

# Distribution and thermal maturity of potential source rocks

The regional petroleum generation potential and thermal maturity of the pre-Upper Cretaceous succession in the study area have been assessed by the evaluation of more than 4000 data points ( $S_1$  and  $S_2$  yields, Hydrogen Index (HI),  $T_{max}$ , total organic carbon (TOC)). These are derived from Rock-Eval pyrolysis and TOC determination of principally cuttings samples from 33 wells situated onshore Denmark and offshore in the Skagerrak and Kattegat areas (Fig. 1). Most of the wells drilled the Lower Cretaceous – Triassic succession, but pre-Permian and Permian strata were also encountered in some wells.

Unreliable  $T_{max}$  or HI values derived from low  $S_2$  yields (i.e. approximately  $<0.2$  mg HC/g rock) or TOC contents have been omitted from the data set. The following thresholds for HI have been applied to evaluate the petroleum generation capacity of the predominantly Type II kerogen dominated source rocks (Peters & Cassa 1994):

HI  $<200$  mg HC/g TOC: gas-prone

HI = 200–300 mg HC/g TOC: mixed oil/gas-prone

HI  $>300$  mg HC/g TOC: oil-prone

Determination of the thermal maturity is based on vitrinite reflectance (VR) and  $T_{max}$  values, and the potential source rock is considered immature for VR values  $<0.6\%R_o$  or  $T_{max}$  values  $<435^\circ\text{C}$ . The  $T_{max}$  range  $435$ – $460^\circ\text{C}$  defines the oil window (Bordenave *et al.* 1993; Peters & Cassa 1994).  $T_{max}$  is, however, also influenced by kerogen type and the mineral matrix, and single  $T_{max}$  values may therefore be less reliable as a maturity parameter (Peters 1986). Average  $T_{max}$  values for specific formations or members with source rocks are therefore used.

## Pre-Permian units

Seven wells have encountered pre-Permian strata in the Danish part of the Norwegian–Danish Basin and Fennoscandian Border Zone. Source-rock data are available from five of them: Frederikshavn-1, Nøvling-1, Rønde-1, Slagelse-1 and Terne-1 (Fig. 1). Bitumen and oil stains have been reported from Lower Palaeozoic rocks onshore Norway and Sweden. In the Oslo Graben, bitumen has been found in fractures in Ordovician limestones and corals, and in southern Norway, close to the Oslo Graben, oil and gas are trapped in Permian volcanic intrusive rocks (Pedersen *et al.* 2005, 2007). In southern Sweden, at Österplana, oil has been found in Upper Ordovician carbonate rocks (Pedersen *et al.* 2007). Pedersen *et al.* (2005, 2007) suggested that the

petroleum was generated from Lower Palaeozoic source rocks. Lower Palaeozoic source rocks and oils are known from the Baltic area, where Lower Silurian shales constitute the principal source (Zdanaviciute & Bojesen-Koefoed 1997). Moreover, oil has been generated from Palaeozoic units in Sweden (Sivhed *et al.* 2004 and references therein).

The up to 90 m thick Middle Cambrian – Lower Ordovician Alum Shale, which is exposed in Skåne, on Bornholm and in southern Norway, possesses source-rock properties. The black marine shales are highly organic-rich with an organic matter content locally up to 30% (Thomsen *et al.* 1987; Bharati *et al.* 1992). In central Sweden, the Alum Shale is immature to marginally mature and has HI values up to above 600 mg HC/g TOC, but in the Fennoscandian Border Zone the shales are overmature (Buchardt *et al.* 1986; Buchardt & Lewan 1990; Bharati *et al.* 1992). The Alum Shale was encountered in the Slagelse-1 and Terne-1 wells. In the Slagelse-1 well, TOC contents are below the reliable detection limit of the carbon analyser, but in the Terne-1 well, TOC contents range from 5.39–10.08 wt%. The Alum Shale in the Terne-1 and Slagelse-1 wells is, however, overmature, with HI values  $<8$  mg HC/g TOC in the Terne-1 well.

High TOC contents and HI values were recorded in the Upper Silurian Nøvling Formation in the Rønde-1 well, where the formation consists of interbedded basalts, grey and red-brown claystones and sandstones with some carbonates (Christensen 1971, 1973). The samples are, however, contaminated by various drilling mud additives, such as diesel, Black Magic<sup>®</sup>, and starch-based mud, which render the data unreliable.

Upper Carboniferous strata were encountered by the Hans-1 well, but no source-rock data are available. The drilled redbed section consists of interbedded sandstones, siltstones and claystones overlain by volcanic rocks and claystones, which are regarded to have no source-rock potential based on the lithology (Michelsen & Nielsen 1991, 1993). Upper Carboniferous coals are, however, significant gas source rocks regionally in Northwest Europe and the southern North Sea (Lokhorst 1998; Gautier 2003). West of the study area, the Carboniferous has been drilled by nine released wells in the Danish Central Graben and the southern part of the Norwegian and UK Central Graben; these strata are of Early Carboniferous age (Bruce & Stemmerik 2003). Thin Lower Carboniferous coals were encountered in the Gert-2 well, and these coals possess a gas/condensate generation potential inherited from the

original vegetation, which is a general aspect of Carboniferous coals (Petersen 2006; Petersen & Nytoft 2006, 2007a, b). Reworked Carboniferous palynomorphs are common in the Jurassic of the Norwegian–Danish Basin suggesting that Carboniferous strata, probably coal-bearing, were originally more widespread (Nielsen & Koppelhus 1990) and may be preserved below the regional Permian unconformity in local deep grabens. These strata may thus potentially constitute a deep-seated source for gas/condensate.

In summary, the well data described here do not demonstrate the occurrence of viable source rocks in the pre-Permian succession. It should be acknowledged, however, that the Silurian is only known from the Rønde-1, Nøvling-1 and Terne-1 wells where less than 450 m of the up to 2600 m thick succession have been investigated (Christensen 1971, 1973; Michelsen & Nielsen 1991, 1993). Similarly, the distribution and nature of Carboniferous strata are very poorly known and it can be speculated that gas/condensate-prone Carboniferous strata may be preserved in local grabens and half-grabens, as recorded from the Central Graben (Bruce & Stemmerik 2003).

## Permian units

Strata of Zechstein and Rotliegend age are present in nine wells, and results of source-rock analyses are available from five of them (C-1, Nøvling-1, Rønde-1, Slagelse-1, Sæby-1; Fig. 1). No petroleum generation has been observed in the analysed well sections. High TOC contents and HI values in the Rotliegend Group in the Rønde-1 well, where the formation is mainly composed of reddish brown sandstones (Jacobsen 1971; Nielsen & Japsen 1991), are artefacts from drilling mud additives.

Cuttings samples, showing a resemblance to black shale, from the Rotliegend section (5092–5260 m) in the Felicia-1A well, yield extraordinarily high HI values (exceeding 1000 mg HC/g TOC) and low  $T_{\max}$  from 425–440°C (Petersen *et al.* 2003b). However, these data are flawed as the samples are contaminated by oil-based drilling mud (Shellsol D-70), which was used below a depth of about 2000 m. Core samples collected from thin black, shaly intervals yield HI values <32 mg HC/g TOC and  $T_{\max}$  values from 480–494°C. This indicates overmaturity of the organic matter and no source potential. Visual inspection of the dispersed organic matter (DOM) by reflected light microscopy (white and fluorescing-inducing blue light) reveals lack of fluorescence of the DOM that is classified as vitrinite (Type III kerogen) and inertinite (Type IV kerogen). Lack of fluorescence and visible liptinitic material is

in agreement with the high organic maturity.  $T_{\max}$  values of 480–494°C correspond roughly to a vitrinite reflectance range of 1.6–1.9% $R_o$ , and at this maturity level the fluorescence behaviour of all types of organic matter has disappeared. On the basis of presently available data, therefore, the Permian succession does not exhibit petroleum generation potential, although it is acknowledged that data are few and the Permian potential cannot be categorically discounted. Thin black, bituminous shales possibly equivalent to the Kupferschiefer in the North German Basin were encountered in the Rønde-1 well (Jacobsen 1971) and thin shales appear to be locally present in the Zechstein succession. The distribution of these facies in the Norwegian–Danish Basin is poorly known.

## Triassic units

Triassic strata are dominated by continental to marginal marine sandstones, mudstones, marls, carbonates and evaporites, and good quality source rocks are not common in the Triassic. Petroleum generation potential has been detected in Upper Triassic strata in the Hans-1, Mejrurp-1, Rønde-1 and Skagen-2 wells. A few HI values up to above 500 mg HC/g TOC have been recorded from mudstones of the marine Oddesund Formation in the Rønde-1 well, and in the Mejrurp-1 well a *c.* 8 m thick interval in the brackish Vinding Formation has HI values up to nearly 700 mg HC/g TOC.

In the Hans-1 well, where parts of the Gassum Formation consist of aggrading parasequences of coastal plain deposits with coal beds, a *c.* 10 m thick interval possesses gas generation potential. In the Skagen-2 well, the uppermost part of the Gassum Formation and the lowermost part of the F-I member of the Fjerritslev Formation comprise lagoonal sediments with a restricted capacity to generate liquid petroleum (see below). In the Mejrurp-1 well, the Gassum Formation is more fine-grained than normal, and certain mudstone intervals have HI values up to 534 mg HC/g TOC; the average HI value for a *c.* 73 m thick mudstone-dominated section is 216 mg HC/g TOC. This unusual development of the formation in Mejrurp-1 is probably related to the position of the well in the secondary rim syncline of the Vejrum salt dome, in the centre of the basin. Movement of salt influenced depositional patterns at many locations in the basin, as shown by seismic data, but only few wells have drilled rim synclines and none show a development similar to that of the Gassum Formation in the Mejrurp-1 well. However, detailed seismic mapping of the Upper Triassic may determine if similar depositional situations and sufficient burial of Upper Triassic potential

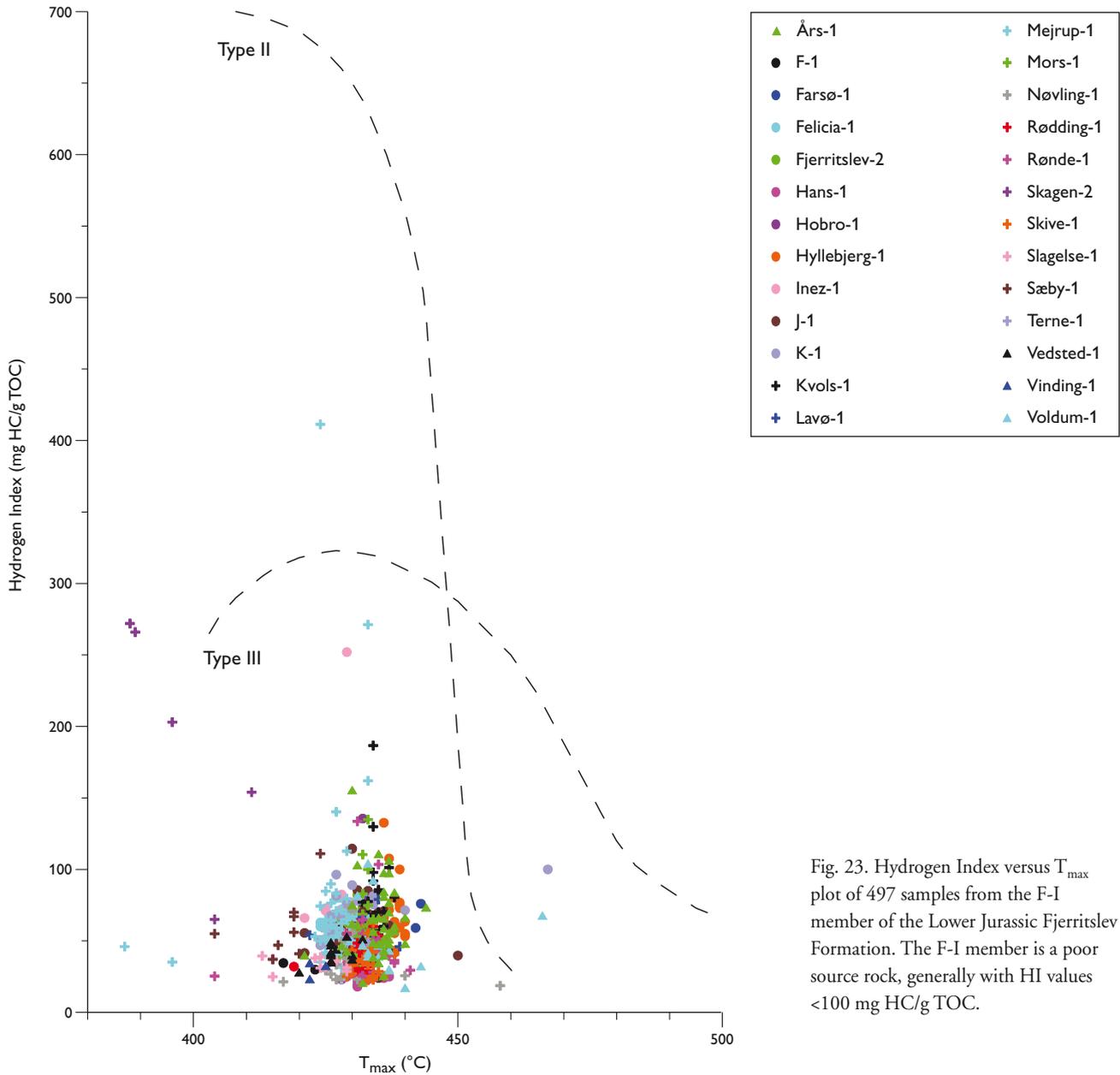


Fig. 23. Hydrogen Index versus  $T_{max}$  plot of 497 samples from the F-I member of the Lower Jurassic Fjerritslev Formation. The F-I member is a poor source rock, generally with HI values <100 mg HC/g TOC.

source rocks occur adjacent to other salt structures.

In summary, apart from a few local occurrences of Upper Triassic units with a limited potential, the Triassic does not possess a petroleum generation potential.

### Lower Jurassic units

With the sole exception of the C-1 well, the Lower Jurassic offshore marine mudstones of the Fjerritslev Formation

have been encountered in all the investigated wells. All four members of the Fjerritslev Formation (F-I – F-IV) are, however, not present in all wells due to Middle Jurassic uplift and erosion over much of the basin (Andsbjerg *et al.* 2001; Nielsen 2003). As a result of the uplift and associated erosion, the F-I member at the base of the formation is regionally the most widespread, being present in all but one well, whereas the F-IV member in the uppermost part of the formation is only present in 20 of the 33 wells. The F-II and F-III members are present in 25 of the wells.

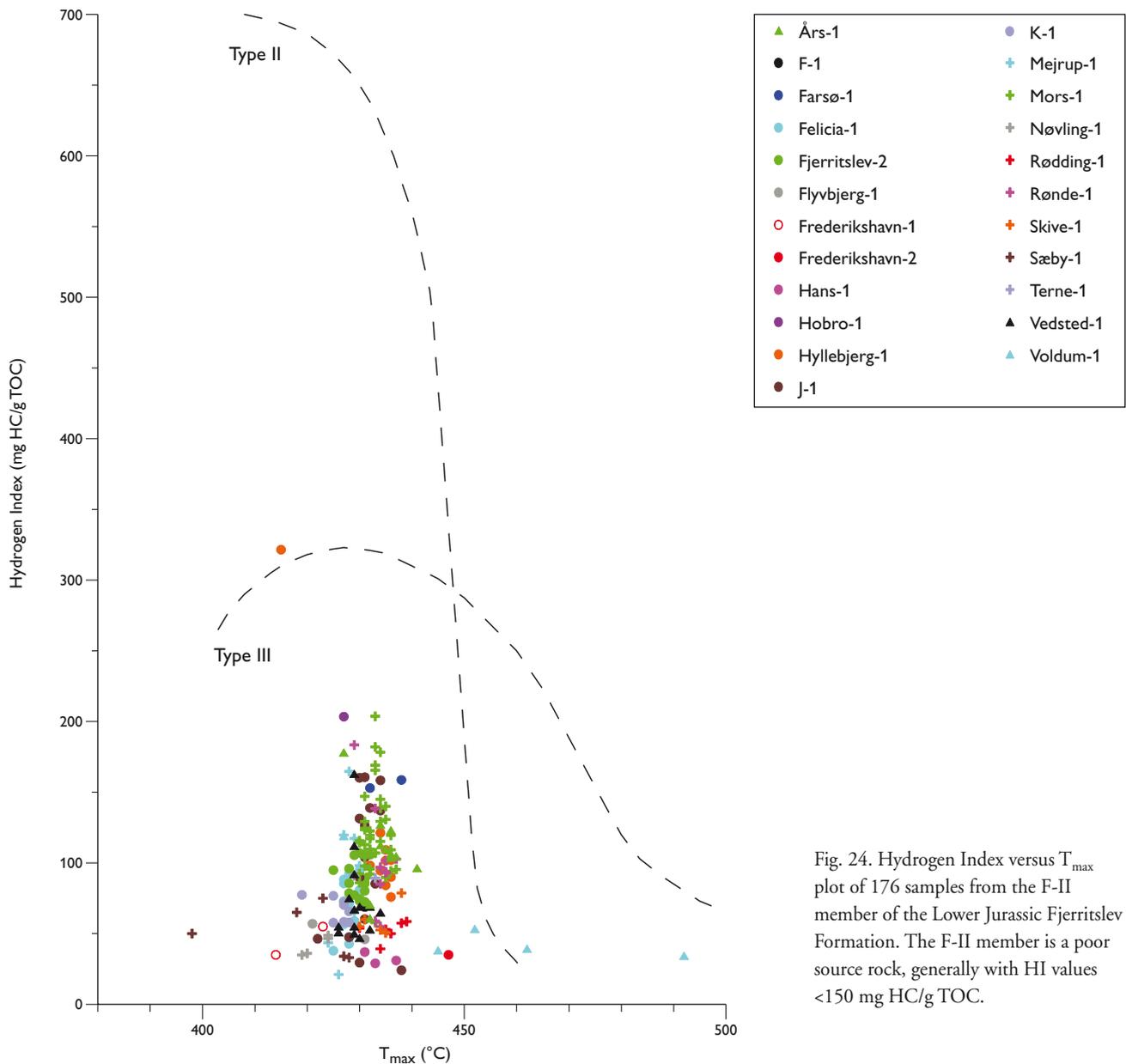


Fig. 24. Hydrogen Index versus  $T_{max}$  plot of 176 samples from the F-II member of the Lower Jurassic Fjerritslev Formation. The F-II member is a poor source rock, generally with HI values <150 mg HC/g TOC.

### F-I member

Only in the Skagen-2 well does the F-I member possess a potential for petroleum generation (Fig. 23). As noted above (Triassic units), a 10 m thick interval spanning the uppermost part of the Gassum Formation and the lowermost part of the F-I member shows HI values ranging from 255–273 mg HC/g TOC. This interval is interpreted to consist of stacked lagoonal deposits that are only locally developed (Sequence Fj 9 of Nielsen 2003).

### F-II member

A marginal petroleum generation potential has been recorded in the F-II member in the Farsø-1 and Mors-1 wells, whereas the member in the Hobro-1 well shows a somewhat better potential (Fig. 24), albeit over a very narrow interval. Within a 6 m thick interval in Hobro-1, the HI values range from 203–340 mg HC/g TOC. The topmost 10 m of the F-II member in Mors-1 has an average HI value of 183 mg HC/g TOC, whereas the average HI value of the member in Farsø-1 is 156 mg HC/g TOC. The F-II mem-

ber in the latter two wells can thus principally be regarded as gas-prone. In the other wells, the mudstones of the F-II member possess no source-rock potential. Generally, the source-rock potential of the F-II member can thus be regarded as limited and primarily gas-prone.

### F-III and F-IV members

The distribution of the F-III and F-IV members is controlled by post-depositional erosion related to the regional early Middle Jurassic uplift that influenced most of the Norwegian–Danish Basin and the Fennoscandian Border Zone. The map in Fig. 15 displays the area within which sediments of F-III or F-IV are preserved; in some wells the combined thickness of the F-III and F-IV members amounts to nearly 400 m (Fig. 25A; see also Table 2). The isopach map suggests that the largest combined thicknesses occur in the Himmerland Graben (Fig. 25B). The entire stratigraphic interval is only preserved in the Sorgenfrei–Tornquist Zone. The analyses of the 33 well sections show that the average quality of the F-III and F-IV members, in terms of potential source rocks for oil generation, is highly variable both stratigraphically and geographically (Figs 26, 27).

In the Kvals-1 and Rønde-1 wells, part of the F-III member constitutes an excellent potential oil source rock (Fig. 26). The uppermost alginite-bearing 40 m of the member in Kvals-1 has an average TOC content of 2.95 wt%, and the interval displays HI values consistently >300 mg HC/g TOC, with a maximum value of 529 mg HC/g TOC and an average value of 429 mg HC/g TOC (Fig. 28, 29A). The marine mudstones in this interval contain abundant algal-derived organic material composed of fluorescing, amorphous organic matter (AOM) and alginite of the *Tasmanites* and *Leiosphaeridia* types (Fig. 28). Associated framboidal pyrite testifies to the oxygen-deficient, organic-rich conditions in the sediment during deposition. This highly oil-prone section overlies a *c.* 25 m thick

interval with an average HI value of 243 mg HC/g TOC. In Rønde-1, the topmost *c.* 18 m of the F-III member are highly oil-prone, with HI values ranging from 263–428 mg HC/g TOC, averaging 355 mg HC/g TOC (Fig. 29B). Similarly, the F-III member in the Haldager-1 well contains a *c.* 25 m thick oil-prone interval, with HI values reaching 425 mg HC/g TOC and averaging 323 mg HC/g TOC (Fig. 30A).

In a number of other wells, the F-III member also possesses a variable petroleum generation potential. The Farsø-1 and J-1 wells show maximum HI values around 300 mg HC/g TOC and average HI values of 214 mg HC/g TOC and 202 mg HC/g TOC, respectively, indicating a limited liquid petroleum generation potential (Fig. 30B). The Mors-1 well has an average HI value of the same order, but the maximum HI value only reaches 266 mg HC/g TOC (Fig. 31A). In the Hobro-1 well, a *c.* 12 m thick interval of the F-III member has an average HI of 233 mg HC/g TOC (Fig. 31B). The F-III member in Fjerritslev-2, Hyllebjerg-1 (Fig. 32A) and Voldum-1 (Fig. 32B) contains intervals with average HI values around 190 mg HC/g TOC, whereas in the Års-1 well, the average value is only 156 mg HC/g TOC. The F-III member of these latter four wells is considered to be principally gas-prone.

In the Rønde-1 well, the F-IV member (55 m thick) is an excellent, organic-rich (average TOC of 3.58 wt%), oil-prone source rock with an average HI value of 435 mg HC/g TOC and a maximum HI value of 543 mg HC/g TOC (Figs 27, 29B). The organic material in this highly oil-prone interval consists of abundant fluorescing AOM, detrital liptinite and *Leiosphaeridia* type alginite (Fig. 33). Both the AOM and detrital liptinite are probably composed of degraded algal material. The occurrence of framboidal pyrite is indicative of oxygen-deficient conditions during deposition of the organic-rich shales. A nearly 50 m thick section of the F-IV member in the Hyllebjerg-1 well has an average HI value of 210 mg HC/g TOC, with a maximum HI value of 371 mg HC/g TOC (Fig. 32A).

Table 2. Net source-rock (SR) thicknesses, F-III and F-IV members of the Fjerritslev Formation

Well	F-III Net SR (m)	F-III Gross (m)	F-III Net/gross	F-IV Net SR (m)	F-IV Gross (m)	F-IV Net/gross	Sum Net SR (m)	Sum Gross (m)	Sum Net/gross	Average HI*, Net SR interval (number of samples)
Haldager-1	31	117	0.26	9	127	0.07	40	244	0.16	294 (7)
Hobro-1	19	154	0.12	7	32	0.22	26	186	0.14	229 (4)
Hyllebjerg-1	35	228	0.15	21	55	0.38	56	283	0.20	246 (14)
J-1	19	98	0.19	0	43	0	19	141	0.13	267 (2)
Kvals-1	79	201	0.39	4	18	0.22	83	219	0.38	369 (28)
Mors-1	118	147	0.80	5	25	0.20	123	172	0.72	221 (17)
Rønde-1	48	145	0.33	44	55	0.80	92	200	0.46	404 (12)
Skagen-2	7	59	0.12	0	29	0	7	88	0.08	203 (1)
Sæby-1	0	53	0	4	38	0.11	4	91	0.04	261 (1)
Voldum-1	14	111	0.13	0	0	0	14	111	0.13	215 (2)

\* Average HI in Net SR intervals based on HI values  $\geq 200$  mg HC/g TOC

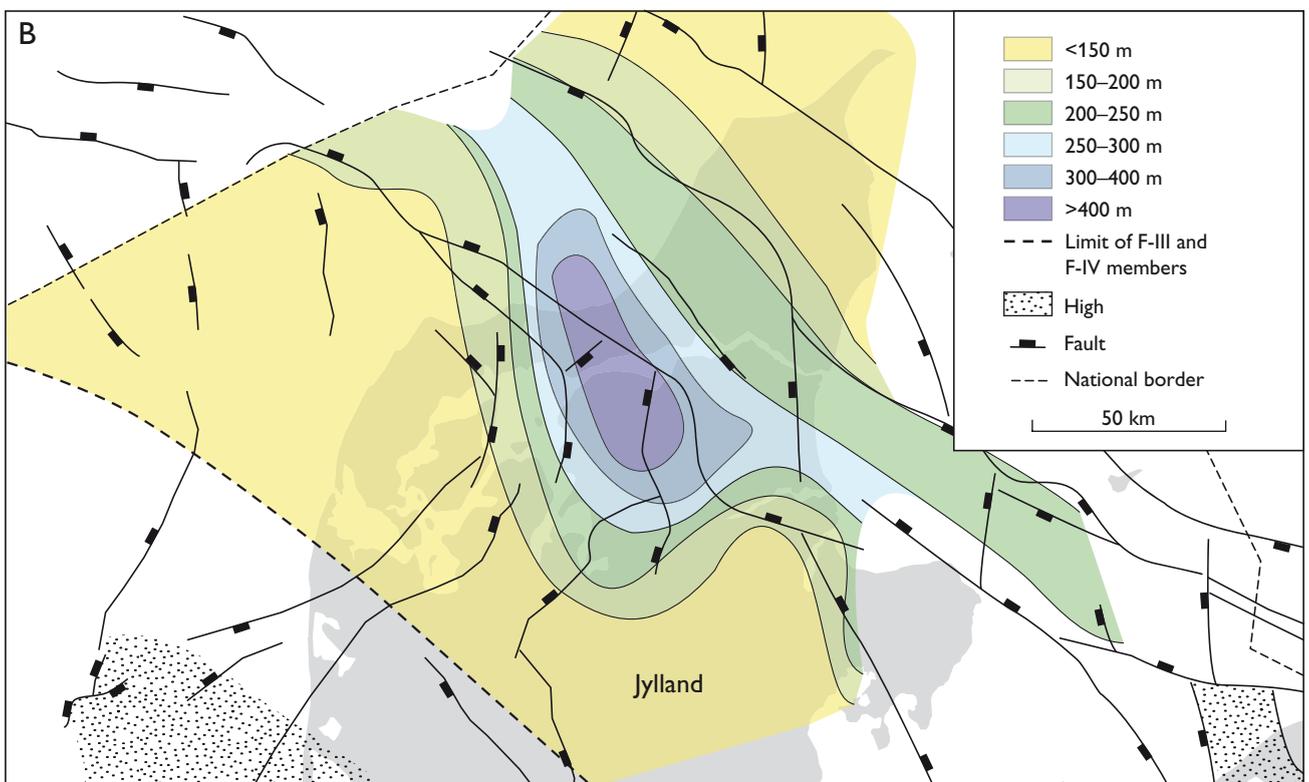
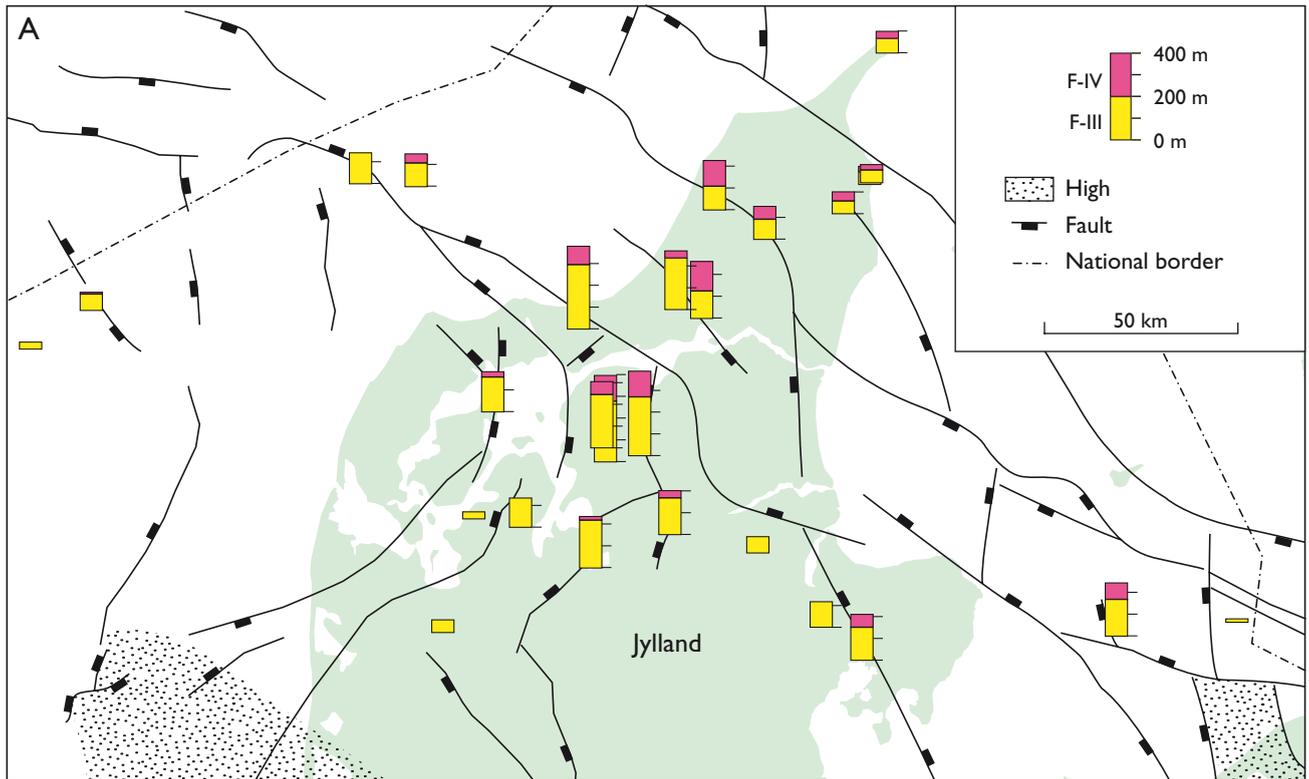


Fig. 25. A: Thickness of the Lower Jurassic lithostratigraphic F-III and F-IV members in the Fjerritslev Formation in the studied wells; the base of each schematic stratigraphic column is located at the well site. B: Isopach map of the combined thickness of the F-III and F-IV members. The largest thicknesses occur in the Himmerland Graben.

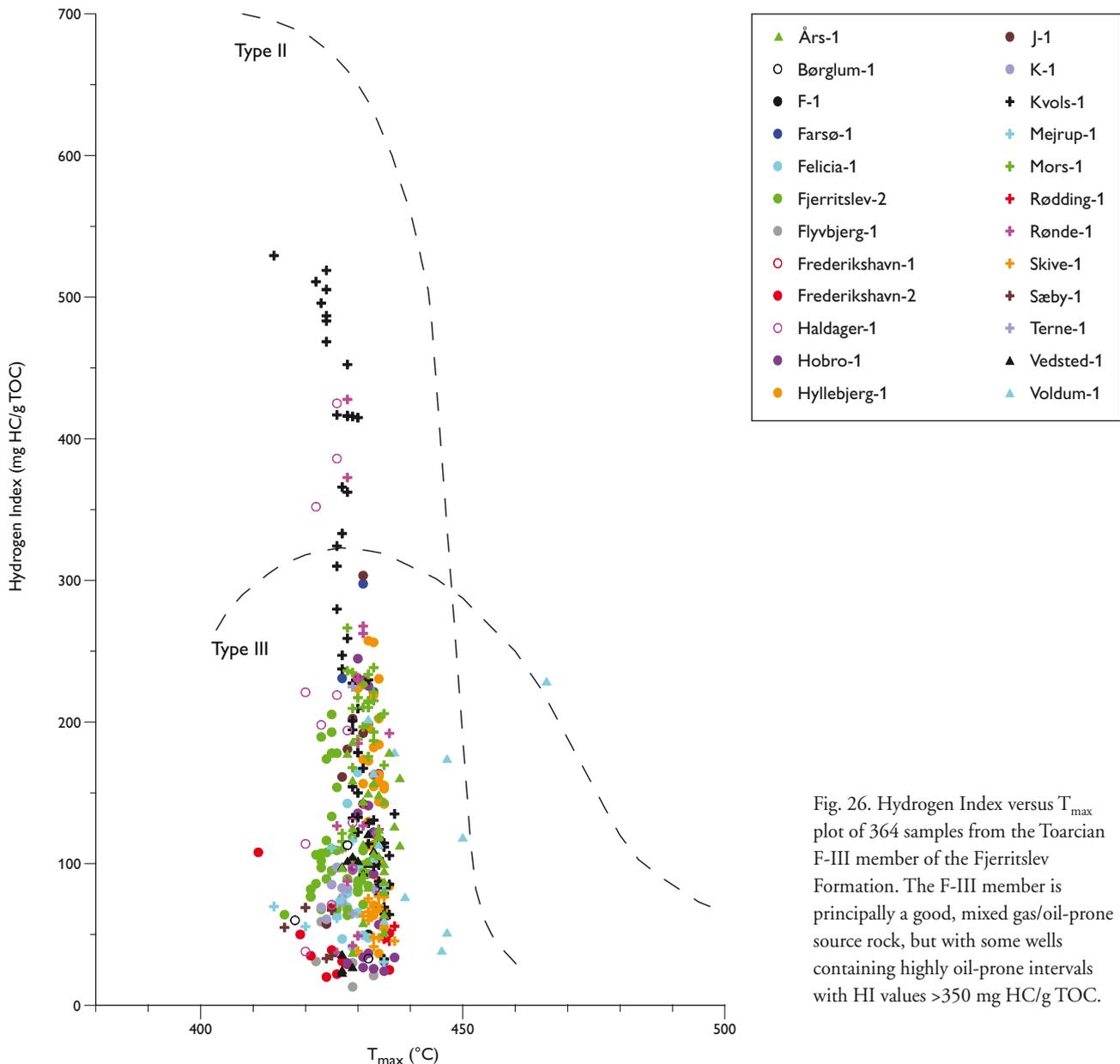


Fig. 26. Hydrogen Index versus  $T_{\max}$  plot of 364 samples from the Toarcian F-III member of the Fjerritslev Formation. The F-III member is principally a good, mixed gas/oil-prone source rock, but with some wells containing highly oil-prone intervals with HI values >350 mg HC/g TOC.

A marginal gas generation potential is shown by the member in the J-1 well (Fig. 30B), where the average HI value is only 130 mg HC/g TOC and the maximum HI value is 178 mg HC/g TOC.

The average HI values in the F-III and F-IV members, calculated from the entire thickness of the members, classify the majority of well-sections as gas-prone and a few as gas-/oil-prone (Fig. 34). The source-rock quality of the F-III and F-IV members, as shown above, varies considerably between wells and within the members in individual wells; average values thus mask specific oil-prone intervals. To illustrate further the evaluation of the source rocks in the F-III and F-IV members, a 'net quality map' was constructed showing the cumulative thickness of intervals with

HI values >200 mg HC/g TOC (Fig. 35A; Table 2) and the net/gross ratio (cumulative thickness/total thickness of F-III + F-IV members). The map thus displays the occurrence and thickness of source rocks with a mixed gas/oil or oil generation potential and suggests that the thickest cumulative source-rock section with HI >200 mg HC/g TOC occurs in the basin centre (Kvols-1, Mors-1 and Rønde-1 wells), where the best source-rock quality also occurs. The Kvols-1 and Rønde-1 wells contain about 80–90 m net oil-prone source rock with average HI values of 369 and 404 mg HC/g TOC, respectively. It is also notable that the Haldager-1 well in the Sorgenfrei–Tornquist Zone contains *c.* 40 m net source rock with an average HI of 294 mg HC/g TOC. The thinner net source-rock thicknesses

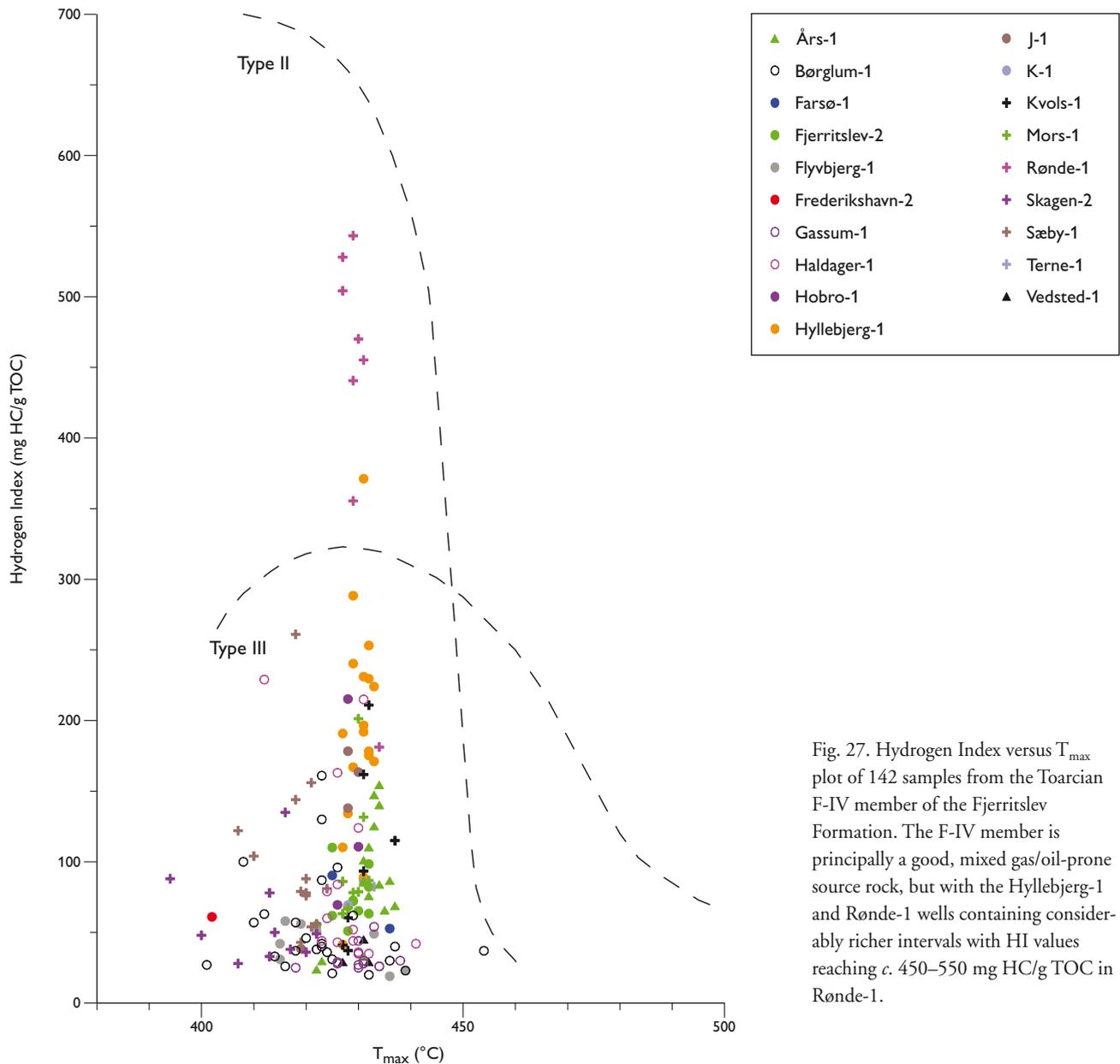


Fig. 27. Hydrogen Index versus  $T_{max}$  plot of 142 samples from the Toarcian F-IV member of the Fjerritslev Formation. The F-IV member is principally a good, mixed gas/oil-prone source rock, but with the Hyllebjerger-1 and Rønde-1 wells containing considerably richer intervals with HI values reaching *c.* 450–550 mg HC/g TOC in Rønde-1.

in the Hobro-1, Hyllebjerger-1 and Voldum-1 wells, which are also situated centrally in the basin, may partly be explained by erosion of the upper part of the F-IV member during the Middle Jurassic uplift event. In other centrally placed wells, such as Mejrup-1, Rødding-1 and Skive-1, the entire F-IV member and most of the F-III member have been eroded, resulting in potential source rocks being thin or absent in these areas.

The limiting factor for the petroleum potential of the study area is the thermal maturity of the richest source-rock units, the F-III and F-IV members. It has been shown that the depth to the top of the oil window, corresponding to a VR of 0.6% $R_o$ , is about 3050–3100 m (Figs 20A, 22A). Using this threshold, the F-III and F-IV members are ther-

mally immature in the investigated wells, also demonstrated by the  $T_{max}$  values (Fig. 35B). The largest discrepancy between  $T_{max}$  and VR values is observed in the Terne-1 well, which compared to the other wells also yields unusually low VR values (Figs 18, 19, 21). The notable lack of hydrocarbon shows in the wells drilled in the study area, including the central deep part, supports the suggestion that the F-III and F-IV source rocks had not, prior to post-Early Cretaceous uplift, been buried to the necessary depth for petroleum generation to occur. The Mors-1 and Års-1 wells represent locations where the Fjerritslev Formation has been buried below the depth of the top of the oil window, but in both wells the petroleum generation potential of the sediments is relatively poor to non-existent.

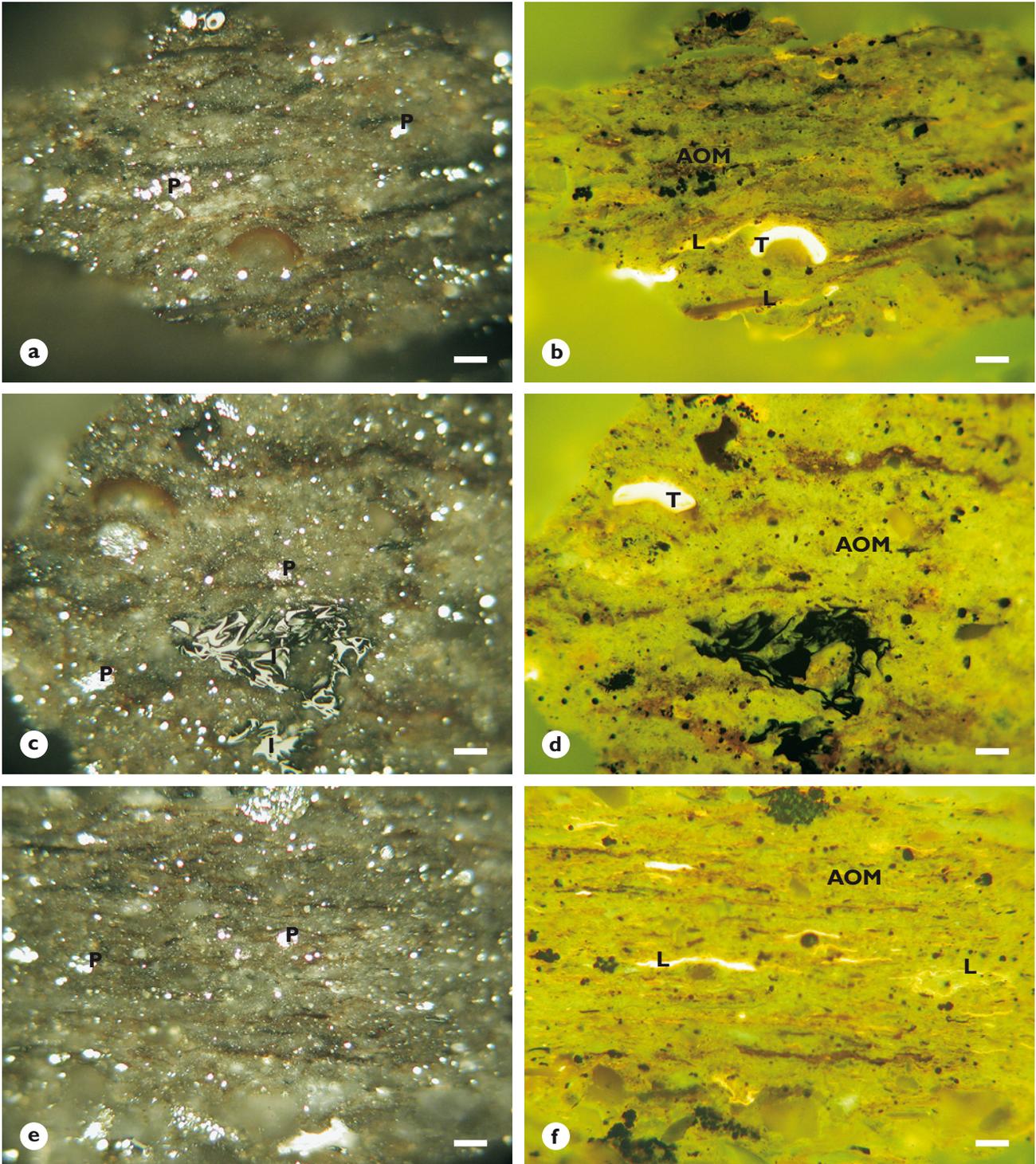


Fig. 28. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30  $\mu\text{m}$ ) of the organic material in the oil-prone F-III member in the Kvols-1 well; left (a, c, e): white light; right (b, d, f): fluorescence-inducing blue light. a-d: Fluorescing, amorphous organic matter (AOM; probably algal-derived) and alginite with *Tasmanites* (T) and *Leiosphaeridia* (L) morphology in cuttings from *c.* 1996 m. Inertinite (I) and framboidal pyrite (P) are also present. TOC = 2.56 wt%, HI = 416 mg HC/g TOC. e, f: Fluorescing AOM (probably algal-derived) and several alginites with *Leiosphaeridia* (L) morphology in cuttings from *c.* 2012 m. Abundant framboidal pyrite (P) present. TOC = 3.57 wt%, HI = 487 mg HC/g TOC.

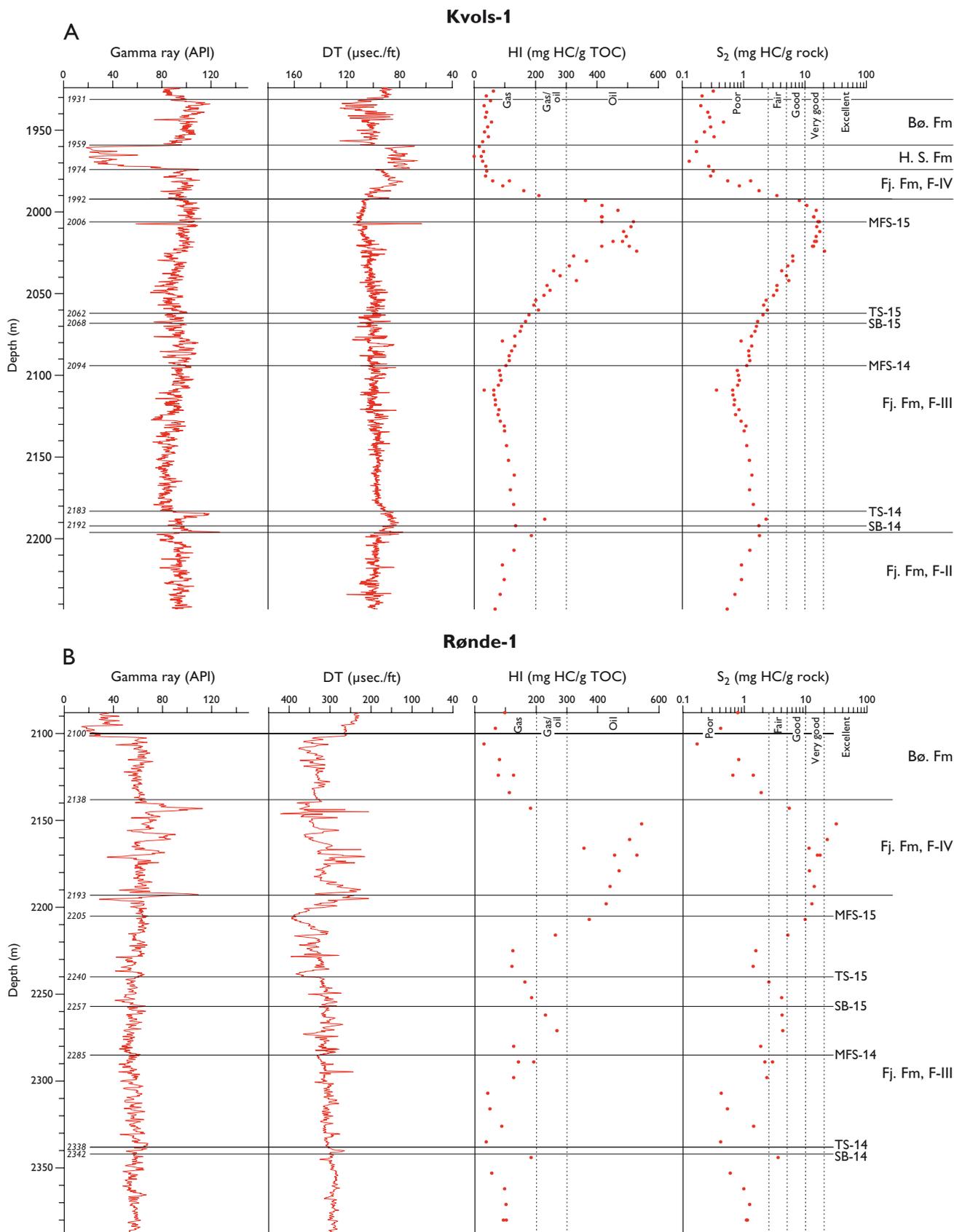


Fig. 29. Plots showing well logs, Hydrogen Index (HI) values, S<sub>2</sub> yields, sequence stratigraphic key surfaces and formations in the Kvols-1 (A) and Rønde-1 (B) wells. Note the oil-prone upper part of the F-III member in Kvols-1 and the oil-prone F-IV member in Rønde-1. DT, sonic velocity; MFS, maximum marine flooding surface; SB, sequence boundary; TS, transgressive surface. Bø., Børglum; Fj., Fjerritslev; H.S., Haldager Sand.

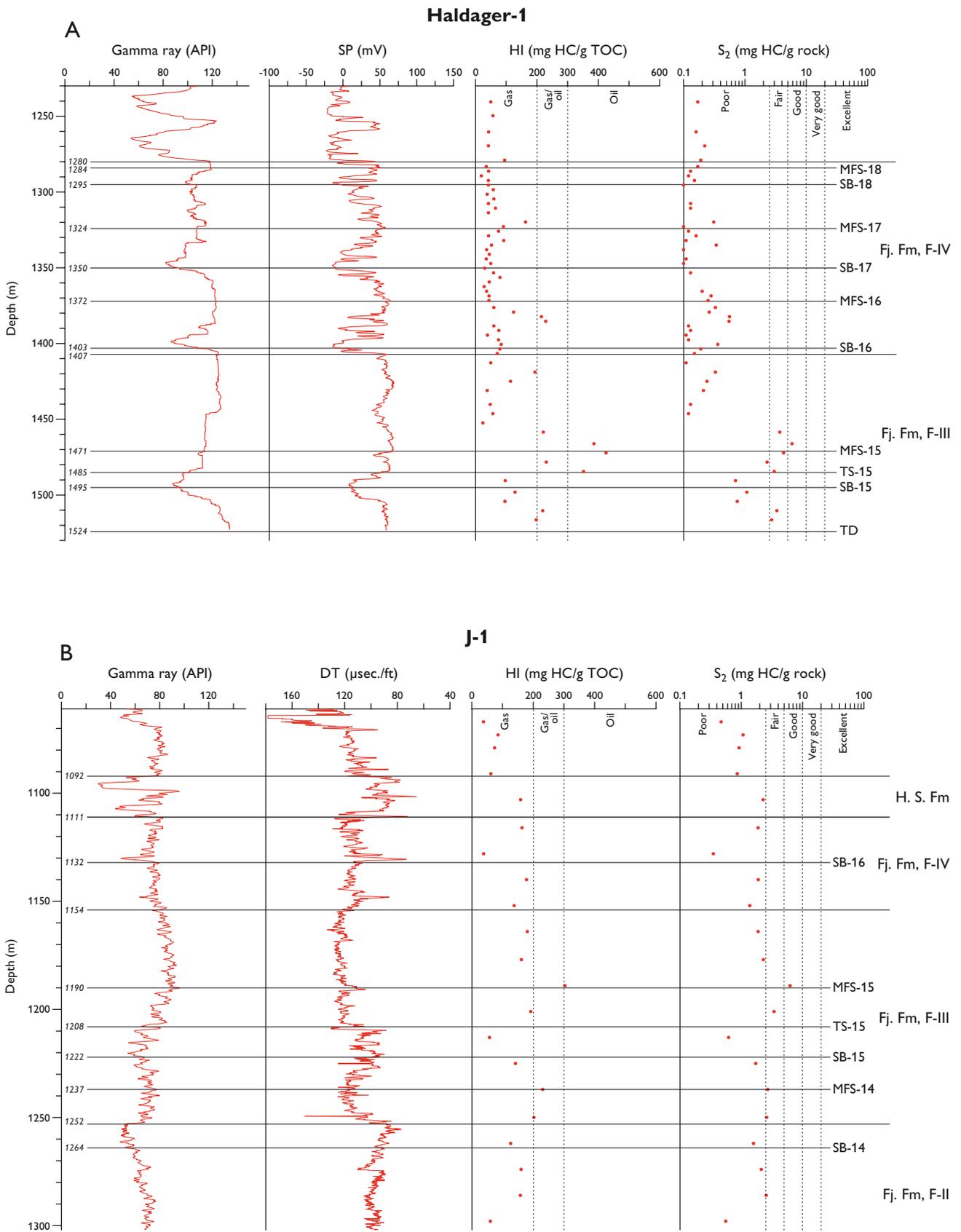


Fig. 30. Plots showing well logs, Hydrogen Index (HI) values, S<sub>2</sub> yields, sequence stratigraphic key surfaces and formations in the Haldager-1 (A) and J-1 (B) wells. Note the oil-prone interval in the F-III member in Haldager-1. DT, sonic velocity; SP, self-potential; TD, total depth. For further abbreviations, see Fig. 29.

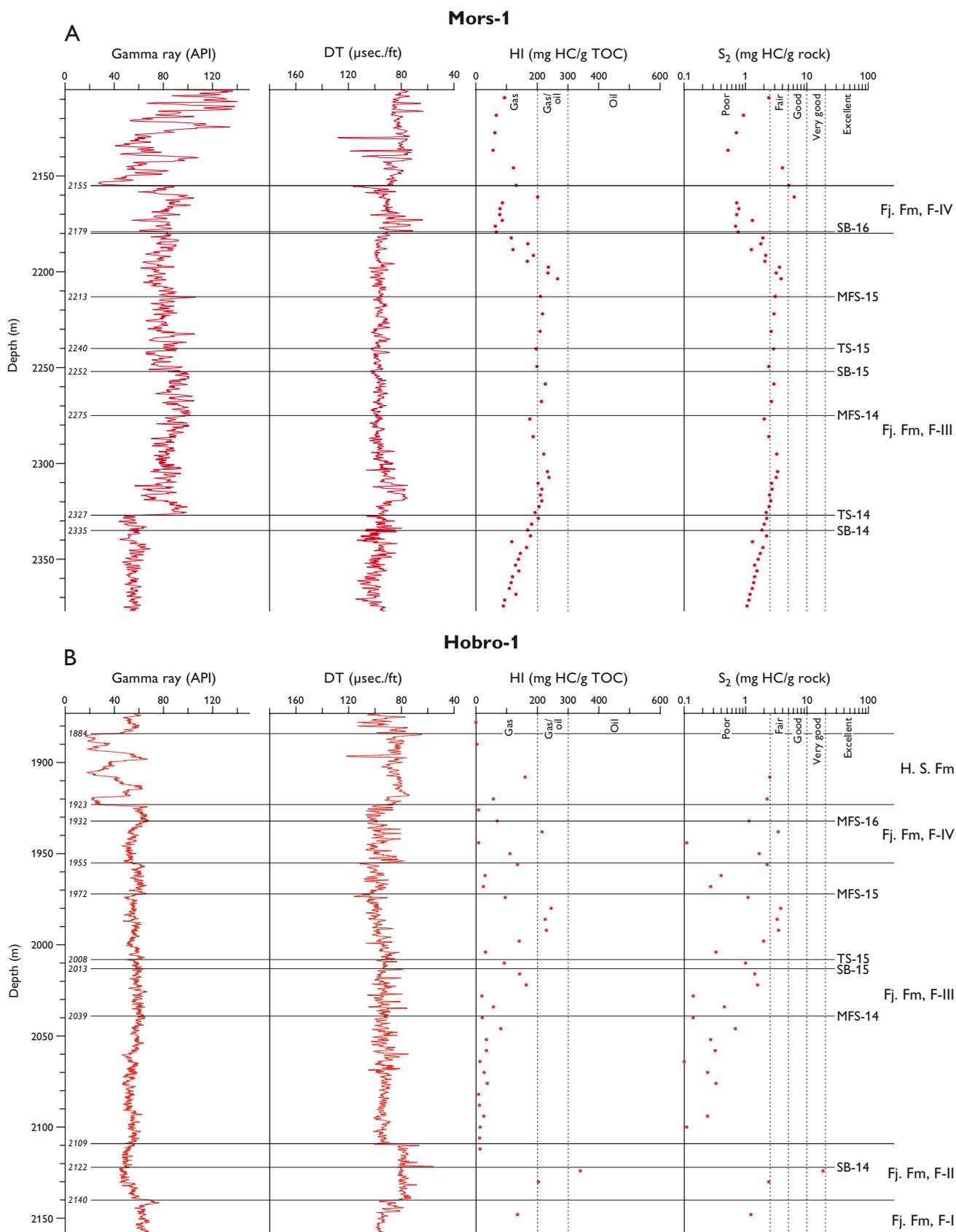


Fig. 31. Plots showing well logs, Hydrogen Index (HI) values,  $S_2$  yields, sequence stratigraphic key surfaces and formations in the Mors-1 (A) and Hobro-1 (B) wells. Note the  $\approx 125$  m thick interval in the F-III member in Mors-1 in which HI values exceeded 200 mg HC/g TOC. DT, sonic velocity. For further abbreviations, see Fig. 29.

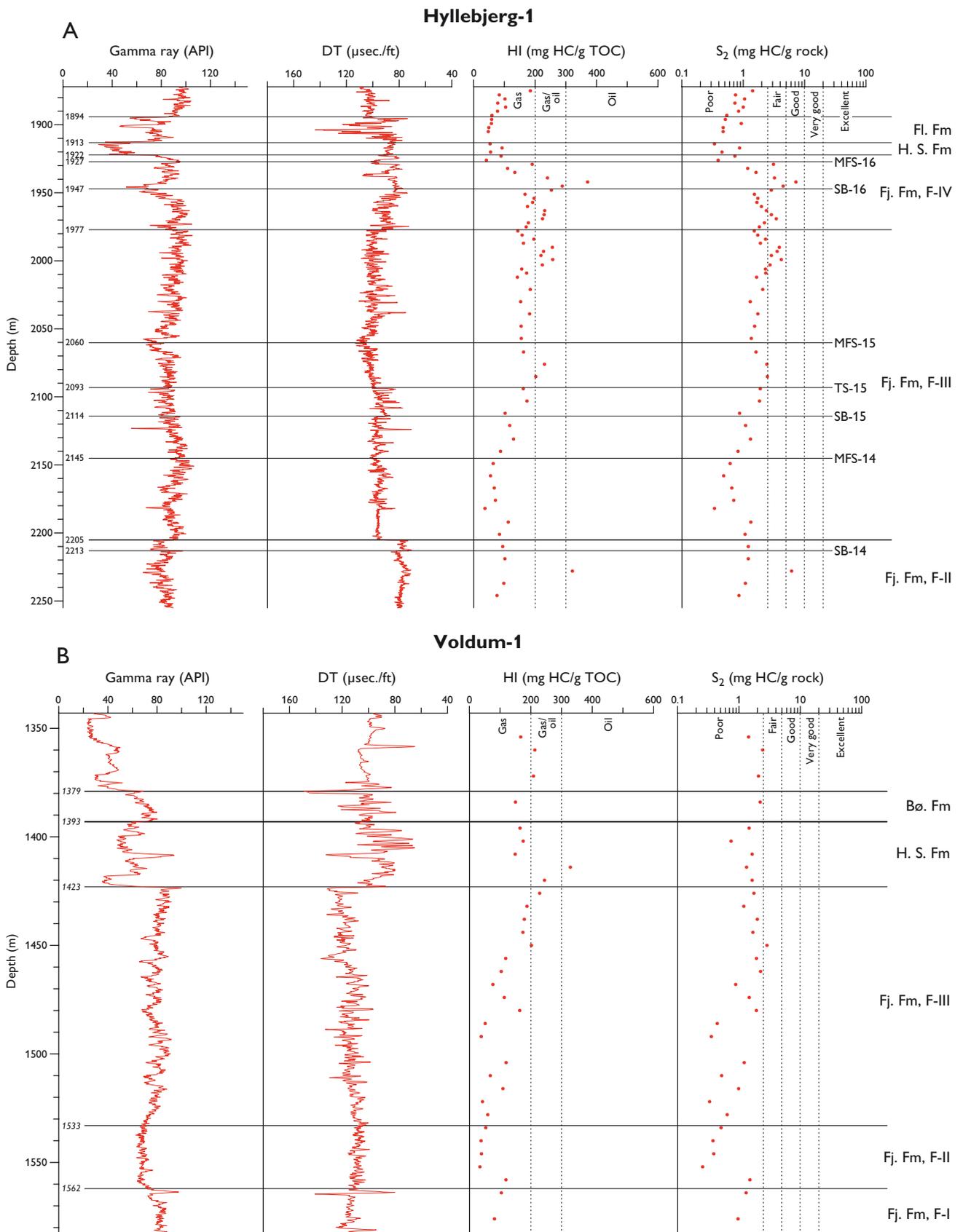


Fig. 32. Plots showing well logs, Hydrogen Index (HI) values, S<sub>2</sub> yields, sequence stratigraphic key surfaces and formations in the Hyllebjerger-1 (A) and Voldum-1 (B) wells. In Hyllebjerger-1, note the increased HI values in the upper part of the F-III member and in the middle part of the F-IV member. DT, sonic velocity. For further abbreviations, see Fig. 29.

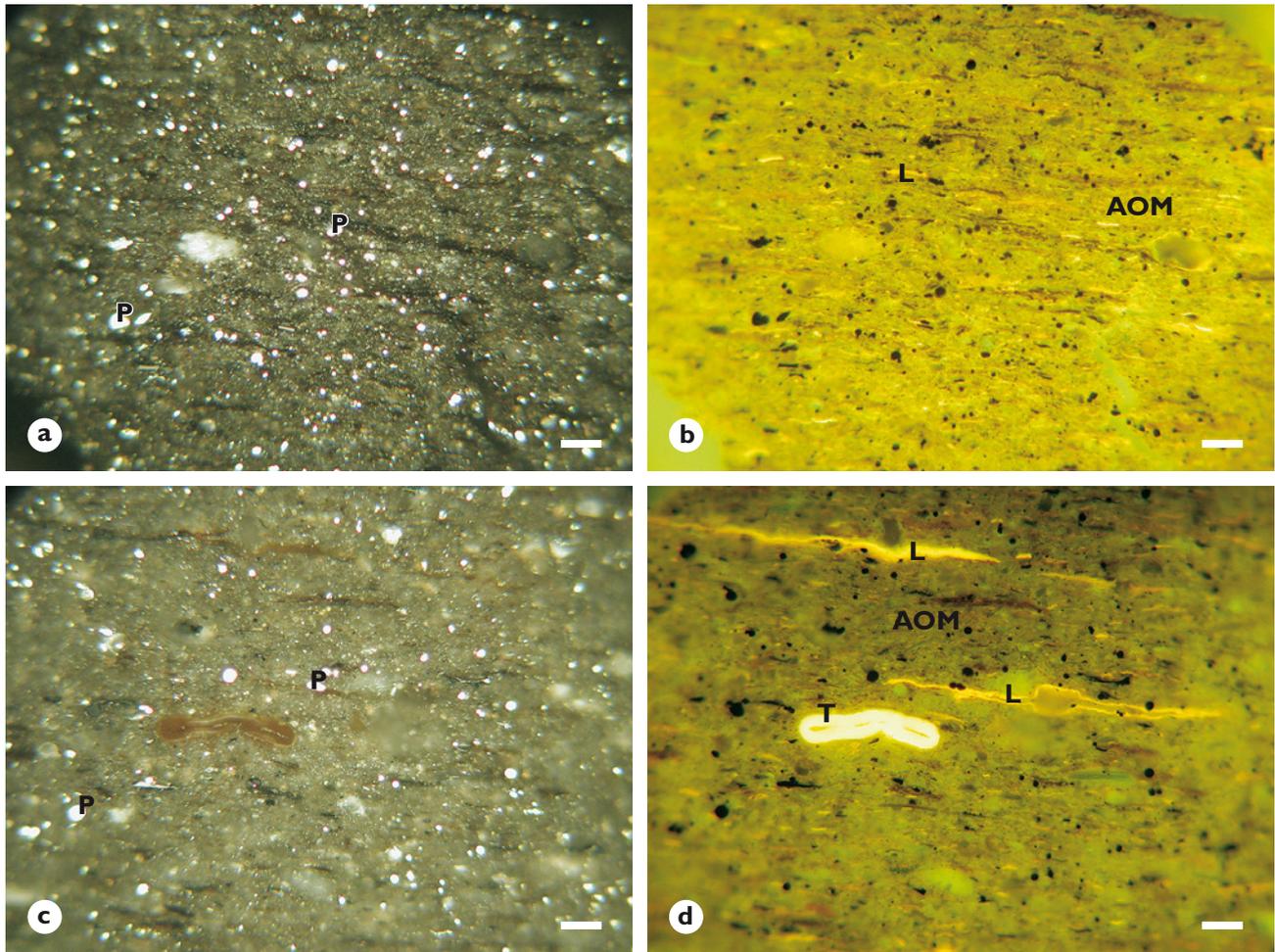


Fig. 33. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30  $\mu\text{m}$ ) of the organic material in cuttings sample (*c.* 2152 m) from the oil-prone F-IV member in the Rønne-1 well; left (a, c): white light; right (b, d): fluorescence-inducing blue light. The cuttings contain an abundance of fluorescing, amorphous organic matter (AOM) and detrital liptinite (probably algal-derived) together with *Leiosphaeridia* (L) and *Tasmanites* (T) alginite. P, framboidal pyrite. TOC = 5.81 wt%, HI = 543 mg HC/g TOC.

### Middle Jurassic units

In the Yme Field in the Egersund Basin, where the Bryne Formation (equivalent to the Haldager Sand Formation) is thickly developed, the formation contains shales that show a good to excellent oil generation potential with TOC values of 2–13 wt% and HI values of 100–480 mg HC/g TOC. Coal seams within the Middle Jurassic – lower Upper Jurassic of this field are also oil-prone in places, with HI values exceeding 400 mg HC/g TOC. Similarly, Middle Jurassic coals and carbonaceous lacustrine–brackish shales of the Lulu Formation are considered to have sourced the oil and gas/condensate accumulations in the Lulita and Harald Fields in the Søgne Basin of the North Sea. In this area, the type of generated petroleum is considered to have been controlled by lateral coal facies variations related to the proximity of peat formation to the coeval coastline

(Petersen *et al.* 1998, 2000; Petersen & Brekke 2001). Coals formed in the coastal reaches of the mires are more oil-prone than their more landward equivalents.

In the study area, the Middle Jurassic Haldager Sand Formation is dominated by fluvial, estuarine and shallow marine sandstones interbedded with marine and lacustrine mudstones and thin coal seams (Nielsen 2003). The generation potential of the formation is low, with only a few exceptions. In the Haldager-1 well, two samples from a 4–5 m thick marine mudstone have high HI values (342 and 637 mg HC/g TOC), and the Terne-1 well shows HI values of 260 mg HC/g TOC. Both wells are situated in the Sorgenfrei–Tornquist Zone where the Middle Jurassic is thickest.

There may thus be a relationship between the gross thickness of the Middle Jurassic succession, the palaeo-

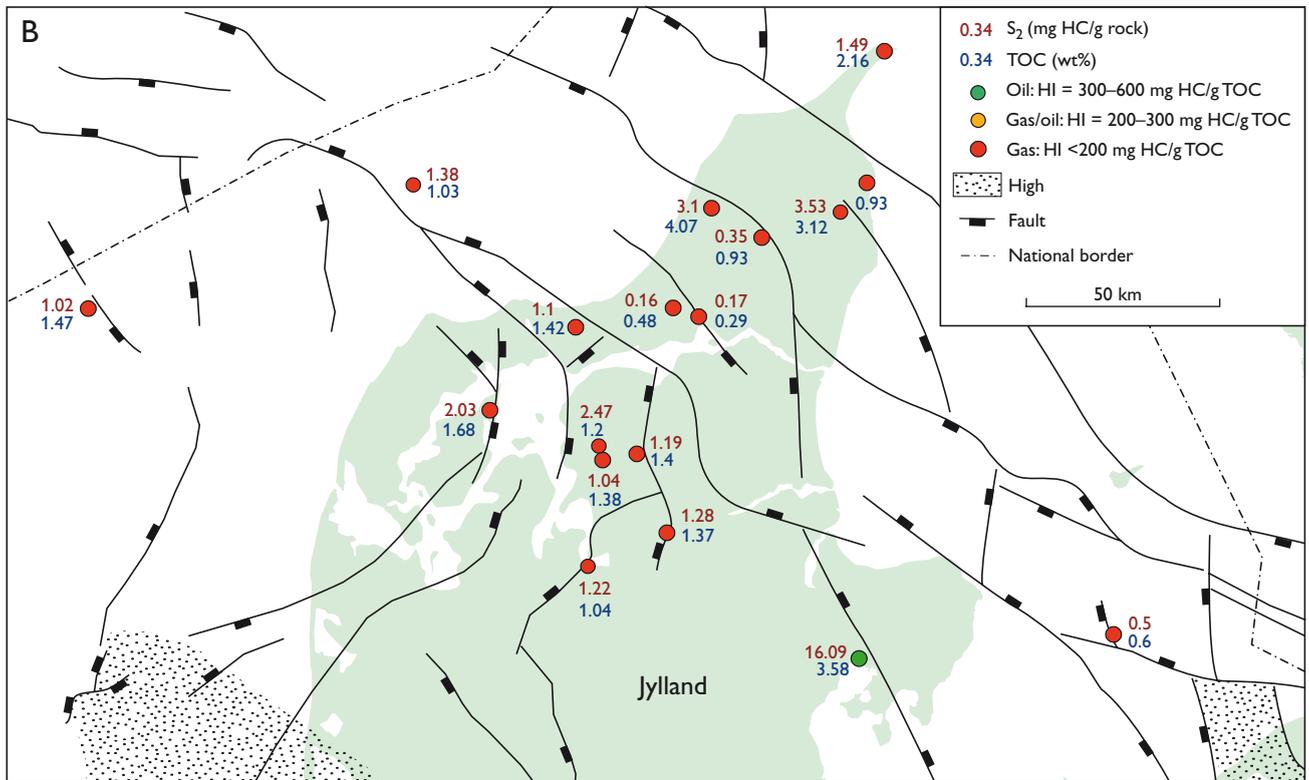
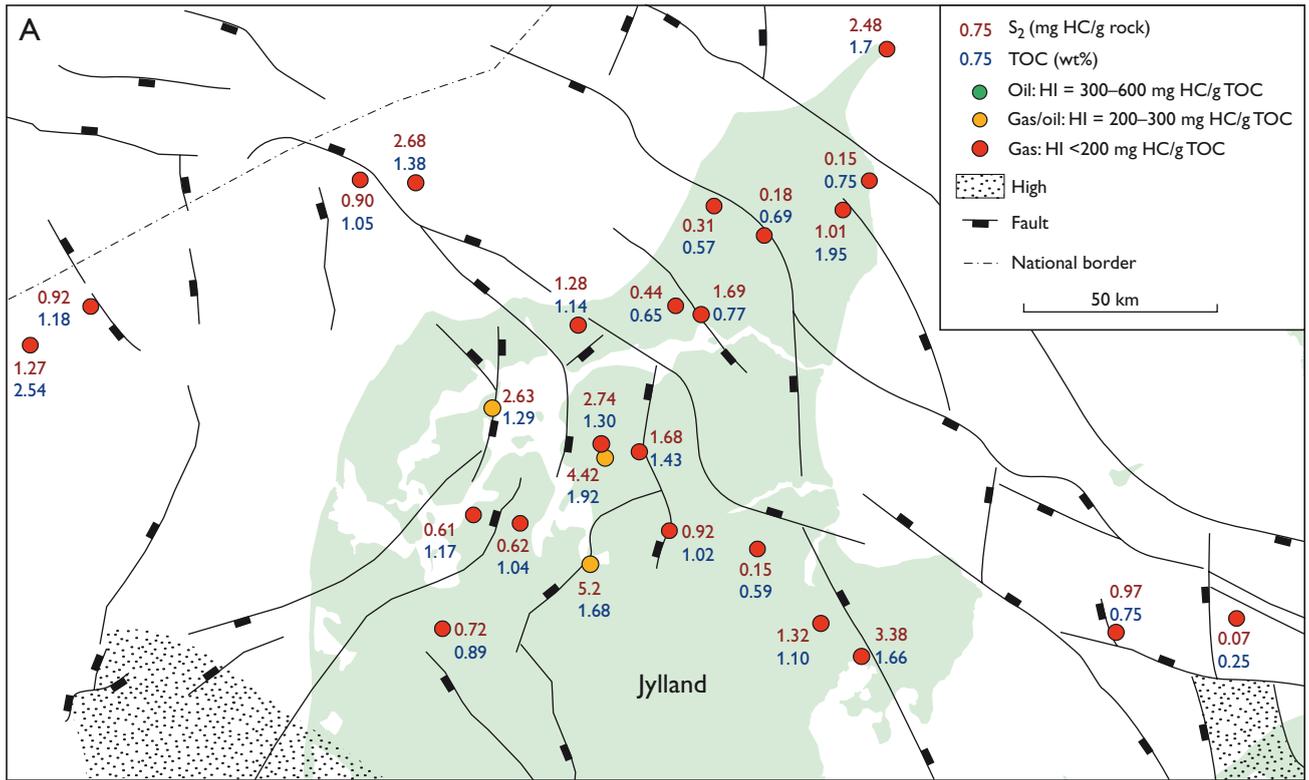


Fig. 34. The average source-rock quality of the Lower Jurassic F-III member (A) and F-IV member (B) of the Fjerritslev Formation.

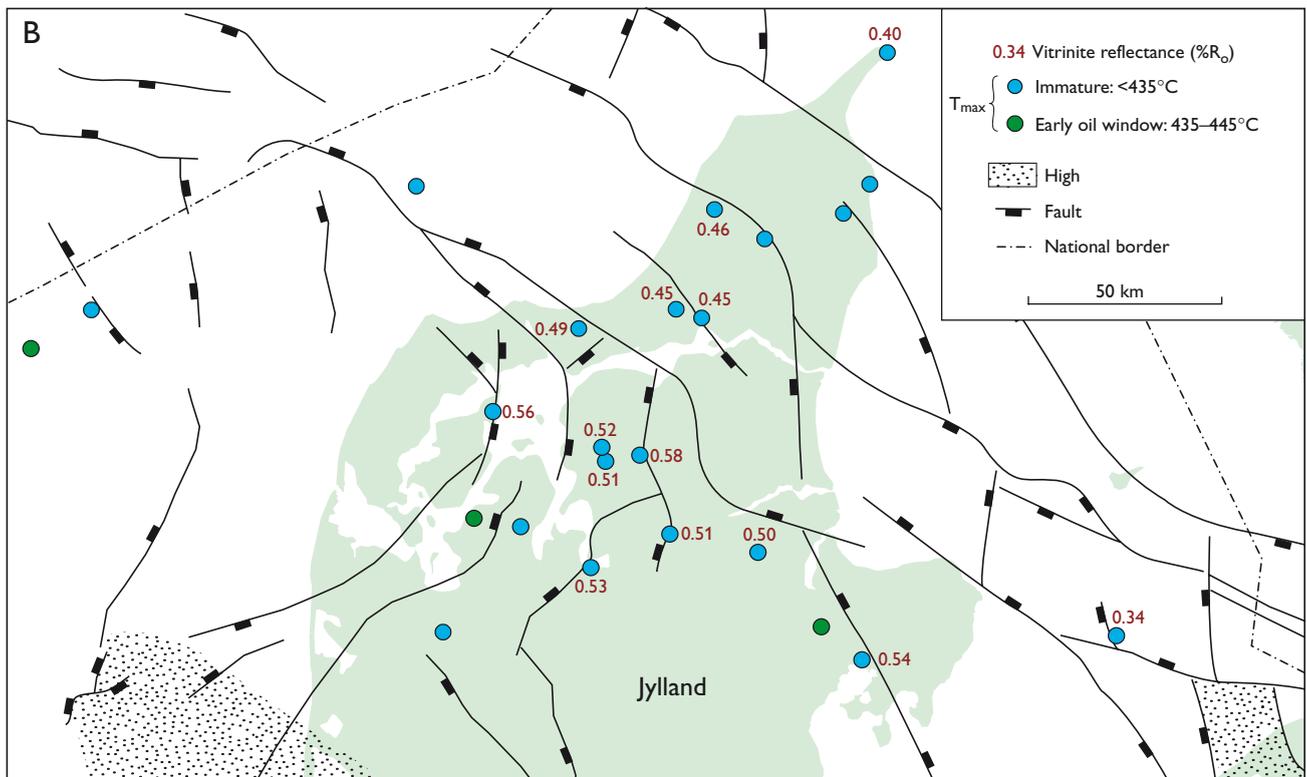
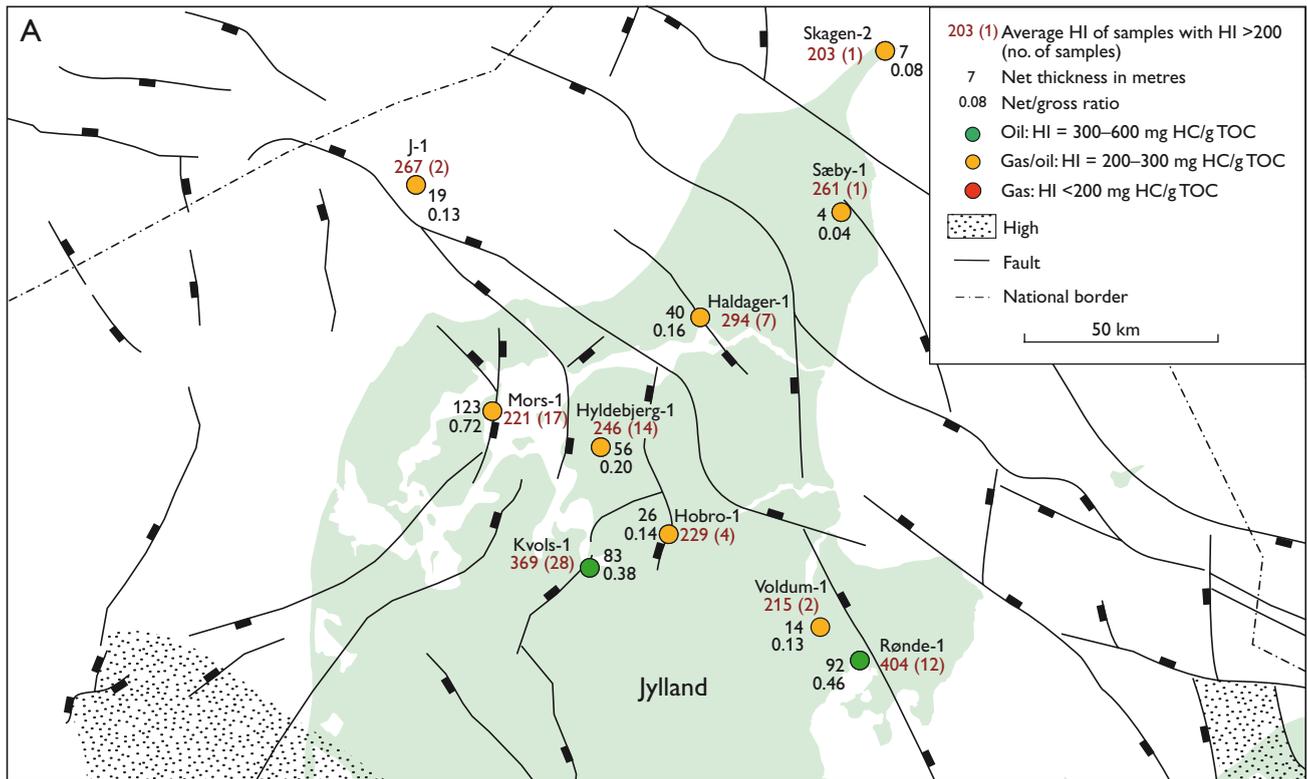


Fig. 35. A: Cumulative net source-rock thickness of the intervals in the F-III and F-IV members with HI values exceeding 200 mg HC/g TOC, i.e. a source rock with a mixed gas/oil or oil generation potential. B: Thermal maturity of the F-III and F-IV members of the Fjerritslev Formation. Vitrinite reflectance and T<sub>max</sub> values indicate immaturity with regard to petroleum generation.

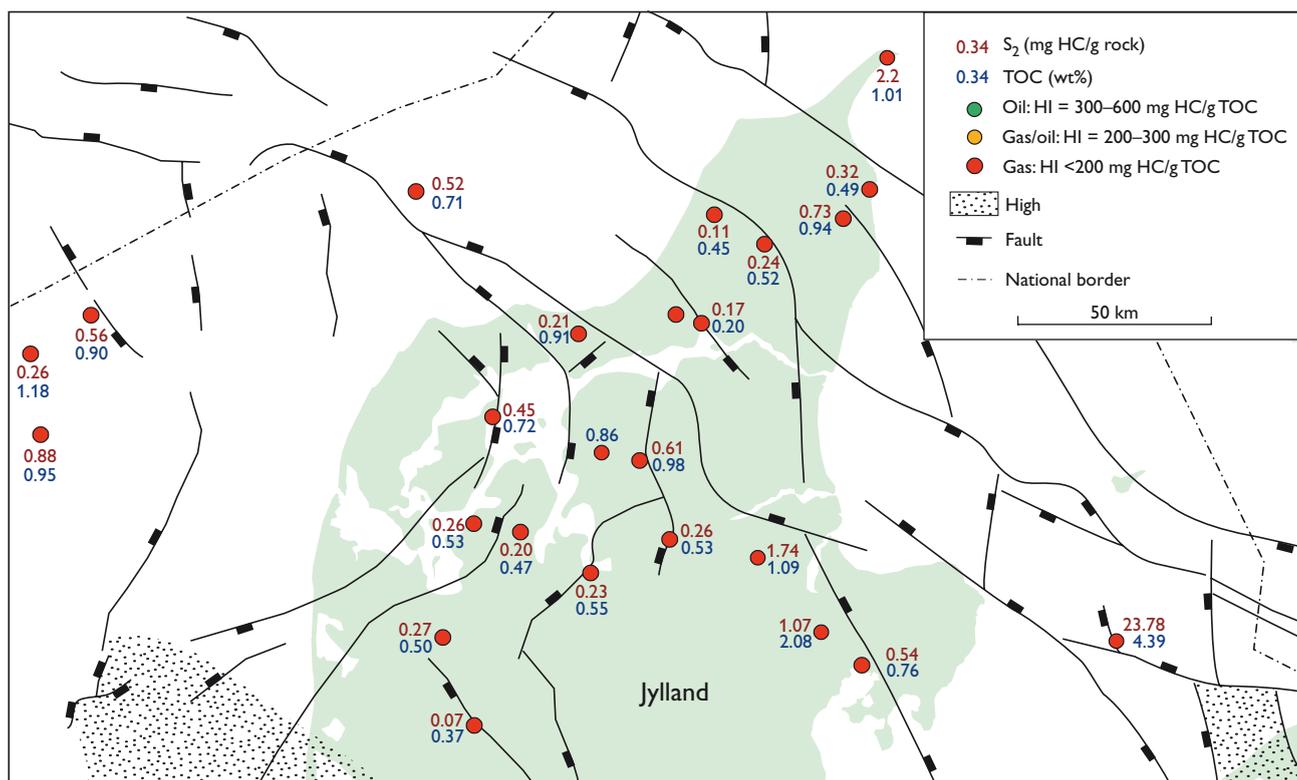


Fig. 36. Average source-rock quality of the entire uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation.

geographic position and the occurrence of shales and coals with an oil generation potential. Oil-prone coals in the Middle Jurassic may be best developed in areas with most pronounced subsidence and hence relatively large rates of formation of accommodation space during deposition.

### Upper Jurassic – Lower Cretaceous units

In most wells, the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation is dominated by shallow marine and paralic siltstones and sandstones (Michelsen *et al.* 2003) with no petroleum generation potential. The average HI of the entire Frederikshavn Formation indicates a gas-prone source potential (Fig. 36), but the formation contains intervals with good to excellent oil generation potential, as demonstrated by the Gassum-1, Hyllebjerg-1, Skagen-2, Sæby-1, Terne-1 and Voldum-1 wells (Figs 37, 38A; Table 3). The section in Terne-1 is particularly noteworthy, with HI values >1100 mg HC/g TOC, although these values in part reflect contamination by gel mud and cement applied during drilling. Nevertheless, solvent-extracted samples are still encouraging, with a cumulative net source-rock unit of *c.* 150 m containing on average 5.7 wt% TOC and HI values of the extracted samples reach-

ing 580 mg HC/g TOC, averaging 478 mg HC/g TOC (Fig. 38A; Table 3). Microscopical kerogen analyses show an abundance of amorphous algal organic matter in the form of filamentous lamalginite and alginite with morphology similar to the extant fresh to brackish water *Botryococcus* algae (Type I kerogen; Fig. 39). Brackish, oxygen-deficient conditions during deposition are suggested by the abundance of framboidal pyrite associated with the organic matter (Fig. 39). The probable lacustrine origin of these deposits in Terne-1 suggests a local development, as the formation is typically of shallow marine to offshore origin (Michelsen *et al.* 2003).

The Skagen-2 well contains a *c.* 78 m thick net source-rock interval with an average HI value of 241 mg HC/g

Table 3. Net source-rock (SR) thicknesses, Frederikshavn Fm

Well	Net SR (m)	Gross (m)	Net/gross	Average HI*, Net SR interval (number of samples)
Gassum-1	17	101	0.17	320 (3)
Hyllebjerg-1	29	146	0.20	243 (4)
Skagen-2	78	176	0.44	241 (7)
Sæby-1	10	105	0.10	329 (1)
Terne-1	150	258	0.58	478 (10)
Voldum-1	26	66	0.39	257 (3)

\* Average HI in Net SR intervals based on HI values ≥200 mg HC/g TOC

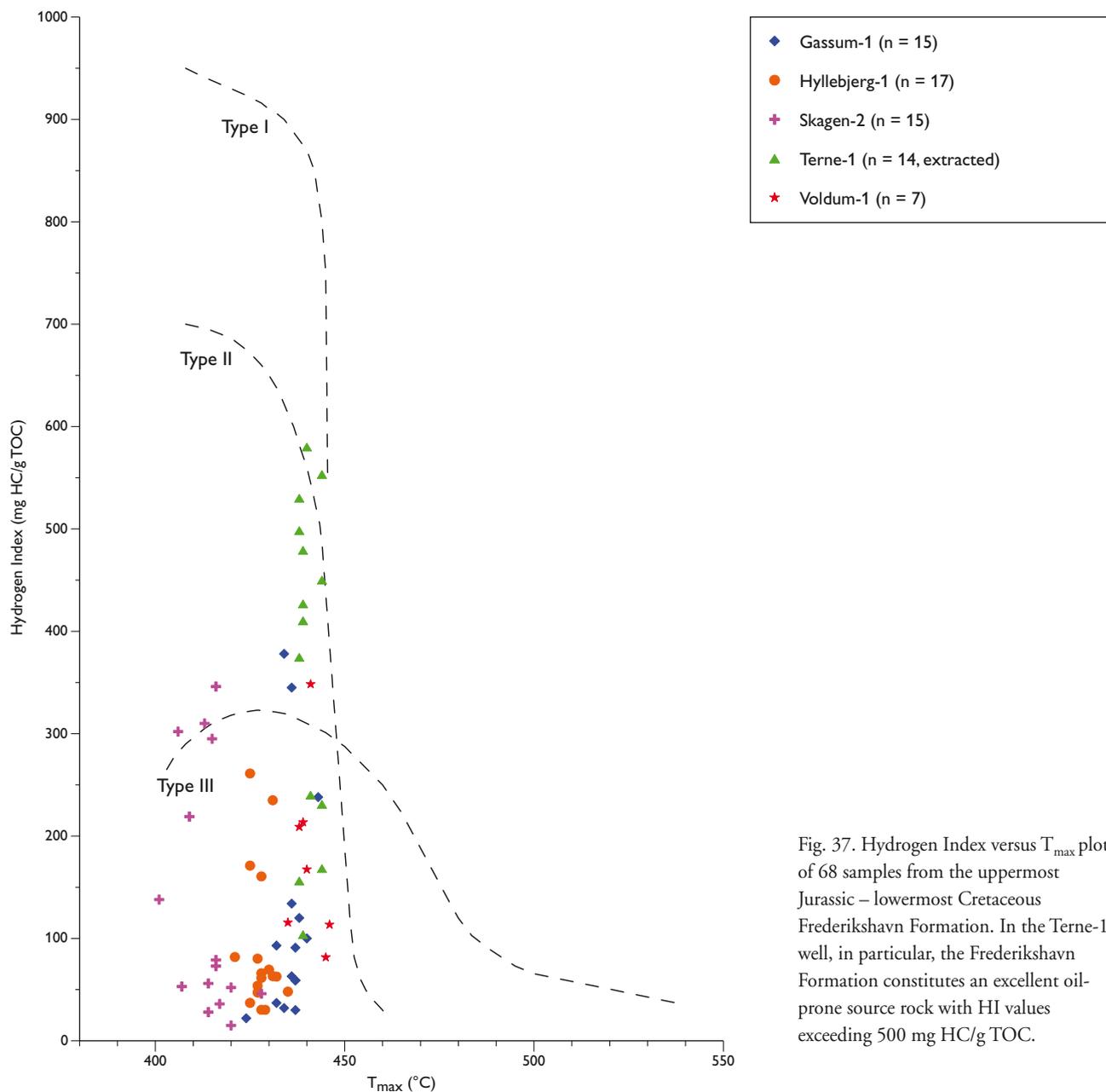


Fig. 37. Hydrogen Index versus  $T_{\max}$  plot of 68 samples from the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation. In the Terne-1 well, in particular, the Frederikshavn Formation constitutes an excellent oil-prone source rock with HI values exceeding 500 mg HC/g TOC.

TOC and a maximum value close to 350 (Fig. 38A). In the Gassum-1 well, most HI values are low but a few samples yield HI values >300 mg HC/g TOC (Fig. 38A); these high values are abnormal compared to the general trend and may reflect thin layers with higher quality kerogen in an otherwise sand-dominated succession. The Hyllebjerg-1 well has a *c.* 29 m thick net source-rock section with an average HI value of 243 mg HC/g TOC, whereas the average HI value of *c.* 26 m net source rock in the Voldum-1 well is 257 mg HC/g TOC (Fig. 38A; Table 3).

The Frederikshavn Formation thus locally contains good to excellent oil source rocks in the study area. Towards the west in the Egersund Basin, the broadly time-equivalent Tau

Formation is known as the principal source for oil, and in the North Sea the uppermost Jurassic – lowermost Cretaceous marine shales of the Farsund Formation and equivalents (Kimmeridge Clay, Mandal and Draupne formations) are well known as the primary oil source rocks (e.g. Ineson *et al.* 2003). As for the Lower Jurassic Fjerritslev Formation, the major problem in the Danish area is to find areas where the Frederikshavn succession is sufficiently buried to be thermally mature with regard to petroleum generation. VR values from 0.36–0.53%  $R_o$  and the majority of  $T_{\max}$  values <430–435°C indicate that the potential source rocks are thermally immature (Fig. 38B).

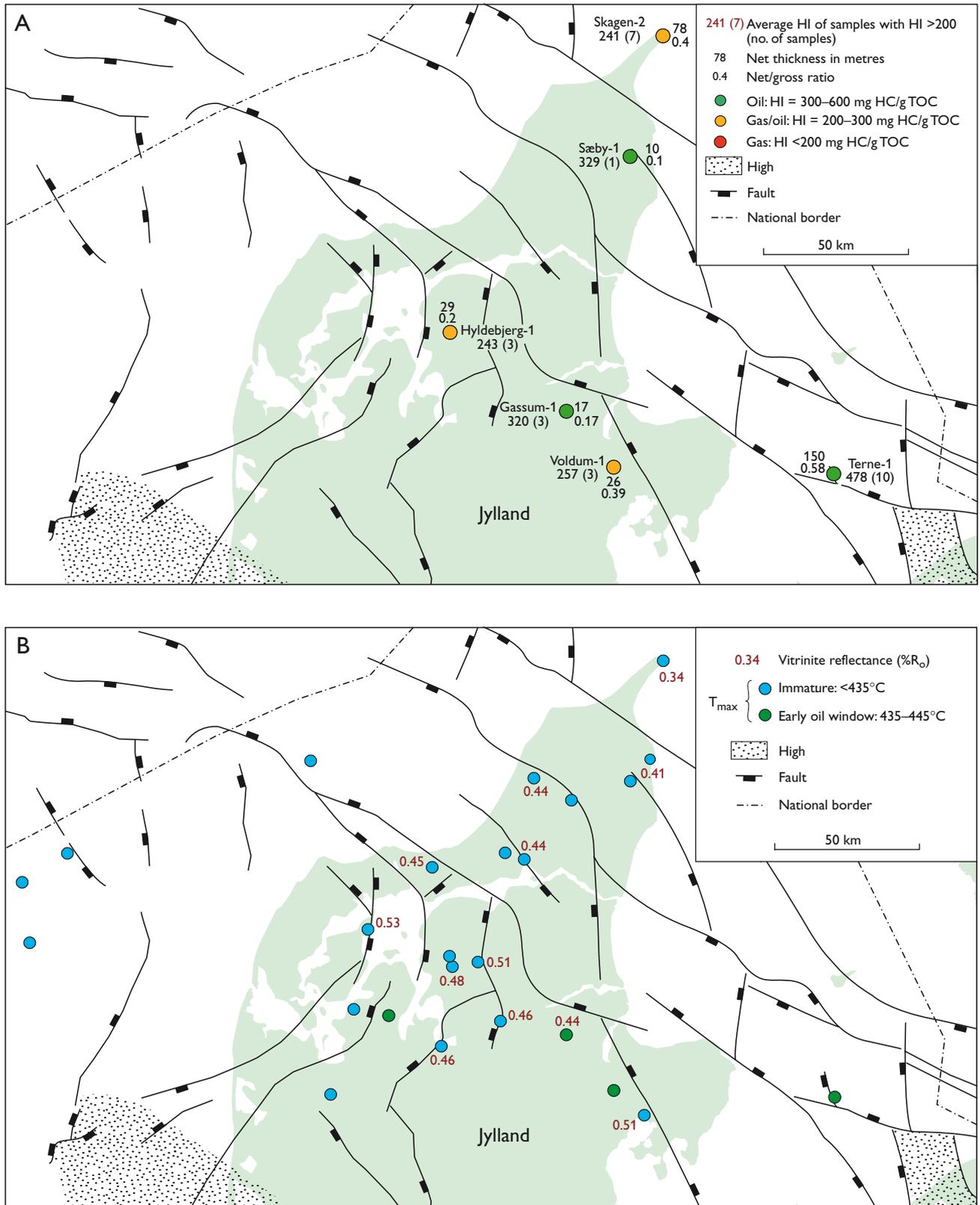


Fig. 38. A: Cumulative net source-rock thickness of the intervals in the Frederikshavn Formation with HI values exceeding 200 mg HC/g TOC, i.e. a source rock with a mixed gas/oil or oil generation potential. B: Thermal maturity of the Frederikshavn Formation. Vitrinite reflectance values indicate immaturity, whereas  $T_{max}$  values may suggest early oil window maturity in four wells located in the central part of the basin or in the Sorgenfrei–Tornquist Zone.

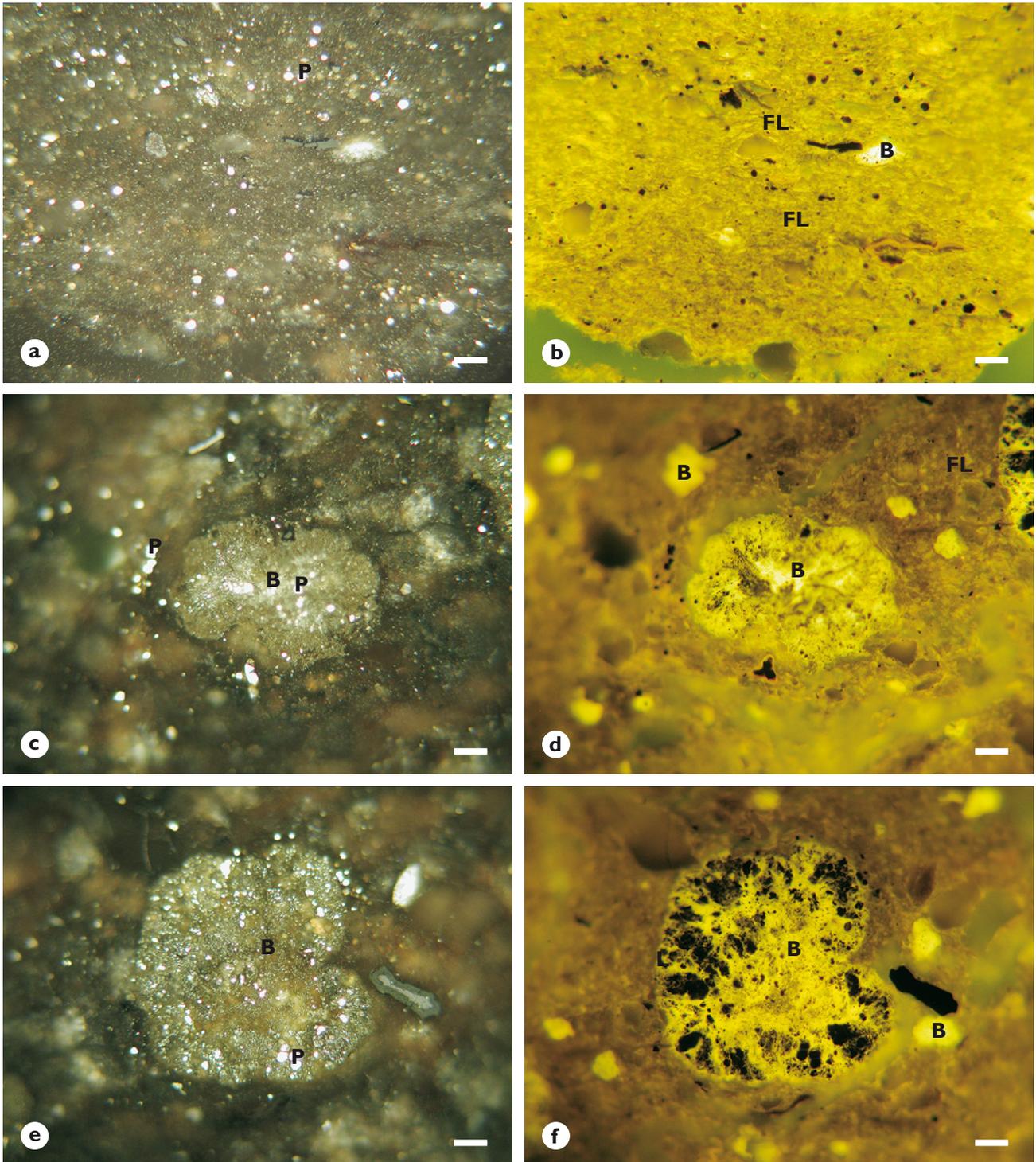


Fig. 39. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30  $\mu\text{m}$ ) of the organic material in the oil-prone lacustrine Frederikshavn Formation in the Terne-1 well; left (a, c, e) white light; right (b, d, f): fluorescence-inducing blue light. a-f: Abundance of fluorescing, filamentous lamalginite (FL) and *Botryococcus*-type alginites (B) of varying size in cuttings from *c.* 200–210 m. Abundant framboidal pyrite (P) has been formed within the large *Botryococcus*-type alginite bodies. TOC = 7.30 wt%,  $\text{HI}_{\text{extracted}} = 498 \text{ mg HC/g TOC}$ .

## Lower Cretaceous units

In general, the Lower Cretaceous succession of the study area contains few and relatively thin potential oil source rocks. Three wells, the Lavø-1, Sæby-1 and Års-1, contain intervals in the Lower Cretaceous (Vedsted Formation or undifferentiated Lower Cretaceous) with a petroleum generation potential. In the Sæby-1 well, a *c.* 20 m thick organic-rich interval has TOC contents up to 5.28 wt% and HI values from 320–472 mg HC/g TOC, averaging

388 mg HC/g TOC; the interval is thus an excellent potential oil and gas source rock. Similarly, a *c.* 20 m thick interval in the Års-1 well possesses a mixed oil/gas generation potential, although the potential is poorer than in Sæby-1 as the HI values range from 210–411 mg HC/g TOC, averaging 294 mg HC/g TOC. In the Lavø-1 well, a *c.* 18 m thick potential source-rock interval with HI values from 175–242 mg HC/g TOC is present. The Lower Cretaceous is, however, thermally immature in all well sections.