Middle Jurassic (Central Graben Group) strata outside the Søgne Basin

Sedimentological description and interpretation of the measured core-intervals

Alma-1x well

The deepest part of the measured succession consists of light grey, homogeneous silty mudstone with a single coaly horizon (Fig. 42B). Upwards the silty mudstone becomes faintly parallel-laminated, and sediment disturbances are occasionally present. Coal particles and streaks are common together with coalified leaves and twigs. The silt content gradually decreases, and the silty mudstone is overlain by a homogeneous, dark grey mudstone. This is followed by a light grey, slightly more silty, homogeneous mudstone with rare sediment disruption.

The shallower part of the cored interval starts with a dark grey, homogeneous mudstone, which upwards changes to a faintly parallel-laminated heterolithic mud- and siltstone (Fig. 42A). The heterolith is increasingly dominated by silt, and gradually changes to a siltstone, followed by a weakly parallel-laminated very fine-grained sandstone. Small-scale faults and sediment disruptions are common. Towards the top the very fine-grained sandstone again changes to a parallel-laminated, heterolithic mudstone and siltstone. The uppermost heterolith contains coal particles and streaks, and plant fossils as coalified leaves and twigs. The sedimentary succession is interpreted to have been deposited in a floodplain environment.

Anne-3a well

Only cuttings have been investigated from this well.

Elly-3 well

The succession starts with a dark grey, homogeneous to very faintly parallel-laminated mudstone with rare small pyrite concretions (Fig. 43). Towards the top the mudstone becomes black and carbonaceous and finally turns into a coaly interval with visible vitrinitic organic matter. Thin light grey beds of homogeneous siltstone and very fine-grained sandstone overlie the coaly level. These are followed by a new homogeneous mudstone interval, which in the lower part is black and carbonaceous. Coal particles and streaks are common, and coalified leaves (probably from ferns) and twigs are present in a narrow interval. The mudstone is overlain by a light grey, generally homogeneous clayey siltstone unit with abundant coal particles, coalified twigs, and probably rootlets. Towards the top of the clayey siltstone the abundance of coal particles increases, possibly associated with an increase in rootlets, and it gradually turns into a black, carbonaceous mudstone.

A succession consisting of more or less homogeneous heterolithic mudstone and siltstone, commonly with coal particles and coalified wood fragments, overlies the carbonaceous mudstone. The sediments were deposited in a low-energy coastal plain setting dominated by floodplain, lakes and lagoons. A mire environment is represented by the coaly level at about 4088 m.

Falk-1 well

The lower part of the succession consists of homogeneous brownish, dark grey mudstone and black, dull carbonaceous mudstone (Fig. 44). The latter contains vitrinite lenses and streaks, and small vertical pyrite cleats are seen in the lenses. Up to millimetre-thick horizontal and bifurcating vertical rootlets are present together with coal particles and coalified leaves and twigs in the upper part of the mudstone interval. The mudstone is succeeded by a grey heterolithic parallel- to faintly parallel-laminated siltstone and mudstone with occasional poorly developed small-scale cross-lamination and intercalated homogeneous dark grey mudstones. Sediment disruption is common. Coal particles and streaks, and coalified leaves and twigs are abundant in the heterolith, and small pyrite concretions may occur. The very fine-grained sandstone bed between 4118 and 4119 m is slumped and structureless with abundant 'floating' organic debris. A dark, carbonaceous mudstone with coal streaks and lenses, and a coal horizon overlies the heterolith. Except for the uppermost part the rest of the measured succession is composed of grey faintly parallel-laminated and homoge-

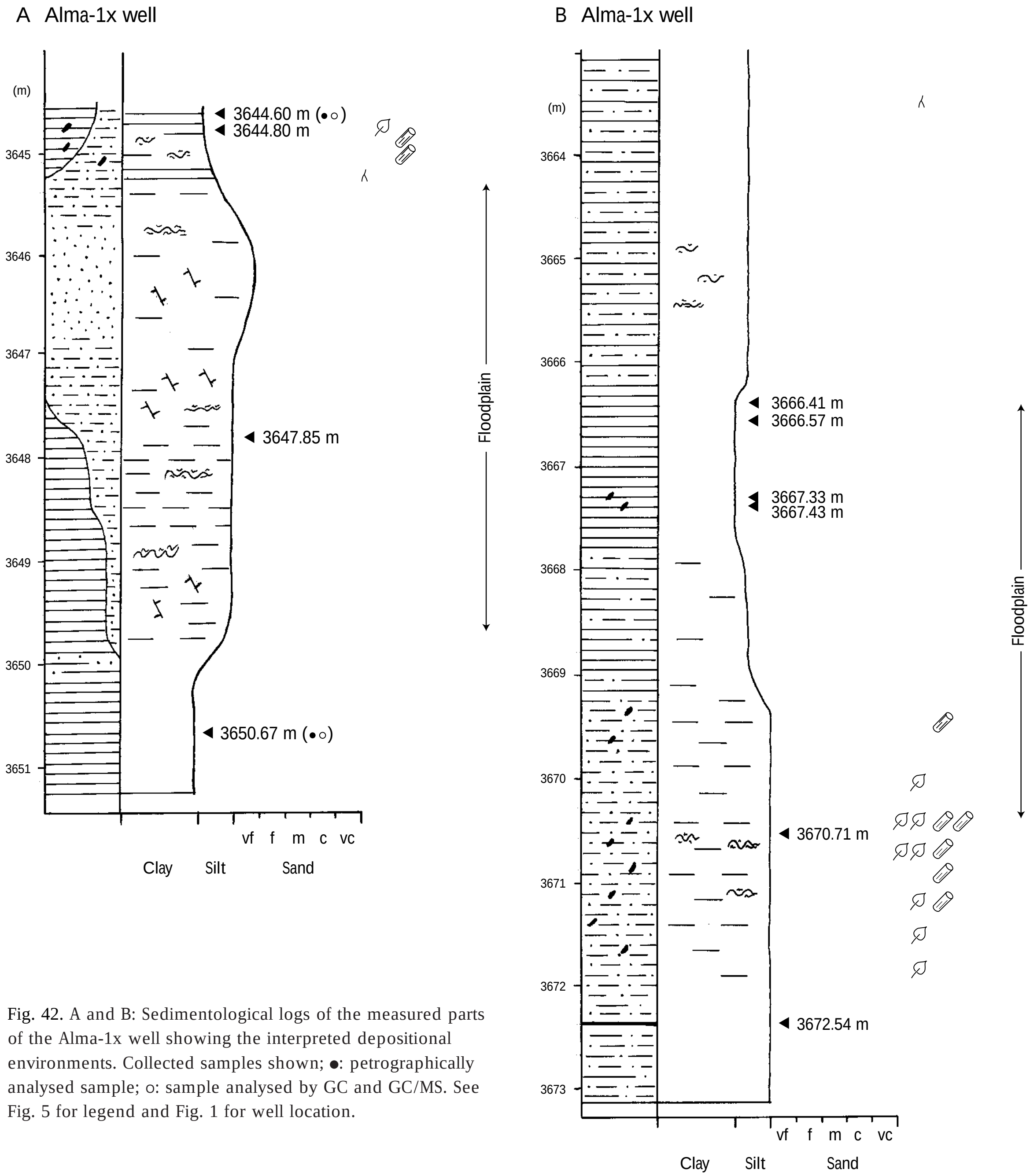


Fig. 42. A and B: Sedimentological logs of the measured parts of the Alma-1x well showing the interpreted depositional environments. Collected samples shown; •: petrographically analysed sample; o: sample analysed by GC and GC/MS. See Fig. 5 for legend and Fig. 1 for well location.

neous heterolithic mudstone and siltstone, and black carbonaceous mudstone. Coal particles and streaks together with plant remains are present. The uppermost carbonaceous mudstone contains silt streaks and lenses, and a coaly horizon contains a level with very coarse-grained sand and gravel. The mudstone is erosionally overlain by a clast-supported conglomerate with grain sizes up to *c.* 2 cm. The deposits are interpreted as deposited in a low-energy coastal plain setting with open-water mires and lakes.

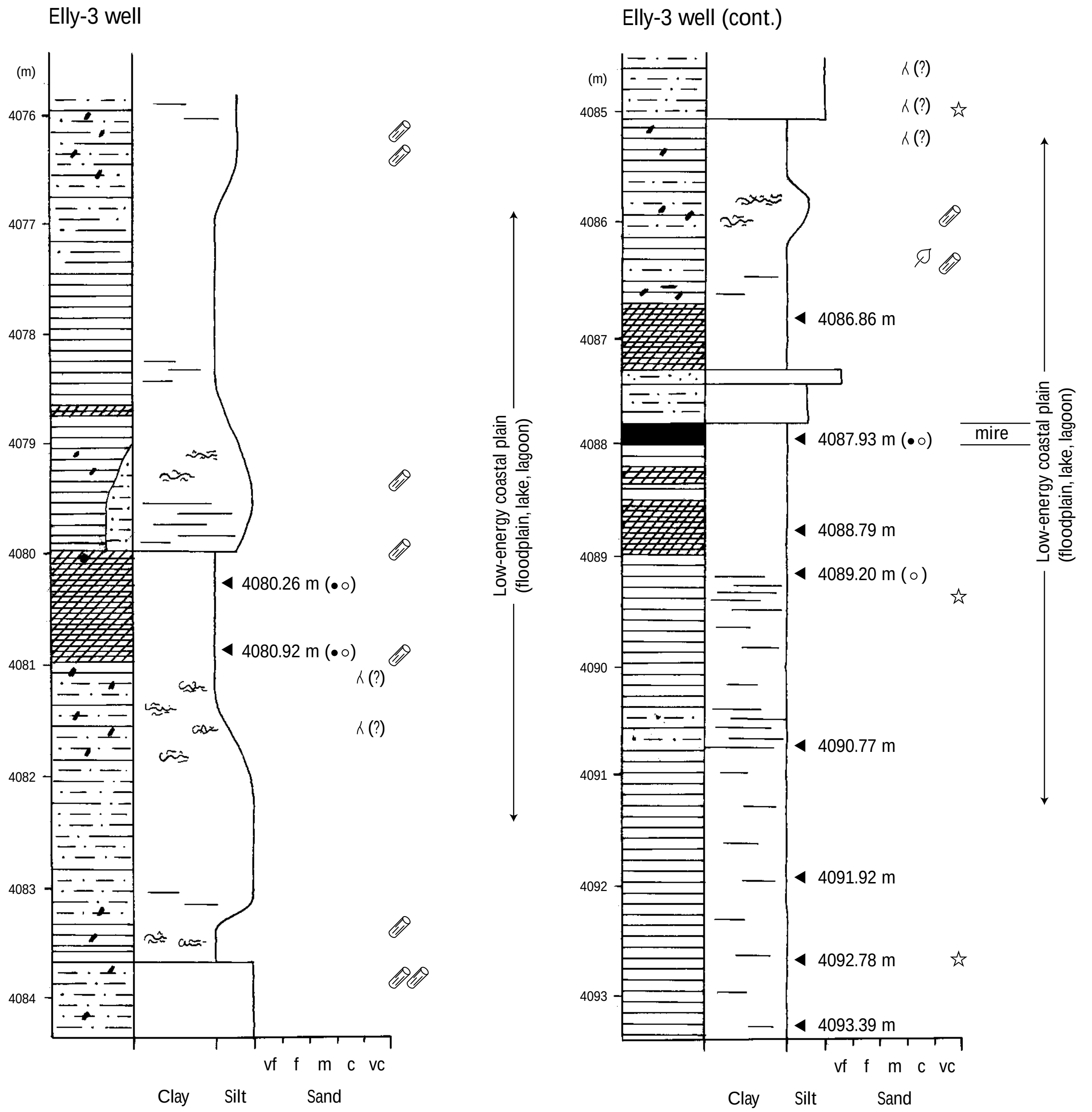


Fig. 43. Sedimentological log of the measured part of the Elly-3 well showing the interpreted depositional environments. Collected samples shown; •: petrographically analysed sample; o: sample analysed by GC and GC/MS. See Fig. 5 for legend and Fig. 1 for well location.

M-8 well

Only cuttings have been investigated from this well.

Skjold Flank-1 well

Section A consists primarily of a mainly dark grey to blackish grey, homogeneous, silty mudstone succession (Fig. 45A). The upper part is rooted by simple roots composed of one main string with small side-roots. Towards the top the mudstone is developed as 3–6 cm thick, red brown to dark grey, rhythmic bands. The silty mudstone is erosionally overlain by siltstone and sandstone beds with flaser-bedding, sediment disruption and organic matter. The uppermost part of section A is developed as a strongly bioturbated heterolithic mudstone and siltstone. The mudstone succession is

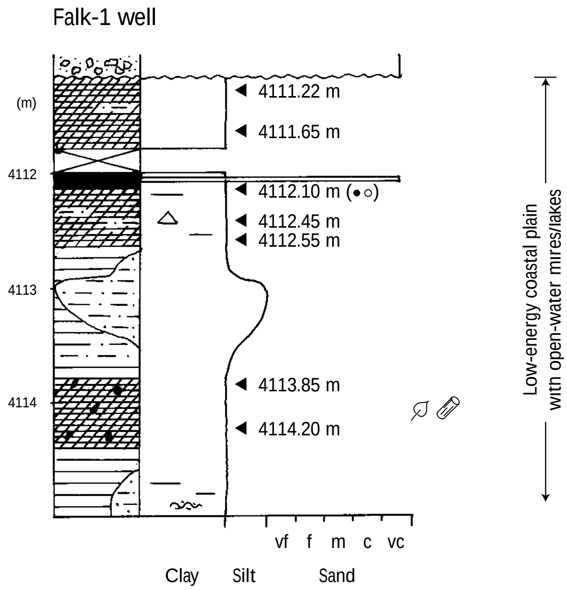
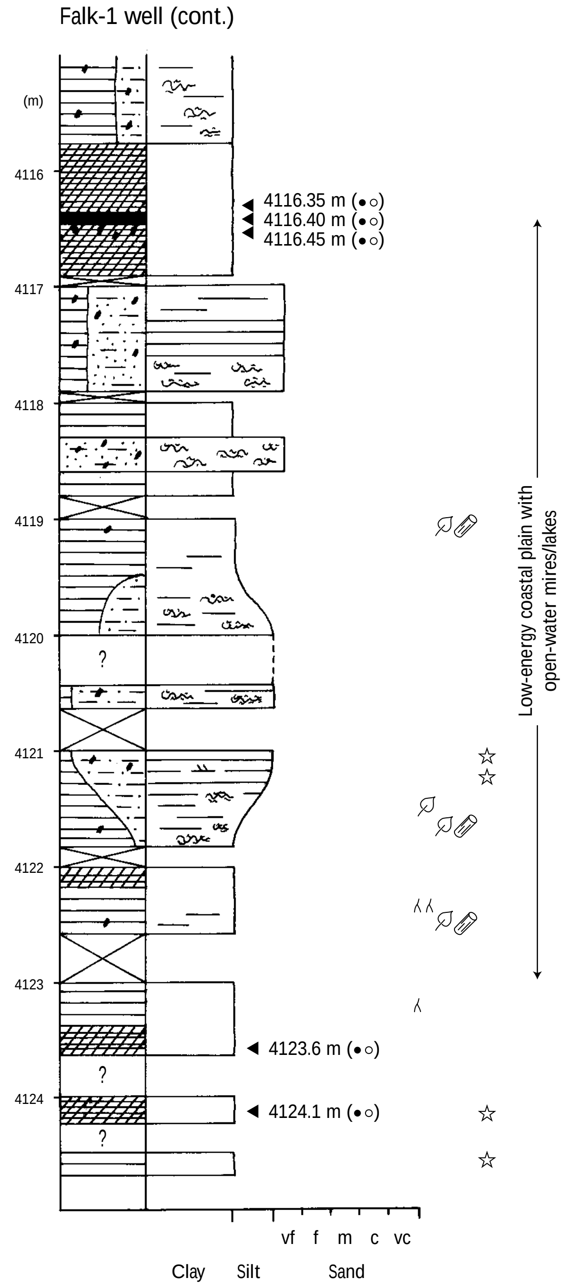


Fig. 44. Sedimentological log of the measured part of the Falk-1 well showing the interpreted depositional environments. Collected samples shown; ●: petrographically analysed sample; o: sample analysed by GC and GC/MS. See Fig. 5 for legend and Fig. 1 for well location.

interpreted to represent lagoon or lake deposits, whereas the siltstone and sandstone beds are interpreted to have been deposited in fluvial channels which may have been tidally influenced.

The lowermost part of section B is a homogeneous dark grey to black and occasionally carbonaceous mudstone (Fig. 45B). Small (millimetre-scale) spherical pyrite concretions have been observed in one of the carbonaceous intervals. Small-scale faults and bioturbation is present. The mudstone is erosionally overlain by homogeneous and micro-flaser-bedded silty or very fine-grained to fine-grained sandstone beds with abundant organic debris and coal laminae. The sandstone beds are succeeded by a heterolithic mudstone and siltstone or very fine-grained sandstone. The lowermost part of the heterolith is weakly parallel-laminated and disturbed, whereas in general the rest is homogeneous. Organic matter in particular is present in the more sandy intervals, while bioturbation occurs where mudstone dominates. The sediments of section B are interpreted to represent lagoonal or lacustrine and ?tidally-influenced fluvial channel deposits.

Section C starts with a succession of homogeneous to faintly parallel-laminated mudstone and siltstone beds (Fig. 45C). The succession is erosionally overlain



by a well-sorted, medium-grained, cross-bedded sandstone, followed by a homogeneous fine- to medium-grained sandstone. The sandstones are topped by an erosion surface characterised by carbonate particles and many shell fragments. Overlying the erosion surface is an interval of fine- to medium-grained sandstones and intraformational conglomerates of layered

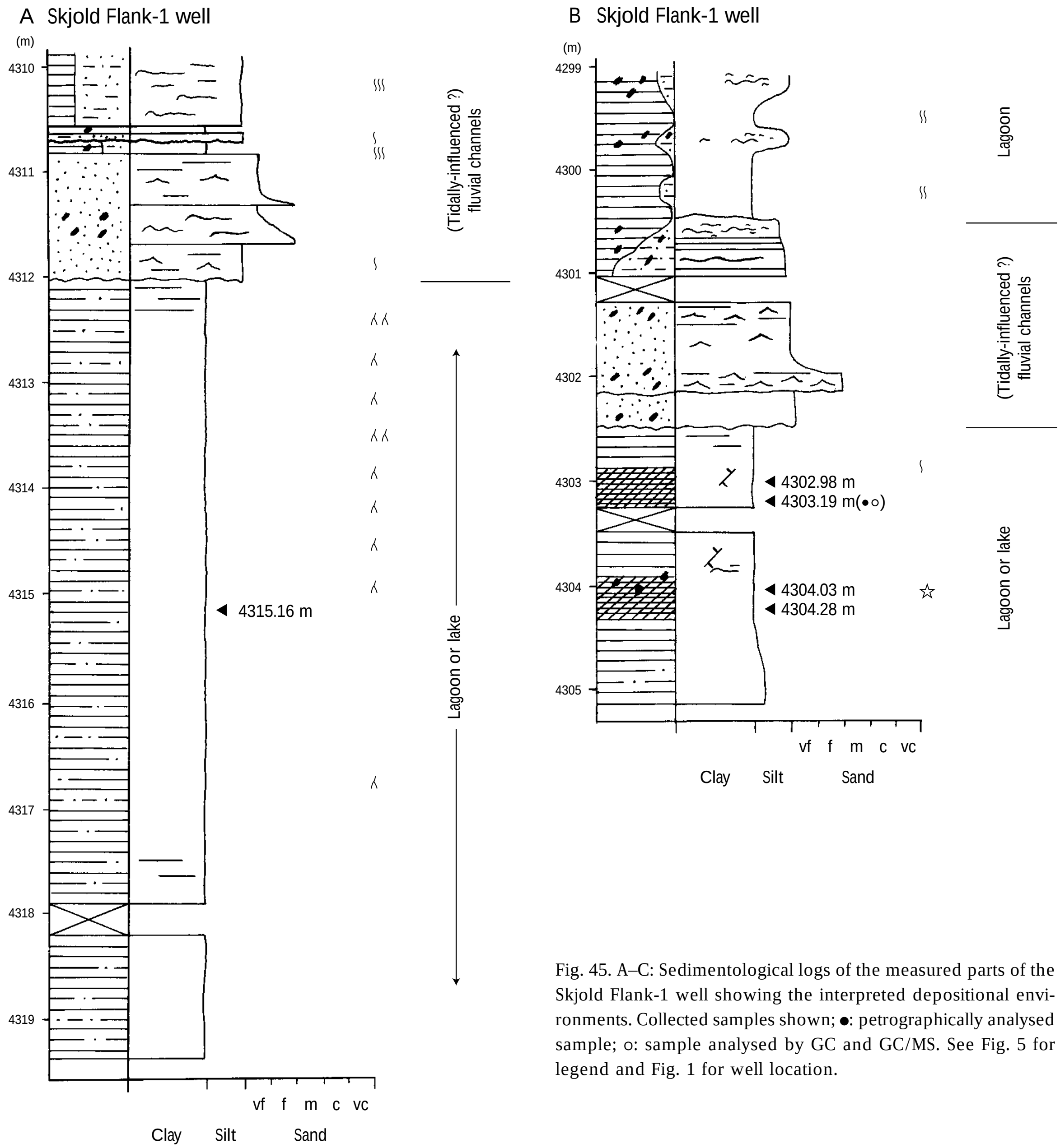
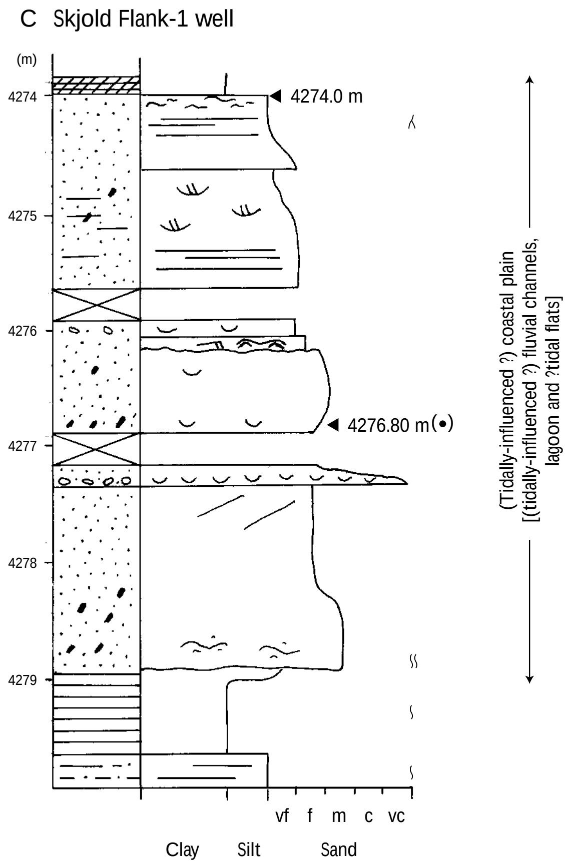


Fig. 45. A–C: Sedimentological logs of the measured parts of the Skjold Flank-1 well showing the interpreted depositional environments. Collected samples shown; ●: petrographically analysed sample; ○: sample analysed by GC and GC/MS. See Fig. 5 for legend and Fig. 1 for well location.

rip-up mudstone clasts. Coaly matter occurs in a weakly flaser-bedded interval. The succession is followed by a unit of mainly fine-grained sandstone beds showing flaser-bedding, cross-bedding, parallel-lamination and occasional herringbone-lamination and small-scale cross-lamination. Coal material may occur on foresets and as laminae. The sandstones are succeeded by siltstone and heterolithic mudstone and siltstone showing faintly parallel-lamination, sediment disruption and small-scale faults. Bioturbation is common. The uppermost homogeneous mudstone is overlain by a poorly sorted medium-grained sandstone rich in coal particles, which in the lower part is bioturbated. This is followed by a mainly homogeneous, greyish, fine-grained sandstone, and an



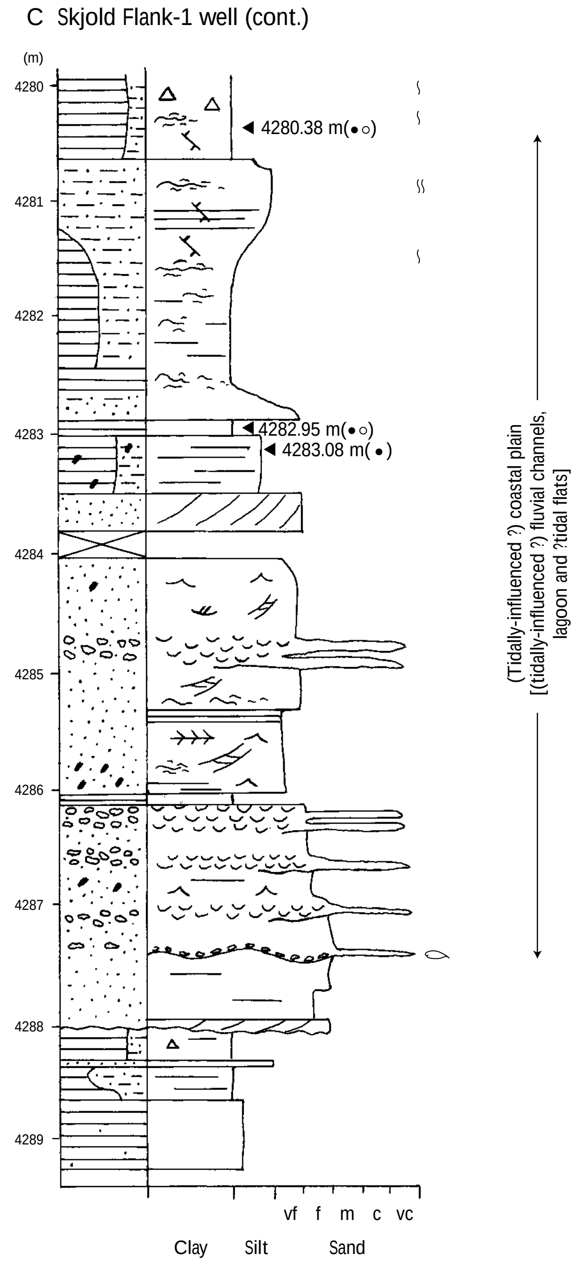


Fig. 45. cont.

intraformational conglomerate of rip-up mudstone clasts. An interval above the conglomerate is dark olive-grey, and contains abundant coal particles and mudstone clasts. A fine-grained sandstone showing interference of wave-current ripples and wavy-bedding overlies an erosion surface. The rest of section C is fining-upwards and the sandstones may show faintly parallel-lamination and small-scale cross-lamination with concentrations of coaly material in the small-scale troughs. In the uppermost part a light grey, rooted sandstone is overlain by a black, carbonaceous mudstone. The sediments of section C are interpreted to have been deposited in a possibly tidally influenced coastal plain setting with ?tidally-influenced fluvial channels, lagoons and ?tidal flats.

Table 16. Alma-1x: kerogen compositions and vitrinite reflectance value

Depth (m)	$\%R_m$	Mineral matrix	Pyrite	Organo-mineral matrix	Liptinitic ter. OM	Terrestrial OM	Kerogen Type
		(vol.%)					
3644.60	0.79	51	3	14*	3	29	111/11b
3650.67	-	92	2	1*	4	1	111

* vitrinitic and liptinitic organo-mineral matrix; ter. = terrestrial

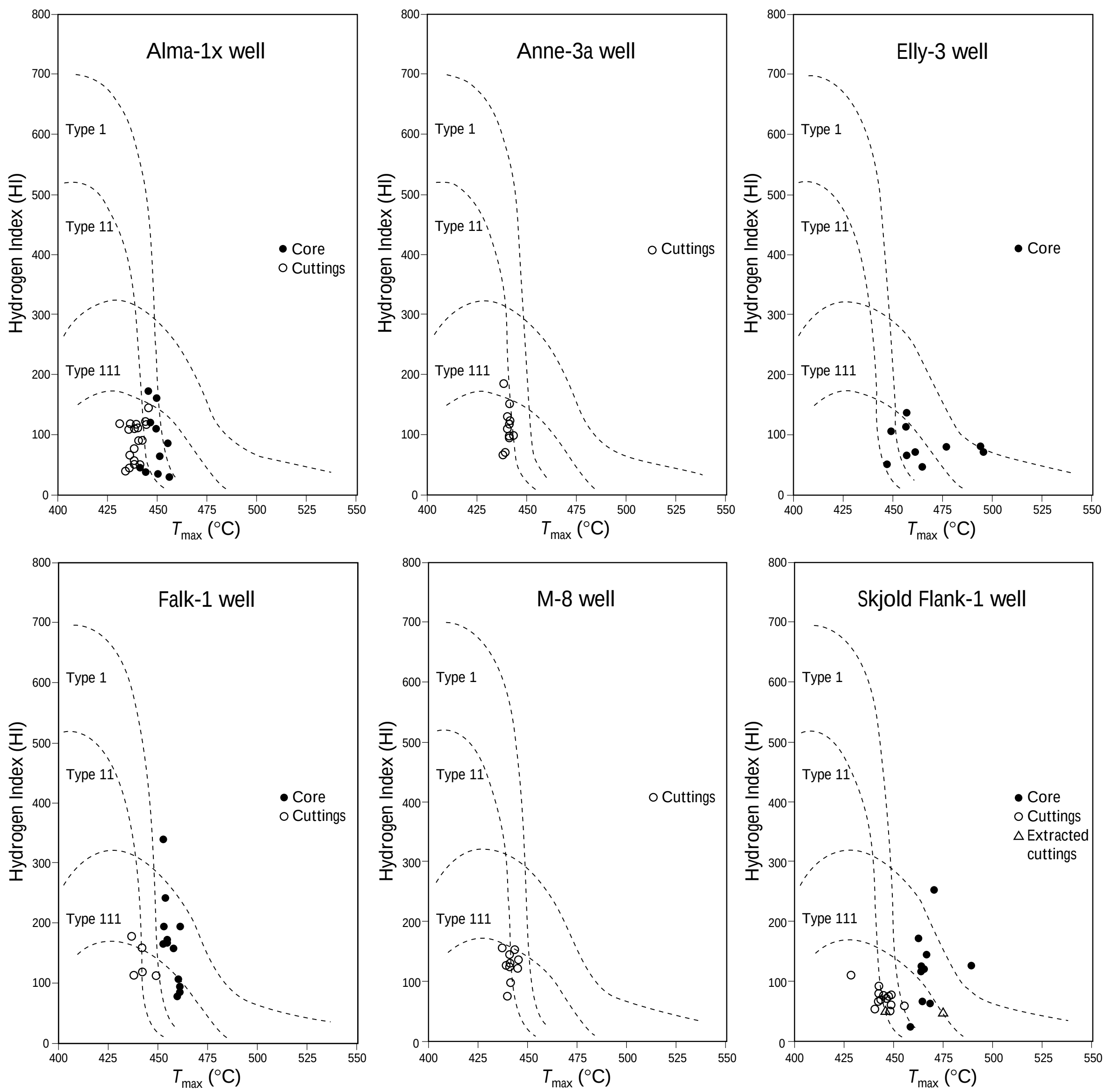


Fig. 46. Hydrogen Index vs. T_{max} plot of core samples, cuttings and extracted cuttings from the Alma-1x, Anne-3a, Elly-3, Falk-1, M-8 and Skjold Flank-1 wells.

Organic petrographic and geochemical results

Alma-1x well

A vitrinite reflectance from 3644.6 m depth gives a value of 0.79 %R_m, inferring a rank of high volatile bituminous A for the organic matter (Table 16). The kerogen composition at the same depth is dominated by terrestrial OM and organo-mineral matrix composed of vitrinitic and liptinitic organic material intimately associated with mineral matter. Liptinic terrestrial OM amounts to 3 vol.%. The TOC is 1.85 wt% and the HI 162 (Table 17). The organic matter content in a sample from a depth of 3650.67 m is lower (TOC = 0.96 wt%). The kerogen is dominated by liptinitic terrestrial OM, and the HI is 121. Based on organic matter composition and HI values the two kerogens are classified as type III/IIb and type III respectively (cf. Mukhopadhyay *et al.* 1985).

T_{max} values from core samples vary between 441°C and 456°C, averaging 449°C, while the cuttings show T_{max} values between 431°C and 445°C, averaging 439°C (Fig. 46; Table 17). TOC contents are in general below 1.5 wt%, and HI values from core samples and cuttings range between 31 and 162 with the majority below 120. Thermally extracted and generated petroleum contents, S_1+S_2, only occasionally exceed 2 mg HC/g rock.

Extracts from two samples (3644.6 and 3650.67 m; Table 18) show a dominance of polar components followed by saturates. The Pr/Ph ratios are 4.31 and 2.47, respectively, and CPI values 1.09 and 1.00.

Table 17. Alma-1x well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI	PI
Core	3644.60	1.85	449	0.60	3.00	162	0.17
	3644.80	7.48	445	2.17	12.98	174	0.14
	3647.85	0.58	449	0.35	0.64	111	0.35
	3650.67	0.96	446	0.14	1.16	121	0.11
	3666.41	0.78	456	0.06	0.24	31	0.20
	3666.57	0.57	450	0.06	0.20	35	0.23
	3667.33	0.46	444	0.06	0.18	39	0.25
	3667.43	0.45	441	0.05	0.21	47	0.19
	3670.71	1.59	455	0.23	1.37	86	0.14
	3672.54	4.03	451	0.54	2.60	65	0.17
Cuttings	3551	1.09	438	0.09	0.64	59	0.12
	3554	1.03	434	0.05	0.41	40	0.11
	3557	1.13	436	0.08	0.51	45	0.14
	3560	1.12	438	0.07	0.64	57	0.10
	3563	1.13	438	0.07	0.59	52	0.11
	3566	1.12	436	0.11	0.75	67	0.13
	3569	1.12	441	0.11	0.57	51	0.16
	3572	1.17	438	0.17	1.30	111	0.12
	3575	1.19	431	0.29	1.41	118	0.17
	3578	1.18	435	0.25	1.29	109	0.16
	3581	1.22	440	0.18	1.37	112	0.12
	3584	1.10	436	0.23	1.31	119	0.15
	3587	1.25	440	0.18	1.14	91	0.14
	3591	1.25	439	0.21	1.48	118	0.12
	3594	1.31	442	0.18	1.20	92	0.13
	3597	1.27	436	0.23	1.51	119	0.13
	3600	1.28	438	0.11	0.99	77	0.10
	3603	3.28	444	0.57	3.88	118	0.13
	3606	2.08	444	0.55	2.54	122	0.18
	3609	3.02	445	0.75	4.37	145	0.15

The 22S/(22S+22R) epimer ratios of the 17α(H),21β(H) C_{31} and C_{32} extended hopanes range between 0.57 and 0.63. The ααα20S/(20S+20R) epimer ratio of the C_{29}

Table 18. GC data and composition of solvent extract fractions (asphaltene-free) from the Alma-1x, Elly-3, Falk-1 and Skjold Flank-1 wells

Well	Depth (m)	Pr/Ph	CPI	EOM	Sat (%)	Aro (%)	Polars (%)
Alma-1x	3644.60	4.31	1.09	51	39	13	48
	3650.67	2.47	1.00	50	37	9	54
Elly-3	4080.26	2.05	1.04	17	18	12	70
	4080.92	2.08	1.05	33	19	20	61
	4087.93	1.71	0.96	10	9	18	73
	4089.20	1.14	1.00	37	17	17	66
Falk-1	4112.10	2.01	1.05	57	23	20	57
	4116.35	3.48	0.98	30	28	7	65
	4116.40	3.59	1.01	28	19	19	62
	4116.45	3.55	1.01	39	23	15	62
	4123.60	4.06	1.01	24	35	21	44
	4124.10	3.17	1.03	30	28	11	61
Skjold Flank-1	4280.38	2.27	1.00	46	18	24	58
	4282.95	2.03	1.20	37	33	5	62
	4303.19	1.96	1.03	34	31	11	58

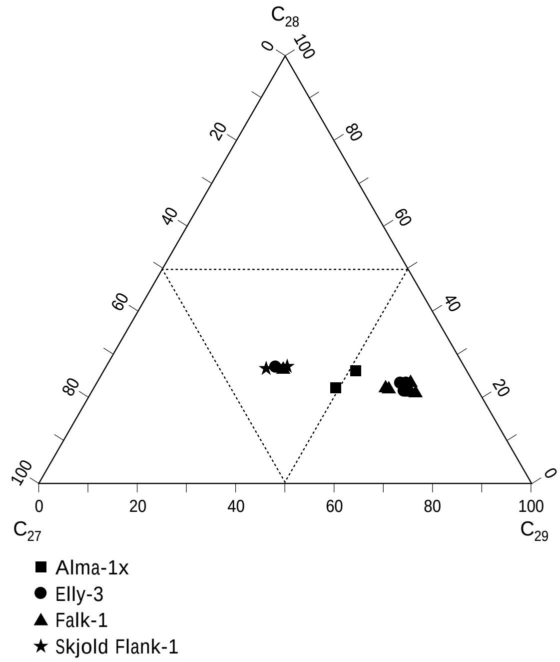


Fig. 47. Normalised $C_{27–29}$ sterane distribution in extracts from the Alma-1x, Elly-3, Falk-1 and Skjold Flank-1 wells. The majority of the samples are dominated by sterane C_{29} suggesting a high content of terrestrial organic matter.

sterane lies between 0.45 and 0.48, while the αββ20(S+R)/[αββ20(S+R)+ααα20(S+R)] ratio is 0.55 (Table 19). The relative proportion of the C_{27}αββ, C_{28}αββ and C_{29}αββ steranes is characterised by high contents of the C_{29} sterane (Fig. 47).

Table 19. Alma-1x, Elly-3, Falk-1 and Skjold Flank-1 wells: sterane isomerisation ratios

Well	Depth (m)	Steranes 29αααS / 29ααα(S+R)	Steranes 29αββ(S+R) / 29αββ(S+R)+29ααα(S+R)
Alma-1x	3644.60	0.45	0.55
	3650.67	0.48	0.55
Elly-3	4080.26	0.47	0.60
	4080.92	0.45	0.60
	4087.93	0.46	0.59
	4089.20	0.46	0.57
Falk-1	4112.10	0.52	0.63
	4116.35	0.45	0.63
	4116.40	0.48	0.60
	4116.45	0.48	0.61
	4123.60	0.46	0.63
	4124.10	0.46	0.60
Skjold Flank-1	4280.38	0.26	0.41
	4282.95	0.40	0.53
	4303.19	0.43	0.57

Table 20. Anne-3a well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI	PI
Cuttings	3441	2.38	440	0.24	3.11	131	0.07
	3450	2.20	441	0.33	2.10	95	0.14
	3460	3.98	443	0.26	3.98	100	0.06
	3469	3.20	441	0.24	3.16	99	0.07
	3478	2.75	440	0.17	3.06	111	0.05
	3487	4.23	441	0.44	6.47	153	0.06
	3496	3.07	441	0.25	3.61	118	0.06
	3505	11.51	438	2.02	21.40	186	0.09
	3519	4.80	441	0.24	5.99	125	0.04
	3530	1.46	439	0.05	1.05	72	0.05
	3533	1.09	438	0.03	0.74	68	0.04

Anne-3a well

Only cuttings are available from this well. TOC contents are within 1.09–11.51 wt%, and the T_{max} values range between 438°C and 443°C (Table 20). HI values range between 68 and 186 (Fig. 46), averaging 114, and thermally extracted and generated petroleum contents, S_1+S_2, are within the range 0.77–23.42 mg HC/g rock, but with the majority < 4 mg HC/g rock.

Elly-3 well

A single vitrinite reflectance measurement carried out on a sample from 4087.93 m depth shows a reflectance value of 1.13 %R_m indicating that the organic matter has just entered the medium volatile bituminous coalification stage (Table 21). The sample has a TOC content of 32.92 wt% and the kerogen is composed of terrestrial OM and vitrinitic organo-mineral matrix, occasionally associated with framboidal pyrite (Fig. 48; Tables 21, 22). Two other kerogen samples (4080.26 and 4080.92 m) have TOC contents of 8.58 wt% and 4.24 wt% respectively, and show dominance of terrestrial OM and minor contents of liptinitic OM. Kerogen typing is difficult due to the rank of the organic matter. However, based on the present kerogen composition and HI values between 107 and 137, the kerogen is classified as type III and possibly IIb.

The TOC contents of the core samples vary between 0.56 wt% and 32.92 wt% and T_{max} values range from 447°C to 495°C (Fig. 46; Table 22). Except for the three

Table 21. Elly-3 well: kerogen compositions and vitrinite reflectance value

Depth (m)	$\%R_m$	Mineral matrix	Pyrite	Organo-mineral matrix	Liptinitic ter. OM	Terrestrial OM	Kerogen Type
		(vol.%)					
4080.26	-	82	0	0	2	16	111/(11b?)
4080.92	-	84	1	0	3	12	111/(11b?)
4087.93	1.13	30	1	10*	0	59	111/(11b?)

* vitrinitic

investigated kerogen samples thermally extracted and generated petroleum contents, S_1+S_2, are below 1 mg HC/g rock.

Extracts are dominated by polar compounds followed by a tendency to dominance of aromatics over saturates (Table 18). The Pr/Ph ratios are between 1.14 and 2.08, and CPI ratios close to 1.

The range of the 22S/(22S+22R) epimer ratios of the 17α(H),21β(H) C_{31} and C_{32} extended hopanes is between 0.56 and 0.64. The ααα20S/(20S+20R) epimer

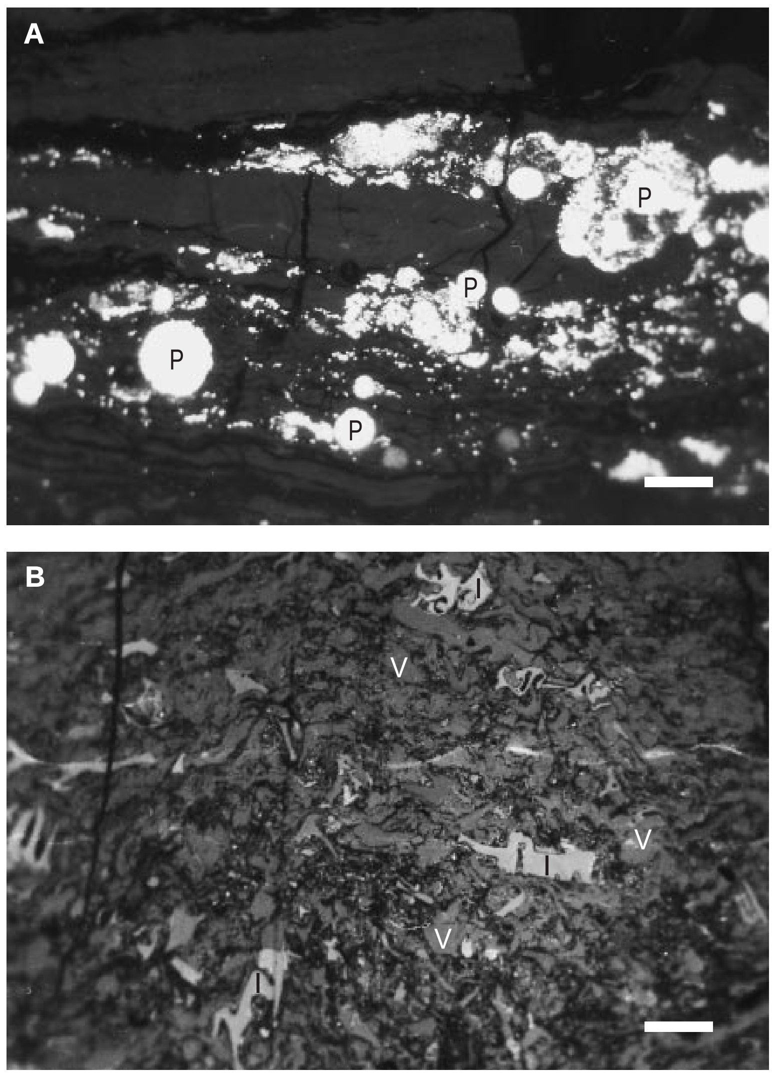


Fig. 48. Photomicrographs of kerogen from the Elly-3 well (sample 4300A, 4087.93 m). **A**: Framboidal pyrite (P) in vitrinite. **B**: Detrital vitrinite groundmass (V) with few inertodetrinite (I) particles and mineral matter. Black and white photographs in reflected white light and oil immersion. Scale bar ~ 35µm.

Table 22. Elly-3 well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2	HI	PI
Core	4080.26	8.58	456	1.03	9.63	112	0.10
	4080.92	4.24	449	0.45	4.54	107	0.09
	4086.86	1.94	465	0.15	0.91	47	0.14
	4087.93	32.92	457	4.08	45.12	137	0.08
	4088.79	1.04	447	0.17	0.52	50	0.25
	4089.20	0.56	477	0.13	0.45	80	0.22
	4090.77	1.01	457	0.23	0.67	66	0.26
	4091.92	0.90	494	0.21	0.71	79	0.23
	4092.78	1.08	461	0.23	0.77	72	0.23
	4093.39	1.02	495	0.25	0.72	71	0.26

ratio of the C_{29} sterane is around 0.46, while the αββ20(S+R)/[αββ20(S+R)+ααα20(S+R)] ratio ranges from 0.57–0.60 (Table 19). With the exception of a single sample with about equal relative proportions of the C_{27}αββ and C_{29}αββ steranes, the C_{29} is the dominant sterane (Fig. 47).

Falk-1 well

Vitrinite reflectance values range between 1.05 %R_m and 1.11 %R_m, inferring a rank of late high volatile bituminous A (Table 23). Microscopically investigated kerogens, having TOC contents from 7.98 to 69.90 wt % (Table 24), are dominated by vitrinitic OM (Fig. 49), of which the majority in the sample from 4116.40 m depth is fluorescent (Table 23). The samples have varying amounts of inertinitic OM, liptinitic OM and organo-mineral matrix (Fig. 49), which may be mainly vitrinitic or liptinitic. The samples contain from 2 to 5 vol.% pyrite. The HI values of the 4 petrographic investigated samples range between 167 and 243 (Table 24). The samples are accordingly classified as kerogen type III. However, the two samples from depths of 4112.10 m and 4116.40 m can, based on petrography and TOC content, be classified as humic coal.

Table 24. Falk-1 well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2	HI	PI
Core	4111.22	6.31	461	2.19	6.12	97	0.26
	4111.65	7.32	460	2.26	8.00	109	0.22
	4112.10	69.90	453	12.35	116.76	167	0.10
	4112.45	5.23	460	1.33	4.18	80	0.24
	4112.55	5.79	461	1.66	5.08	88	0.25
	4113.85	6.16	458	1.52	9.82	160	0.13
	4114.20	15.92	455	3.79	26.82	168	0.12
	4116.35	27.75	453	5.00	54.46	196	0.08
	4116.40	51.37	454	9.78	124.82	243	0.07
	4116.45	35.24	455	5.89	61.86	176	0.09
	4123.60	7.98	461	2.45	15.66	196	0.14
	4124.10	22.40	453	7.52	76.38	341	0.09
Cuttings	4051	2.36	437	1.50	4.27	181	0.26
	4081	2.45	438	1.21	2.82	115	0.30
	4111	2.87	442	1.79	3.47	121	0.34
	4141	6.65	449	2.69	7.65	115	0.26
	4171	2.46	442	1.46	3.96	161	0.27

The T_{max} values from the core samples vary between 453°C and 461°C, averaging 457°C, while 5 cuttings only average 442°C (Fig. 46; Table 24). HI values range between 80 and 341 with more than 50% having values greater than 160. Thermally extracted and generated petroleum contents, S_1+S_2, are highest for the organic-rich samples (Table 24).

Extracts are dominated by polar compounds followed by saturates (Table 18), and Pr/Ph ratios range between 2.01 and 4.06. CPI ratios are close to 1.

Five of the six investigated samples yield 22S/(22S+22R) epimer ratios of the 17α(H),21β(H) C_{31} and C_{32} extended hopanes in the range 0.52–0.68, whereas an outlier yields 0.47 and 0.87. The ααα20S/(20S+20R) epimer ratios and the αββ20(S+R)/[αββ20(S+R)+ααα20(S+R)] ratios of the C_{29} sterane range from 0.45–0.52 and

Table 23. Falk-1 well: kerogen compositions and vitrinite reflectance values

Depth (m)	%R_m	Mineral matrix (vol.%)	Pyrite (vol.%)	Organo-mineral matrix (vol.%)	Liptinitic ter. OM (vol.%)	Vitrinitic OM (vol.%)	Inertinitic OM (vol.%)	Kerogen type
4112.10	-	2	5	0	1	51	41	111
4116.35	-	30	2	13*	0	52	3	111
4116.40	1.05	1	2	0	4	93#	4	111
4116.45	1.11	-	-	-	-	-	-	-
4123.60	-	78	2	5**	2	9	4	111
4124.10	1.07	-	-	-	-	-	-	-

* vitrinitic organo-mineral matrix; **mainly liptinitic organo-mineral matrix; # mainly fluorescing; ter. = terrestrial

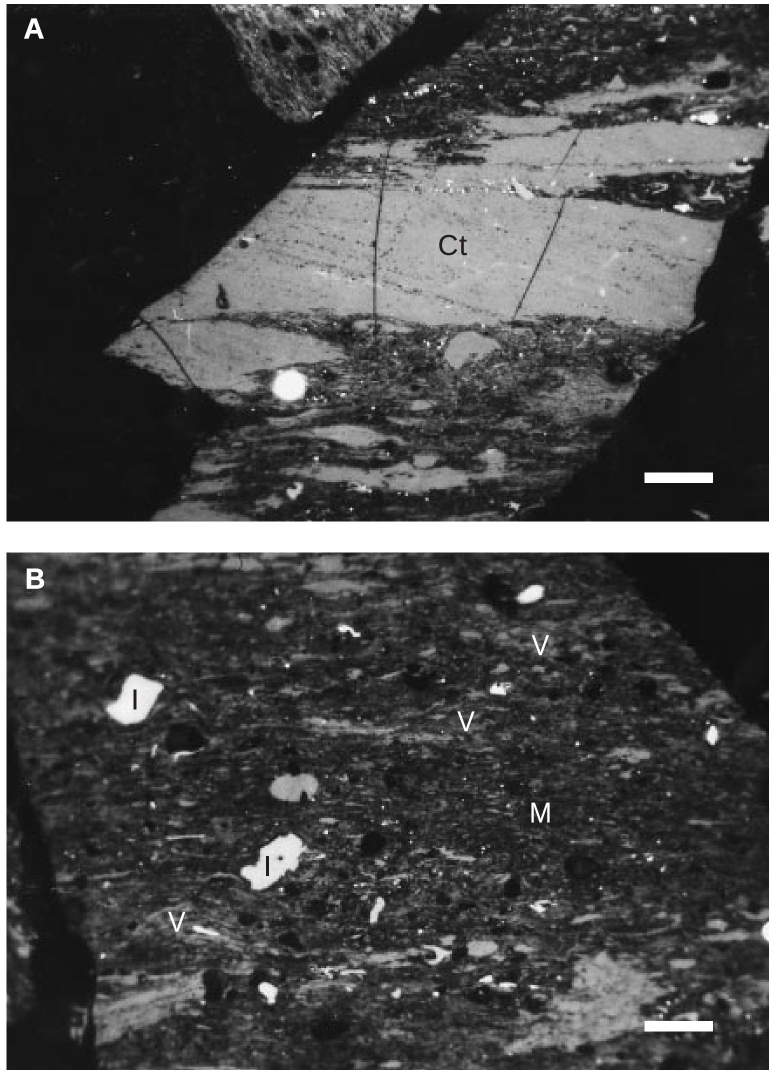


Fig. 49. Photomicrographs of kerogen in the Falk-1 well (sample 4334A, 4116.35 m). **A**: Collotelinite band (Ct) surrounded by detrital vitrinite and mineral matter. **B**: Detrital vitrinite (V) intimately associated with mineral matter (M) and a few inertodetrinite (I) particles. Black and white photographs in reflected white light and oil immersion. Scale bar ~ 35μm.

0.60–0.63 respectively (Table 19). With the exception of a single sample with about equal relative proportions of the $C_{27}\alpha\beta\beta$ and $C_{29}\alpha\beta\beta$ steranes, the C_{29} constitutes above 59% of the steranes in the remainder of the samples (Fig. 47).

M-8 well

Only cuttings are available, and they have TOC contents between 1.27 wt% and 11.27 wt% (Table 25). T_{max} values range from 437–445°C. HI values and thermally extracted and generated petroleum contents, S_1+S_2, are in the ranges 76–156 and 1.46–20.14 mg HC/g rock, respectively (Fig. 46; Table 25). The majority of the S_1+S_2 contents are, however, < 3 mg HC/g rock.

Skjold Flank-1 well

Two reflectance measurements both yield the value of 1.22 $\%R_m$ indicating a medium volatile bituminous rank (Table 26). Microscopic kerogen analyses of three samples, having TOC contents between 0.84 wt% and 1.53 wt% (Table 27), reveal a dominance of terrestrial OM and small proportions of organo-mineral matrix (Table 26).

Table 25. M-8 well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2	HI	PI
Cuttings	3100	1.48	439	0.52	1.88	127	0.22
	3109	1.52	441	0.54	1.92	126	0.22
	3118	1.72	441	0.63	2.22	129	0.22
	3127	11.27	443	2.88	17.26	153	0.14
	3136	5.57	445	1.99	7.58	136	0.21
	3146	2.63	445	0.88	3.24	123	0.21
	3155	1.80	441	0.61	1.76	98	0.26
	3164	1.38	440	0.42	1.04	76	0.29
	3173	1.27	437	0.77	1.98	156	0.28
	3182	1.39	441	0.63	2.02	145	0.24

Table 27. Skjold Flank-1 well: screening data

Sample type	Depth (m)	TOC (wt%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2	HI	PI
Core	4274.01	7.21	468	1.61	4.70	65	0.26
	4276.80	40.96	464	3.75	50.86	124	0.07
	4280.38	0.84	470	0.36	2.14	255	0.14
	4282.95	1.18	462	0.33	2.06	174	0.14
	4283.08	60.98	466	5.79	89.42	147	0.06
	4302.99	1.99	463	0.36	2.38	120	0.13
	4303.19	1.53	463	0.38	1.94	127	0.16
	4304.03	7.48	464	1.01	5.14	69	0.16
	4304.28	1.98	458	0.51	0.52	26	0.50
	4315.16	0.90	489	0.22	1.16	128	0.16
Cuttings	4173	1.37	446	0.81	1.00	73	0.45
	4188	1.32	442	0.92	0.90	68	0.51
	4218	2.59	440	1.34	1.42	55	0.49
	4234	2.25	443	1.33	1.57	70	0.46
	4249	2.32	445	1.44	1.80	78	0.44
	4264	5.68	447	2.04	2.95	52	0.41
	4279	4.04	455	1.35	2.55	63	0.35
	4295	4.90	448	1.53	3.92	80	0.28
	4310	2.58	442	1.71	2.43	94	0.41
	4325	2.59	428	1.97	2.95	114	0.40
	4340	1.45	446	0.85	1.10	76	0.44
	4356	1.23	442	0.48	1.01	82	0.32
	4371	2.16	448	0.94	1.37	63	0.41
Extracted cuttings	4203	1.96	446	0.16	1.05	54	0.13
	4389	11.89	475	0.21	6.17	52	0.03

The pyrite content ranges from 1 to 5 vol.%. Kerogen composition and HI values in the range 127–225 for the three samples suggest the kerogen should be classified as type III and possibly also type IIb for the sample from 4280.38 m depth.

T_{max} values from core samples range between 458°C and 489°C; the majority are in the range 462–468°C (Fig. 46; Table 27). Cuttings with TOC contents between 1.23 wt% and 11.89 wt% show, except for two samples, significantly lower T_{max} values (Fig. 46; Table 27). HI values are also generally lower, while thermally extracted and generated petroleum contents, S_1+S_2, vary between 1.21 and 6.38 mg HC/g rock.

Three core extracts are dominated by polar compounds (Table 18). In the two samples containing kerogen type III saturates are second, whereas aromatics are second in the sample (4280.38 m) containing kerogen type III and possibly type IIb. The Pr/Ph ratios lie between 1.96 and 2.27 and the CPI ratios close to 1.

The 22S/(22S+22R) epimer ratios of the 17α(H),21β(H) C_{31} and C_{32} extended hopanes yield, except for a single outlier (0.28), values between 0.55 and 0.62. The ranges of the ααα20S/(20S+20R) epimer ratios and the αββ20(S+R)/[αββ20(S+R)+ααα20(S+R)] ratios of the C_{29} sterane are, with the exception of a single outlier (0.26 and 0.41, respectively), from 0.40–0.43 and 0.53–0.57 respectively (Table 19). The relative proportions of the C_{27}αββ, C_{28}αββ and C_{29}αββ steranes show a general dominance of C_{27} sterane followed by C_{29} sterane (Fig. 47).

Table 26. Skjold Flank-1 well: kerogen compositions and vitrinite reflectance values

Depth (m)	$\%R_m$	Mineral matrix (vol.%)	Pyrite (vol.%)	Organo-mineral matrix (vol.%)	Liptinitic ter. OM (vol.%)	Terrestrial OM (vol.%)	Kerogen type
4276.80	1.22	-	-	-	-	-	-
4280.38	-	81	5	1	0	13	111/(11b?)
4282.95	-	90	1	0	0	9*	111
4283.08	1.22	-	-	-	-	-	-
4303.19	-	87	1	2	0	10*	111

* mainly vitrinitic; ter. = terrestrial

Discussion

Organic maturity

The two wells from the Heno Plateau, Elly-3 and Falk-1, yield vitrinite reflectance values between 1.05 %R_m and and 1.13 %R_m from a depth of about 4 kilometres (Tables 21, 23). The T_{max} values from the Elly-3 well show a wide range. However, the three most organic-rich samples show values from 449 to 457°C. This range and the comparatively narrow range of T_{max} values (average 457°C) from core samples of the Falk-1 well, are in good agreement with the vitrinite reflectances (Table 24). Higher T_{max} values may be related to interference by mineral matrix or the nature of the organic matter (inertinite) (Peters 1986). The lower temperatures obtained from cuttings from the Falk-1 well may be caused by lignite added to the drilling mud. Biomarker ratios are, as expected at this level of maturity, close to equilibrium (Table 19). Thus, with respect to thermal maturity the organic matter has passed the peak of oil generation (approximately between 0.8 and 1.0 %R, cf. Hunt 1996), and is found in the late oil window.

The remaining wells are situated in the Salt Dome Province in the southern part of the Danish Central Graben. The Skjold Flank-1 well yields two vitrinite reflectance values of 1.22 %R_m at approximately 4280 m depth, and the majority of the T_{max} values derived from core samples range from 462 to 468°C indicating a level of maturity of the organic matter close to the end of the oil window and the start of condensate generation (Tables 26, 27). The measured vitrinite reflectance values match perfectly the modelled reflectance values from a depth of about 4300 m (GEUS, unpublished data). Cuttings yield lower T_{max} values which may be caused by drilling mud additives like lignite. Biomarker ratios are slightly below equilibrium and show lower values than modelled epimerisation ratios (Table 19). This may imply influence from migrated products.

The Alma-1x, Anne-3a and M-8 wells exhibit lower maturities. A vitrinite reflectance value from a depth of about 3645 m in Alma-1x yields a value of 0.79 %R_m (Table 16). This value is in good agreement with the average T_{max} value (439°C) of the cuttings, and to some degree also with modelled vitrinite reflectance values for this depth (GEUS, unpublished data). However, core samples show higher values (average 449°C; Table 17), and core samples with comparatively high TOC contents (1.85 and 7.48 wt%) and HI values (162 and 174) probably give reliable T_{max} values of 449°C and 445°C suggesting that the vitrinite reflectance value may be too low. A vitrinite reflectance value corresponding to these T_{max} values would be between 0.9 and 1.0 %R_m. The highest T_{max} values are commonly associated with low HI values implying interference from inert organic matter. In the Alma-1x well the biomarker ratios have nearly reached equilibrium (Table 19).

Cuttings from approximately 3440–3530 m depth in Anne-3a show similar T_{max} values as the cuttings from Alma-1x (Table 20), thus corresponding to a vitrinite reflectance between 0.7 %R_m and 0.8 %R_m. This is slightly more than measured and modelled vitrinite reflectance values from a depth of about 3500 m in the Anne-3a well (Thomsen *et al.* 1995). Cuttings from the interval 3100–3182 m in M-8 also yield similar T_{max} values (Table 25), but here measured vitrinite reflectance values (%R_m about 0.77; Thomsen *et al.* 1995) match the pyrolysis temperatures.

The maturity parameters indicate that the organic matter in the Alma-1x, Anne-3a and M-8 wells is within the early catagenesis stage of maturation and is close to or within the peak oil generation range in the oil window.

Petroleum generative potential

Organic maturity parametres from the Elly-3 well indicate a level of thermal maturity corresponding to the late oil window. Some core samples from the Elly-3 well still have HI values above 100 and give high S_2 yields, but generally the organic matter is depleted in hydrogen and only a limited generative potential remains (Table 22). The T_{max} versus HI diagram suggests the core samples follow the pathway of kerogen type II (Fig. 46), and petrographic investigations of the organic material suggest a composition of kerogen type III and possibly IIb (Table 21). The high relative proportion of C_{29} sterane in the majority of the samples from Elly-3 indicates a strong input of terrestrial organic matter from higher land plants (Huang & Meinschein 1979; Philp 1994; Fig. 47). Influence from kerogen type II material is however suggested by the comparatively low Pr/Ph ratios (Table 18), in particular in the sample from 4089.20 m depth which has a Pr/Ph ratio of 1.14 and furthermore exhibits a slight dominance of C_{27} sterane, which is considered to be a marine indicator (e.g. Hunt 1996). These observations could imply an initially good generative potential of the organic matter in Elly-3. In that context it is notable that a terrigenous oil has been recovered in the nearby Elly-2 well: the Pr/Ph ratio is 2.06 and relative proportions of C_{27} and C_{29} steranes are 24% and 52% respectively (GEUS, unpublished data).

The Elly discovery, expected to be set in production in 1999, contains primarily gas (expected reserve: 5 billion Nm^3) and minor oil (expected reserve: 1 million m^3; Danish Energy Agency 1997).

The organic matter in the Falk-1 well has a similar level of thermal maturity as that observed in Elly-3. The maturity level infers exhaustion of the petroleum generative potential. However, high S_2 yields indicate that generative potential still remains (Table 24), and several HI values close to or above 200 indicate a good generative capacity (Fig. 46). Although petrography and Pr/Ph ratios generally above 3 support a classification of the organic matter as kerogen type III, the deposition in low-energy, open-water mires or lakes with restricted oxygen availability, as shown by the carbonaceous mudstones, and the presence of organomineral matrix and liptinitic terrestrial organic matter may account for the comparatively high HI values and the ability to generate petroleum at this level of maturity (Fig. 44; Tables 18, 23).

Several HI values between 100 and 200 obtained from core samples from Skjold Flank-1 and relatively high S_2 yields imply that the organic matter, constituted by kerogen type III and possibly type IIb, may possess the capability to generate condensate and gas even at the present level of thermal maturity (Fig. 46; Table 27). This is corroborated by computed petroleum generation depth trends for kerogen types II and III which show that in the Central Graben Group these kerogen types are within the condensate/gas window (GEUS, unpublished data). It is likely that the marine influenced coastal plain (as shown by dominance of C_{27} sterane, Fig. 47) with a variety of depositional environments, like lakes and lagoons, in places favoured the sedimentation and preservation of petroleum-prone organic matter.

The petrographic composition of the organic matter in the Alma-1x well is composed mainly of kerogen type III and some type IIb. However, although the organic matter with respect to thermal maturity is within the peak oil generation range the generally low HI values and S_2 yields suggest a rather poor petroleum generative potential (Fig. 46; Table 17). The overall floodplain environment seems in general to have been unfavourable for deposition of oil-prone organic matter.

The HI values from the Anne-3a and M-8 wells only in a few cases exceed 140 implying a limited petroleum generative capacity of the organic matter (Fig. 46; Tables 20, 25). The position of the cuttings in the HI versus T_{max} diagrams does not indicate a depth trend, but the presence of kerogen type II could be implicated. The comparatively low generative capacity, however, is probably related to a dominance of kerogen type III in the cuttings.

Conclusions

The coal seams of the Bryne Formation in the Søgne Basin

1. Peat accumulation occurred in coastal mires. Increased marine influence is observed in the Lulu-1 and Amalie-1 wells, where lagoonal, estuarine channel, shoreface and offshore siliciclastic sediments dominate.

2. The cumulative coal seam thickness decreases in a seaward direction from 5.05 m in the West Lulu-2 well, to 3.27 m in West Lulu-1 and 1.57 m in West Lulu-3, decreasing to 0.98 m in the Lulu-1 well, and to 0.60 m in the Amalie-1 well. This thinning of the seams towards the palaeo-shoreline is related to a more rapid outpacing of the rate of peat accumulation by the watertable rise linked to a relative sea-level rise.

3. A spatial coal seam distribution shows that the seams R1 and T4 are the most extensive; the precursor mires occupied the majority of the Danish part of the Søgne Basin. A seam split of seam R1, named R1a, is only present in the West Lulu-1 and West Lulu-3 wells. The precursor mire of seam T2 was also extensive, but did not reach the southern part (Amalie-1 well) of the basin. The mires represented by seams T1 and T3 had a limited extent and were restricted to the north-western part of the Danish Søgne Basin.