous with the migration. Combining these features with the regionally maturity controlled variation of the physical and chemical parameters of the bitumen it seems that migration took place before and during the deepest subsidence.

The few examples of carbonate host rocks outline a complex diagenetic history but also provide specific data on the temperature and composition of the fluids associated with the mineral precipitation and hydrocarbon migration.

The dispersed bitumen and the bitumen in primary pores seem to reflect the regional maturity trend. The migration from source to host rock, often over very short distances, probably took place before and during the deepest subsidence. The bitumen-stained carbonates in the Henson Gletscher example are clearly post-dated by one or several episodes of dissolution and mineral precipitation associated with macroscopic solid bitumen. The fluid inclusion data (homogenisation temperature and freezing temperature) (fig. 56) and the stable isotope composition of the carbonate minerals (fig. 57) (see further details and discussion by Jensenius, 1987) suggest that the precipitation of the saddle dolomite took place from ^{18}O-shifted seawater with a $\delta^{18}O_{SMOW}$ composition around +6‰ at temperatures between 155°C and 165°C. These temperatures are too high to be caused by deep burial alone. The higher temperatures and the high reflectance of the macroscopic solid bitumen may be explained by the influence of hot solutions ascending from the deeper part of the basin, at feature which is commonly described from saddle dolomites associated with bitumen in Mississippi-valley type of mineralisation (e.g. Macqueen & Powell, 1983; Krebs & Macqueen, 1984).

In the asphalt seep from the thermally immature southern part of Wulff Land a completely different precipitation sequence is deduced (see details in Jensenius, 1987). The dolomite grainstone (D0) (no hydrocarbon

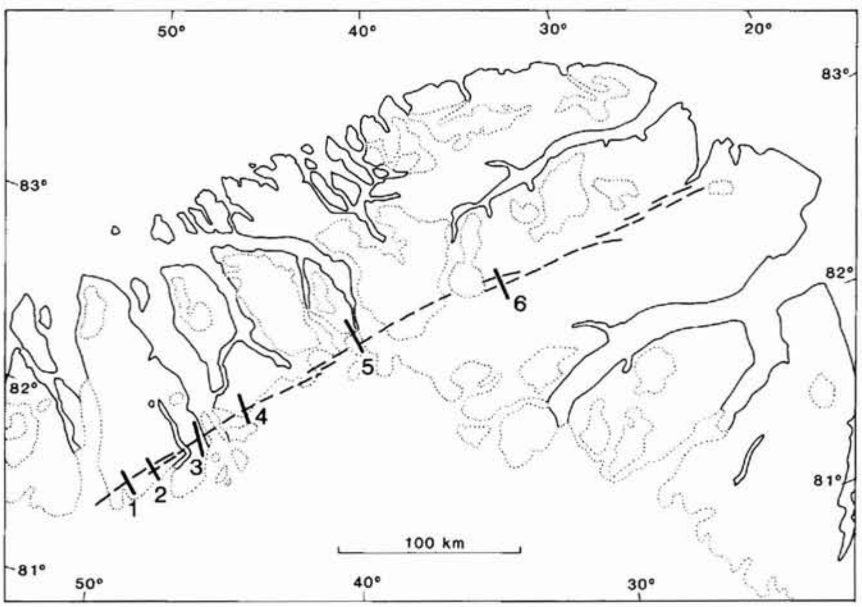


Fig. 58. Map showing the pattern of the major fault zone in the southern part of Wulff Land to Peary Land. Sections across the fault zone are shown in fig. 59.

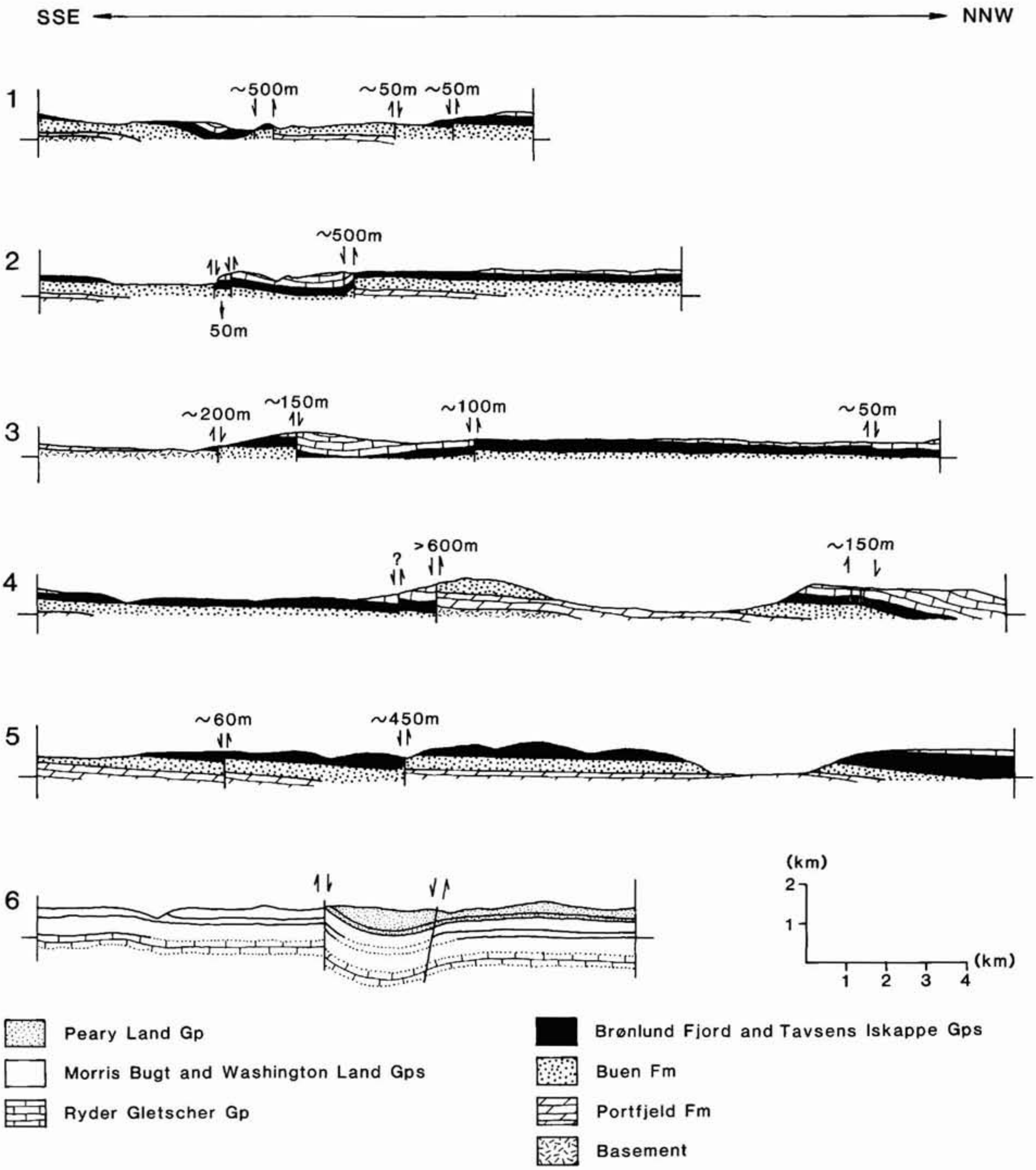


Fig. 59. Constructed sections across the major fault zone in the southern part of Wulff Land to Peary Land. See fig. 58 for location. Sections 1–4 are based on field work by H. F. Jepsen, section 5 by J. S. Peel and section 6 by S. A. S. Pedersen.

staining) recrystallized under the presence of slightly ^{18}O-shifted seawater ($\delta^{18}O_{SMOW}$: +1 – −3%) at temperatures of 90°C to 100°C. The fracture-filling saddle dolomite (D1), and Fe-rich saddle dolomite (D2) precipitated at slightly higher temperatures between 105°C to 115°C and 115°C to 125°C, respectively. The Fe-rich calcite, related to the hydrocarbons, formed at temperatures between 80°C and 90°C, whereupon the remaining space in the fractures was filled with oil. Subsequent to degradation and shrinkage of the oil, highly ^{18}O-depleted modern Arctic meteoric water entered the rocks and precipitated thin crusts of calcite (C2). The proposed temperatures of precipitation are considerably lower than those of the saddle dolomites in the Henson Gletscher Formation, but also in this case somewhat higher than the expected temperature at the deepest subsidence. The lower temperatures of the Fe-rich calcite associated with the asphalt are in accordance with the geochemical results. The presence of cyclic biomarkers in the asphalt and the low reflectance clearly demonstrate that the hydrocarbons have not suffered any strong thermal alteration.

Structural setting and migration pathways

The structural setting of the three bitumen groups varies considerably from relatively simple to highly complex and therefore has strong implications on possible pathways and trapping of hydrocarbons.

The bitumens of group I (associated with the source rocks in the Cambrian Henson Gletscher Formation) occur in a simple structural setting characterized by shallow dips between 1.5° and 6° towards the north and northwest (Christiansen *et al.*, 1987). This pattern favours a simple up-dip migration towards the south through conduits closely associated with the source rocks (sandstones and coarse-grained carbonates). The few bitumens recorded at higher stratigraphic levels probably migrated along fractures and faults.

The bitumens of group II (associated with Silurian source rocks) also occur in a simple setting with shallow dips between 1° and 4° northwards (Christiansen & Nøhr-Hansen, 1989). The calcarenites and conglomerates, which host most of the recorded bitumen and therefore are considered the most likely migration conduits, occasionally display dips of more than 10° close to the reefs. The close association of source rocks and migration conduits favours an up-dip migration towards the south into platform carbonates or into Silurian reef complexes (see also fig. 69).

The bitumens of group III (in the southern part of the region without any known source rocks) occur in an area which generally is considered structurally simple with shallow northerly dips. The presumed long distance of migration and the variety of host rocks make detailed interpretation of possible pathways difficult.

A number of the reported bitumens are within or from the near vicinity of the major fault zone which has been traced from southern Wulff Land throughout the region to southern Peary Land (fig. 58). In the area north of the major fault zone, most of the Cambrian and Ordovician strata dip between 1.5° and 3° towards the north. A minor number of flexures and post-depositional faults have been observed. These faults only display minor vertical displacements, commonly with a northerly downfaulting between 30 and 75 m.

The configuration of the major fault zone is highly variable along strike (fig. 59). The zone is up to about 7 km wide and the individual faults display a variation in vertical displacement between 150 m of northerly downthrow to 600 m of southerly downthrow (fig. 59). The total vertical displacement is variable but in most cases with a southerly downthrow. Internally, the fault zone is dominated by synformal structures, occasionally with flank bed dips up to 30° (fig. 59). This structural style, especially the variation in thickness, number of individual faults and varying direction of vertical displacement, suggests a major strike-slip component of the fault zone. This deformation postdates any of the exposed sediments and it might have taken place before, after or contemporaneously with the expected main phase of hydrocarbon generation and migration during the Ellesmerian orogeny (see discussion in Chapter 8). Consequently, it is difficult with the present knowledge to deduce the migration history and implications of the observed type III bitumens. The most promising traps in terms of expected size seem to be situated immediately north of the major fault zone; this is also the area with the most simple (and probably most efficient) migration pathway.

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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

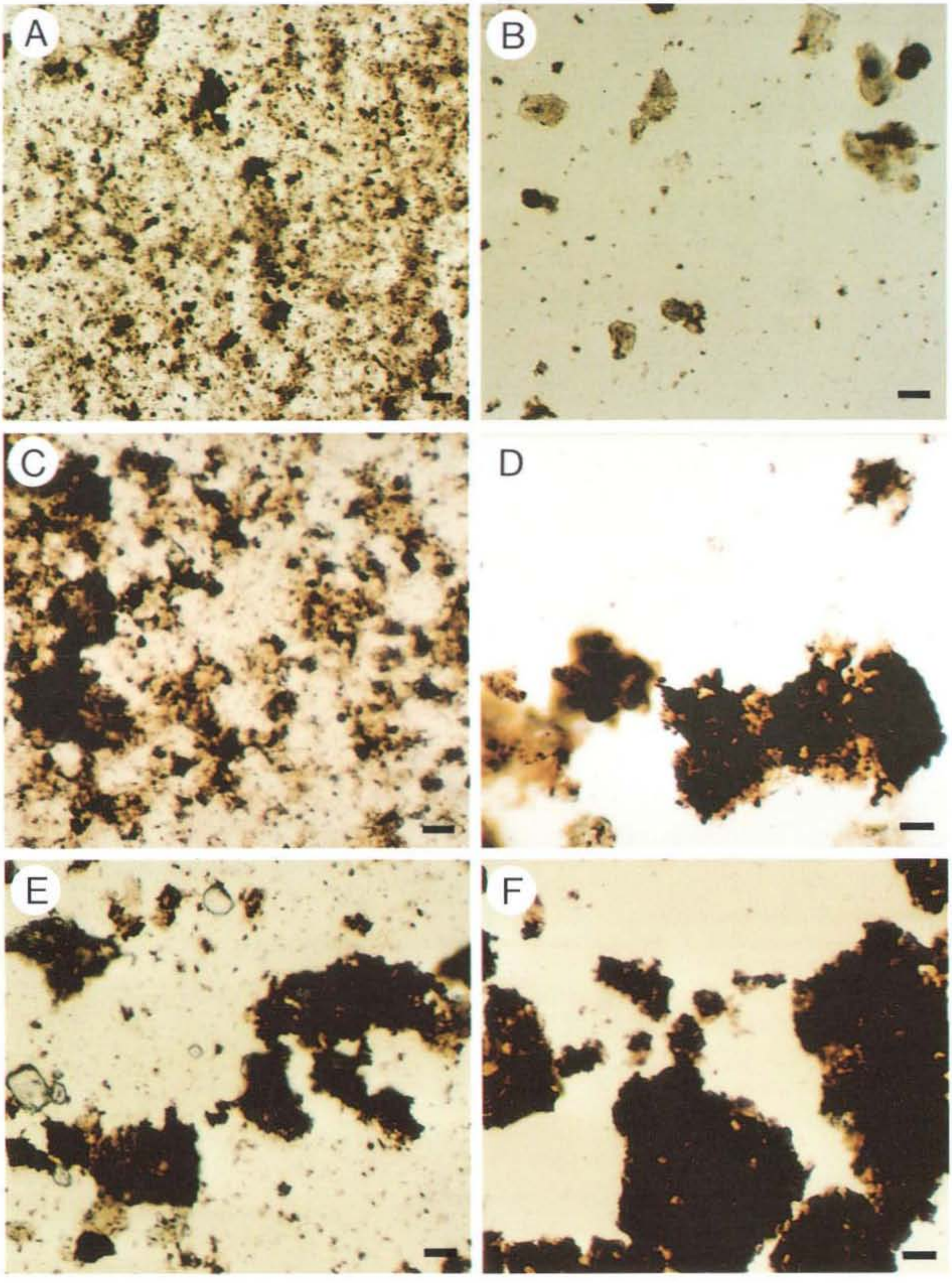

Plate 2. Cambrian palynomorphs

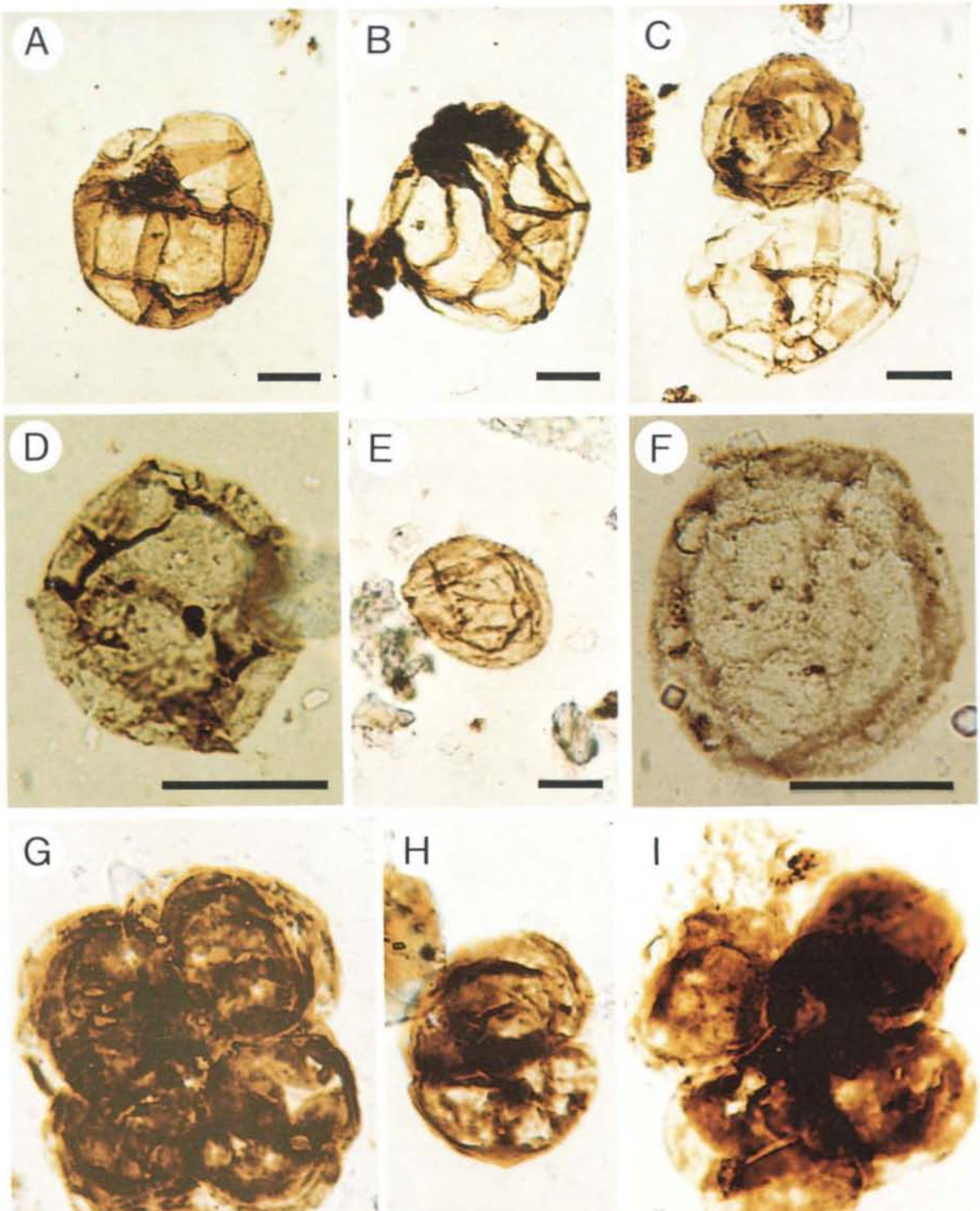

Plate 3. Ordovician palynomorphs

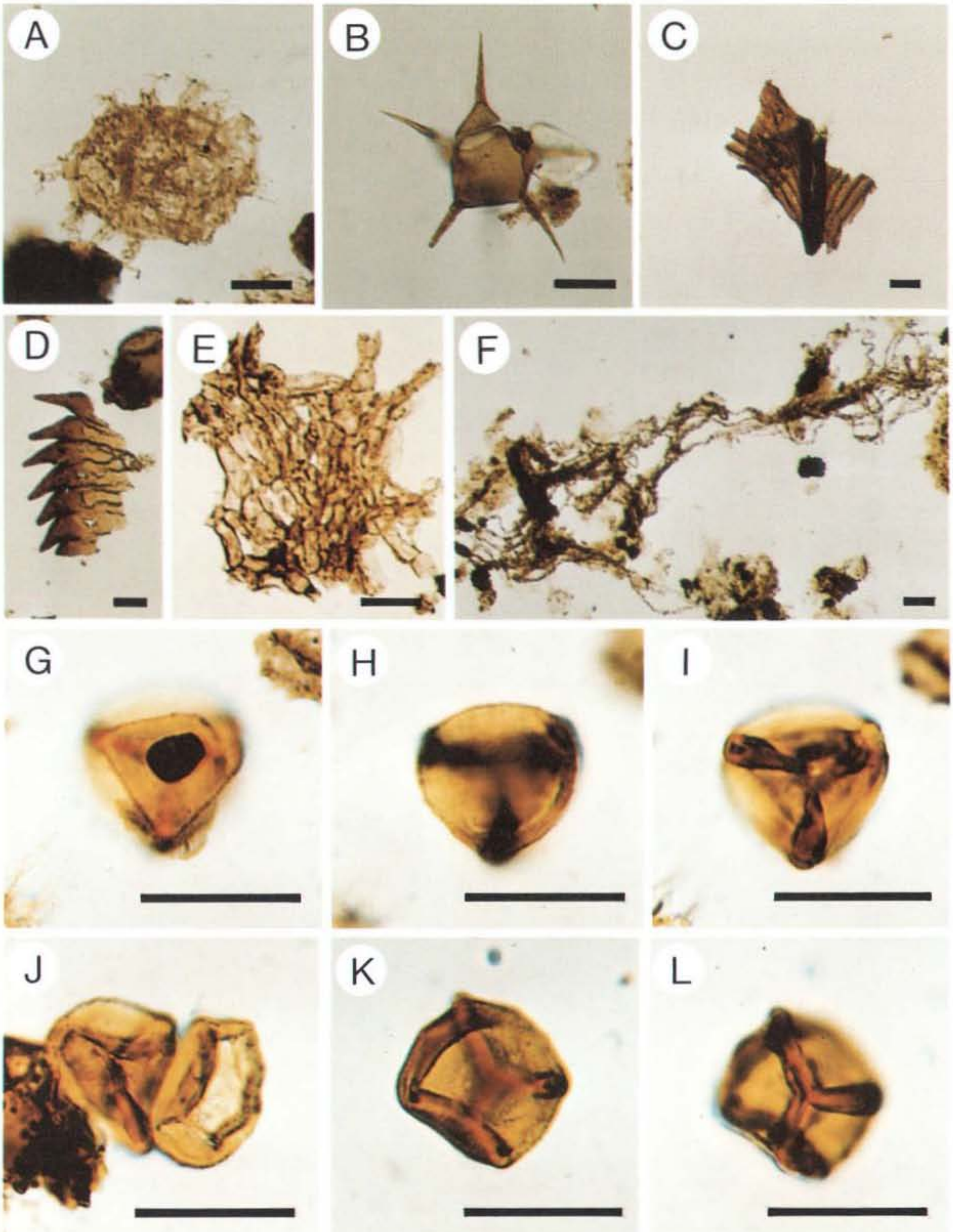

Plate 4. Silurian palynomorphs

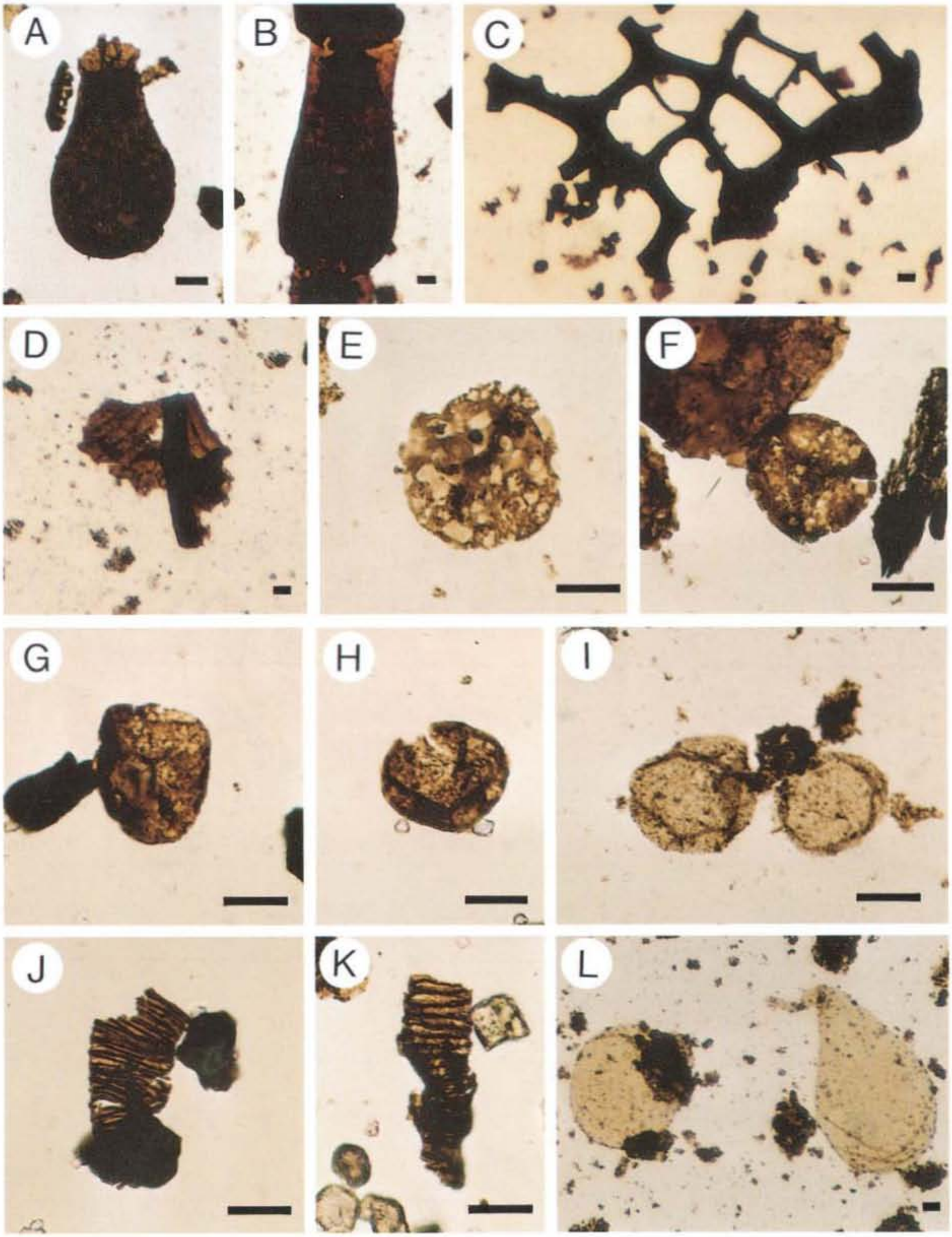

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

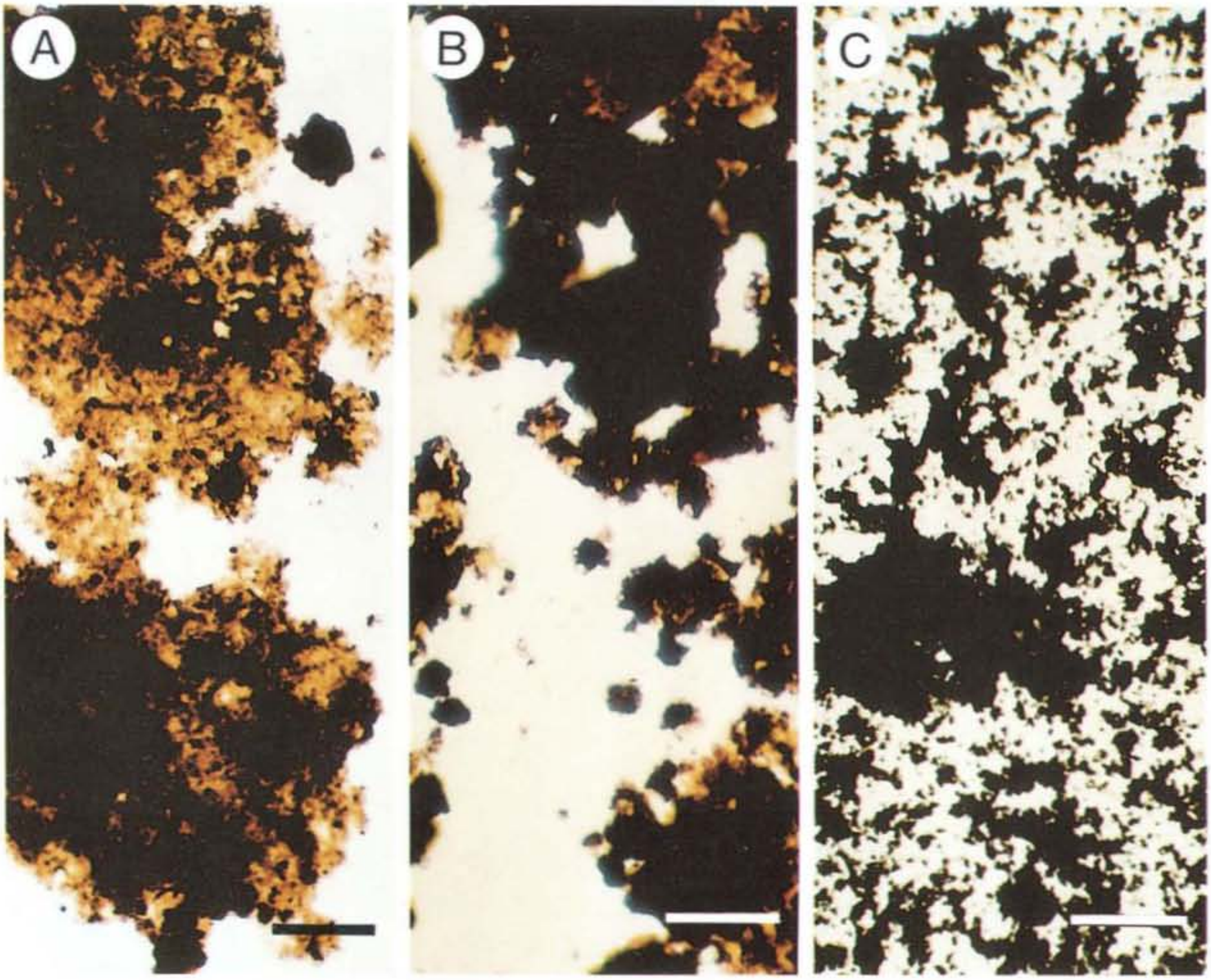

Plate 5. Progressive coloration of amorphous kerogen with increasing thermal alteration

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

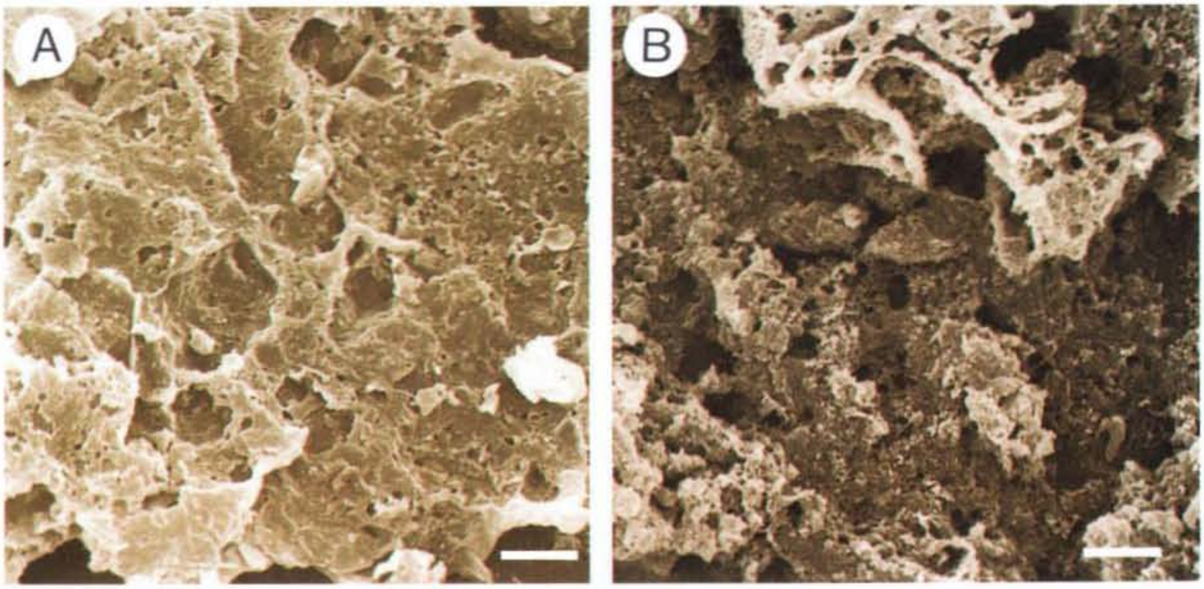

Plate 6. Change in structure of amorphous kerogen with increasing thermal alteration as observed in the scanning electron microscope

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

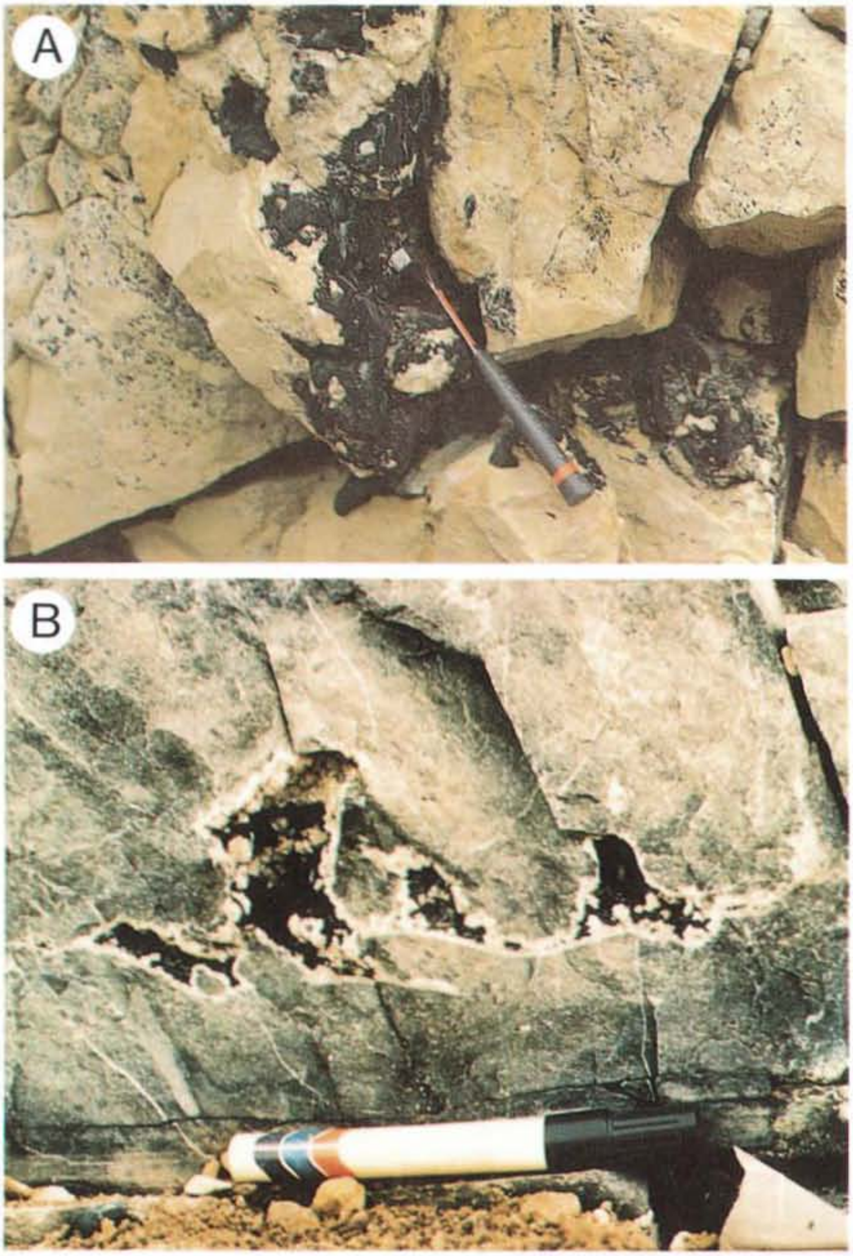

Plate 8. Macroscopic bitumen in slabs

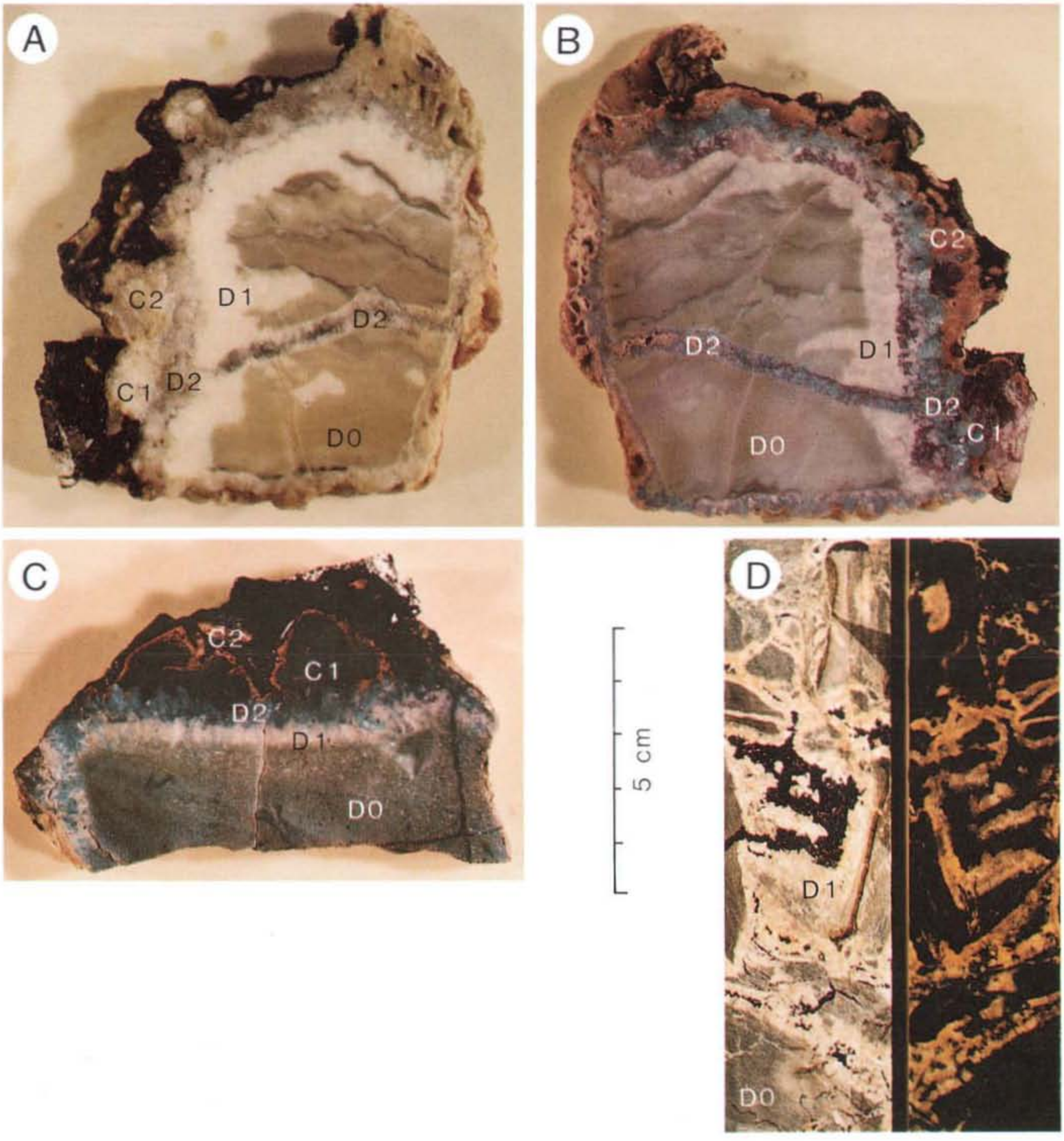

Plate 9. Bitumen in thin section

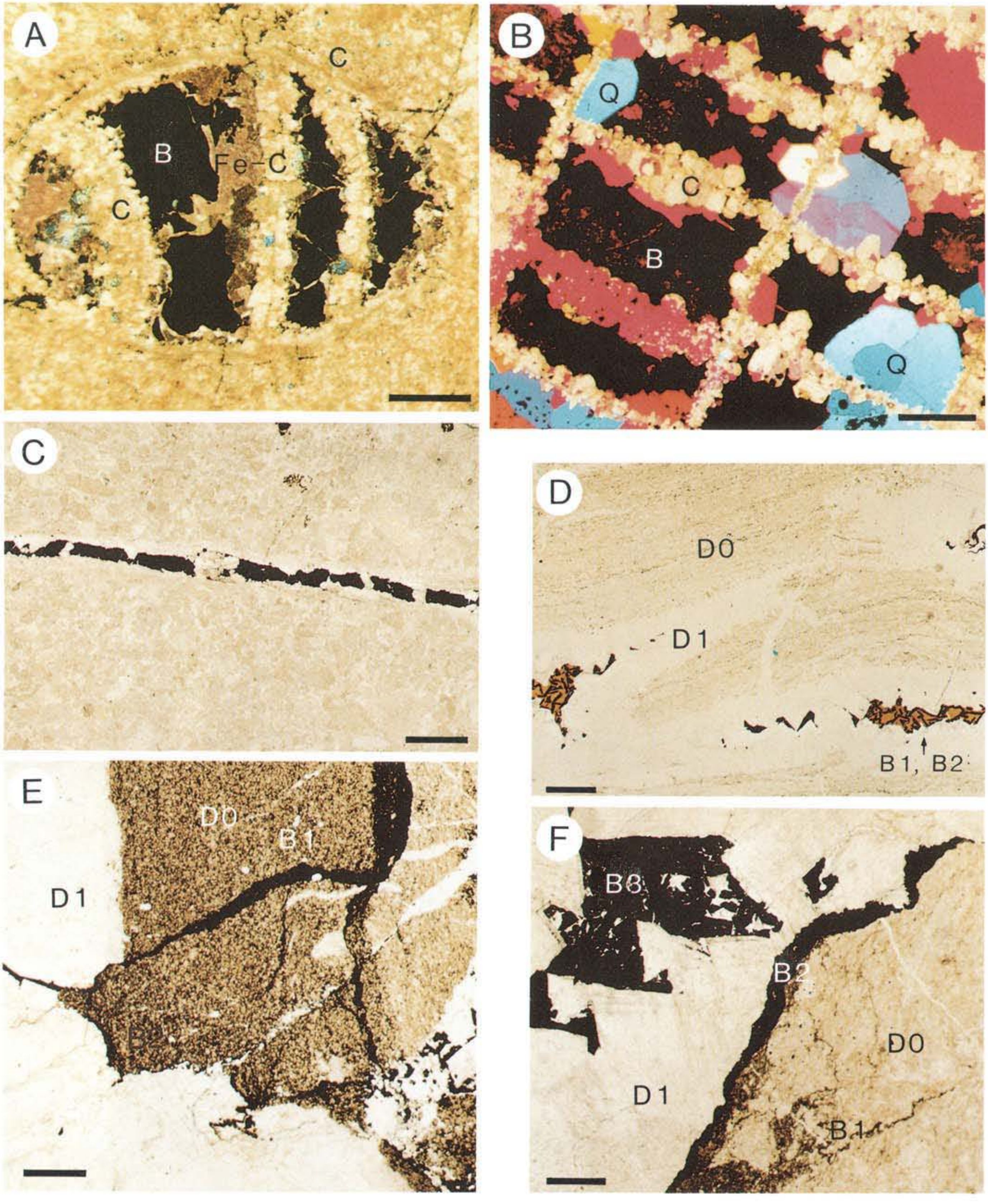

Plate 10. Bitumen in palynologically prepared samples observed in microscope or in SEM

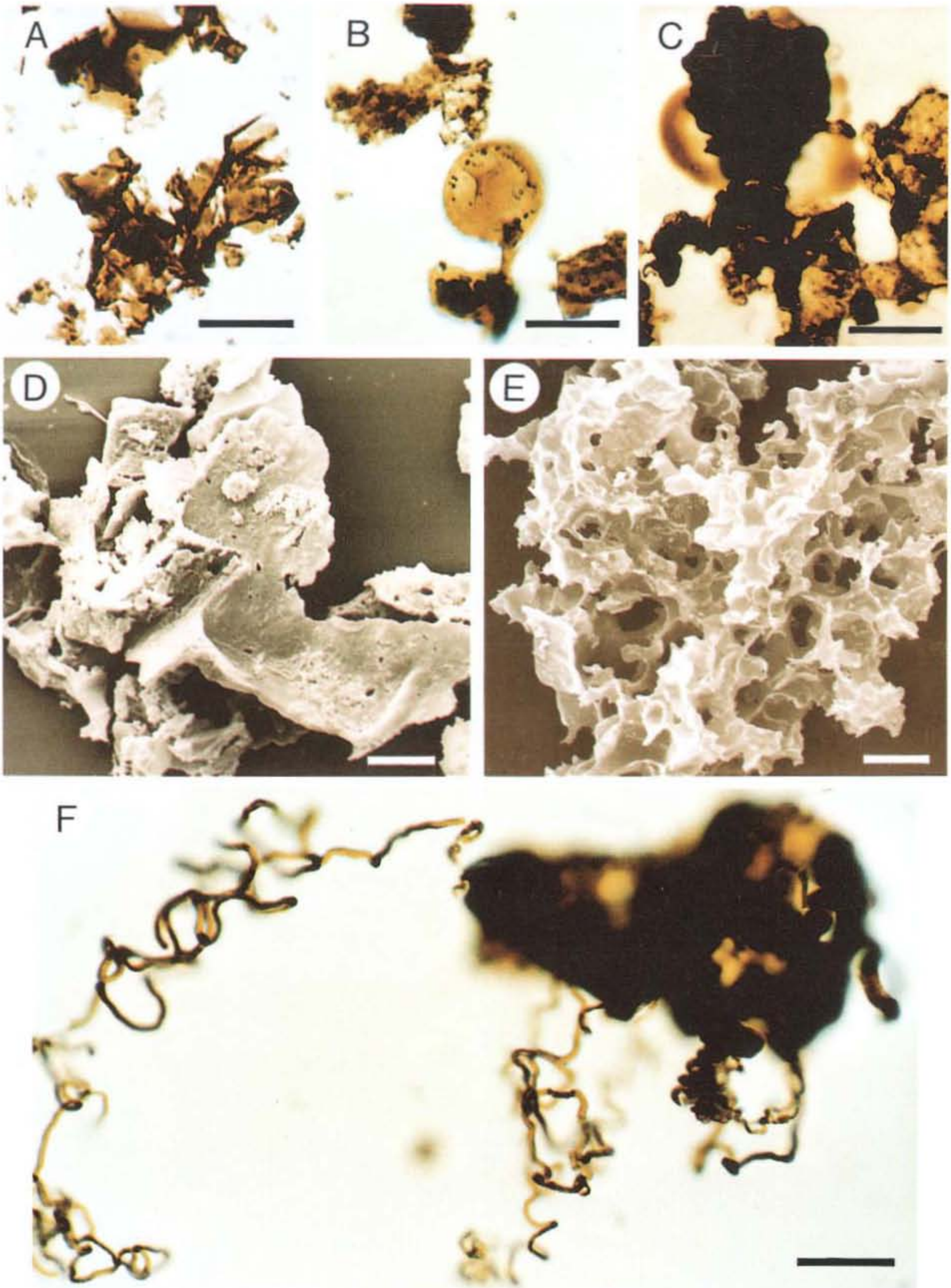

Plate 11. Bitumen in polished section

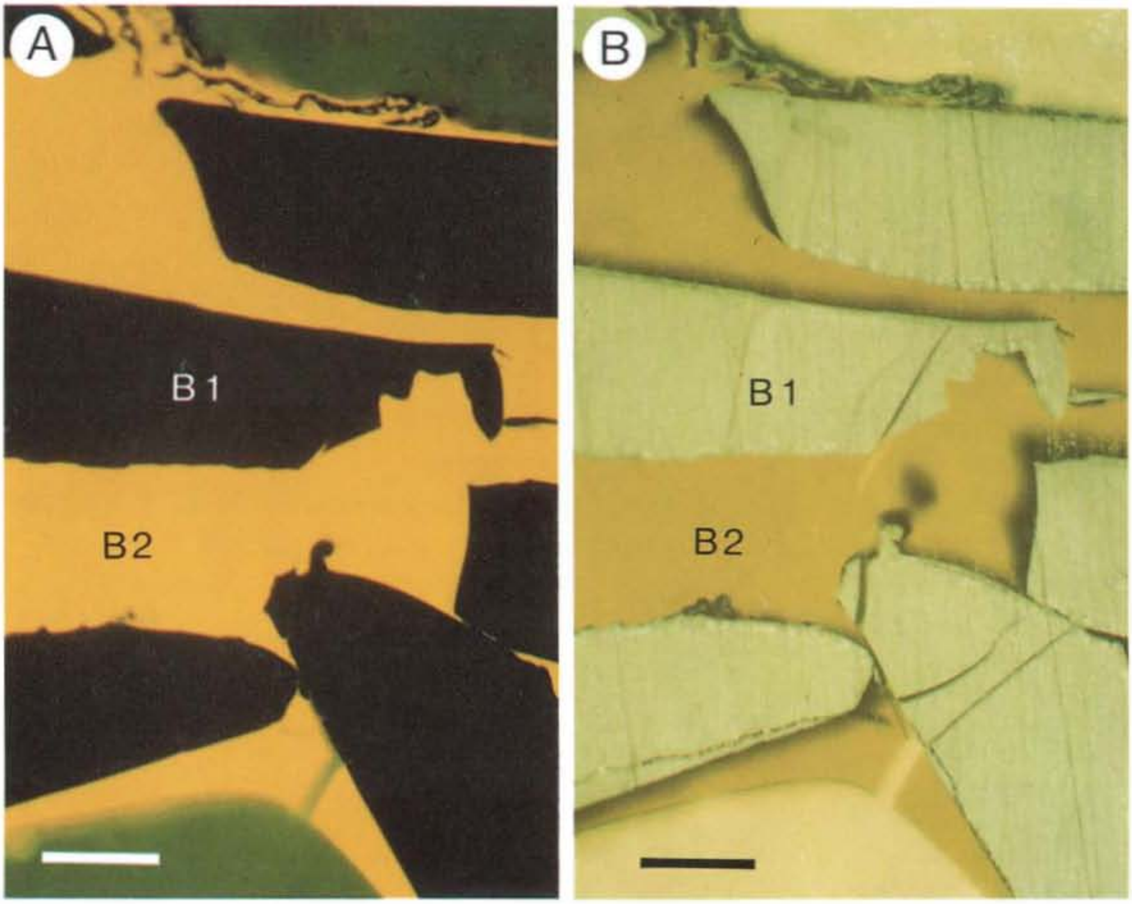

Plate 11. Bitumen in polished section

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.