DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/110

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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EFP-2000

ENS Journal nr. 1313/00-0005

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Revideret EFP-2000 ansøgning

Den 2. december 1999

Efter aftale fremsendes revideret projektansøgning vedrørende projektet "Kulbrintepotentialet i det Norsk-Danske Bassin".

Med venlig hilsen

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Ansøgningsskema EFP 2000

Side 1 af 4

se vejledning i kapitel 3

1. Projekttitel:

Kulbrintepotentialet i det Norsk-Danske Bassin

Programområde: Olie og naturgas / efterforskning

Kort beskrivelse af projektets formål: Projektets overordnede mål er at opstille en konceptuel model for udviklingen af dele af den Mesozoiske lagserie i det Norsk Danske Bassin med særligt henblik på forekomsten og udbredelsen af potentielle kildebjergarter.

Dette mål vil blive forfulgt gennem et integreret geologisk/geofysisk/geokemisk studie, omfattende kompilering af eksisterende data samt inddragelse og produktion af nye data. Hovedvægten vil blive lagt på kortlægning af genkendlige nøgleflader af sekvenstratigrafisk signifikans, koblet med studier af genkendelige enheders kildebjergartspotentiale og dettes rumlige variation.

Projektet udgør første fase af et større projekt. Projektets anden fase, hvortil til forventes ansøgt om midler i 2001, vil blandt andet omfatte numerisk modellering og detailstudier at udviklingen af randsænker omkring udvalgte saltstrukturer

2. Projektansvarlig virksomhed/institution: Danmarks og Grønlands Geologiske Undersøgelse (GEUS)

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Seniorforsker Lars Henrik Nielsen, Seniorforsker Karen Dybkjær, Seniorforsker Jørgen A. Bojesen-Koefoed, Seniorforsker Henrik I. Petersen, Seniorrådgiver Hans Peter Nytoft, Seniorrådgiver Per Rosenberg, alle GEUS

3. Finansiering og ressourceindsats Virksomhed/institution	EFP-tilskud (1000 kr.)	Anden finansiering (1000 kr.)	Månedsværk (mand-måned)
GEUS (bialg 1)		1224	34
EFP (bilag 2)	1514		
I alt	1514	1224	34
Totaludgift (1000 kr.) (bilag 1.) 2738	**EFP-tilskud i % af totalbudget 55**		

4. Dato 30 november 1999 Underskrift (Projektansvarlig)

5. Projektbeskrivelse

Uddybende materiale om projektet kan vedlægges som bilag, men projektet skal som hovedregel kunne vurderes på nærværende beskrivelse:

Projektets første fase (2 år) vil hovedsagelig undersøge de mest betydningsfulde risikofaktorer i forbindelse med olie- og gasefterforskning i det Norsk-Danske Bassin, nemlig forekomsten af gode kildebjergarter og eksistensen af køkkener, hvor disse kan tænkes at være tilstrækkeligt modne til at olie- og/eller gas-dannelse kan have fundet sted.

I Centralgraven er den øvre jurassiske kildebjergart velkendt, hvorimod fokus i det Norsk-Danske Bassin i højere grad må rettes mod kildebjergarter af anden geologisk alder. Publicerede såvel som upublicerede data peger på at der i både Trias (Gassum Fm.) og i Nedre Jura (Fjerritslev Fm.) lagserierne kan forekomme intervaller med kildebjergartspotentiale. Disse kilderbjergarter kan tænkes at være modne i randsænker omkring saltstrukturer. Undersøgelser af tilgængeligt, men endnu uanalyseret eller utilstrækkeligt analyseret materiale fra Sverige (3D SV 328 boringen, Sandåkra, Hässleholm), mulige olieudsivninger i Skåne, Nordsøen/Skagerrak (Felicia-1boringen) og Kattegat (Terne-1 boringen) forventes at kunne kaste mere lys over kildebjergartspotentialet i den jurassiske lagserie.

En nærmere analyse af disse spredte indikationer vil kunne kaste lys over de mulige forekomster af kildebjergarter i området og over deres generative potentiale og modenhed, samt over forekomsten af køkkener og mulige fælder.

Projektet gennemføres på frigivent materiale, eller materiale som GEUS ad anden vej har erhvervet sig adgang til. Hvis der i projektets løb fremkommer nye data fra eventuelle efterforskningsaktiviteter i området vil disse blive inddraget i det omfang der kan opnås tilladelse hertil. Endvidere er der vist interesse for projektet fra koncessionshaverne i området (Amerada Hess). Sammenfattende vil hensigten med projektets første fase være at:

- kompilere eksisterende data vedrørende Mesozoiske kildebjergarter i studieområdet, herunder opdatere databasen for at bringe datakvalitet i overensstemmelse med nutidens forbedrede analyseteknik (se nedenfor).
- gennemføre analyser af hidtil ikke analyseret materiale for at komplettere eksisterende undersøgelser
- undersøge mulige kildebjergarters udbredelse ved hjælp af seismisk kortlægning af udvalgte sekvensstratigrafiske flader.
- Ved hjælp af organisk geokemiske undersøgelser at kortlægge mulige kildebjergartes kvalitets- og modenhedsvariation i det omfang data tillader dette gennemført på en meningsfuld måde
- opstille en konceptuel model for den sekvenstratigrafiske udvikling af relevante dele af den Mesozioske lagserie med særlligt henblik på forudsigelse af forekomsten af mulige kildebjergarter.

Afhængigt af prøvetype og den enkelte analysetypes relevans vil de anvendte metoder omfatte :

- palynostratigrafi/palynofacies (datering og kerogentype)
- organisk petrografi/maceralanalyse, vitrinitreflektans (modenhed og kerogentype).
- organisk geokemisk analyse (Rock-Eval pyrolyse, TOC, TS, biomarkere, aktiveringsenergibestemmelser, Pyrolyse-GC, IR-spektrometri/IR-mikroskopi, vådpyrolyse, etc.)

Projektets anden fase vil omhandle numerisk modellering og diverse strukturelle detailstudier med henblik på at undersøge mulige køkkener og migrationsveje. Midler til gennemførelse af projektets anden fase forventes ansøgt i 2001.

Ansøgningsskema EFP 2000

6. Sammenhæng med tidligere EFP-projekt(er) og andre nationale forskningsprogrammer.

Projekttitel:	Reference (j.nr.):
EFP-98 Terrigene aflejringers kildebjergartspotentiale	1313/98-0022
Forskerakademiet (Ph.D. projekt Lars Henrik Nielsen)	

7. Kvantificeret effekt på dansk energiforbrug og -forsyning:

Projektet vil bidrage til at opstille nye mål for olie og gas efterforskningen i den del af det danske område, der er underlagt "åben dør" licens-ordningen, og hvor der kun finder begrænsede efterforskningsaktiviteter sted.

8. Resultaternes betydning for andre væsentlige samfundsforhold:

Ved at muliggøre opstilling af nye mål for kulbrinteefterforskningen vil projektet potentiell kunne anspore til større industriinteresse og forøget efterforskningsaktivitet i det Norsk-Danske Bassin.

9. Projektets internationale sammenhæng og betydning:

Projektet bidrager væsentligt til en forøget regionalgeologisk forståelse af danske landområder, såvel som af omliggende offshore-områder, herunder Det Norsk-Danske Bassin, områderne syd herfor, samt den østlige Nordsø.

10. Hvorledes tænkes resultaterne udnyttet ?:

Projektets resultater vil blive søgt publiceret i relevante internationale tidsskrifter og fremlagt i form af posters/foredrag ved internationale konferencer. Afhængig af de opnåede resultater vil det blive overvejet at udarbejde en Geology of Denmark Survey Bulletin. Endvidere vil resultaterne blive brugt i forbindelse med GEUS løbende rådgivning af myndighederne og i markedsføringen overfor olieindustrien.

Vedr.: EFP projekt 1313/00-0005
J.nr. GEUS: 071-156

Kære Marianne,

Du har stillet en række spørgsmål vedrørende ovennævnte projekt. Svarene på dine spørgsmål er skrevet ind i din mail efter hvert spørgsmål, som du bad om. Jeg håber du finder svarene fyldestgørende, så vi kan få afsluttet sagen.

Kommentarer til EFP projekt 1313/00-0005

Projektet skulle oprindeligt være afslutte i fjerde kvartal af 2001. Udsættelse blev givet i december 2001 til afsluttelse af projektet den 1 november 2002. Den 19 december 2002 blev rapporten modtaget.

Svar: Det er normal praksis med EFP-projekter, som det også fremgår af tilsagnskrivelsen, at slutrapport skal være afleveret senest 2 måneder efter projektet er afsluttet, hvilket er sket.

Generelt:

- Figurtekst i liste for sig selv ? Bedes ændret

Svar: I en rapport som denne, hvor der er lagt vægt på at bringe mange illustrationer af meget forskellig karakter, er det meget tidskrævende at inkludere figurtekster direkte på illustrationerne. For nogle typer, som f.eks plot fra Landmark, er det vanskeligt at inkludere fyldestgørende tekster. Det bedste kompromis under hensyntagen til resourceforbrug og ønsket om at bringe fyldige tekster er derfor en selvstændig liste.

- Hvad er boringernes alder?

Svar: I Introduktion side 3 hvor bore databasen omtales er der i linie 4 refereret til Nielsen & Japsen (1991), hvori blandt andet alderen på de anvendte boringer er angivet.

- Er der tidligere foretaget geokemiske / source rock evalueringer (analyser) af området eller brøndene? I projektbeskrivelsen står der : "Gennemføre analyser af hidtil ikke analyseret materiale for at komplimentere eksisterende undersøgelser"

Svar: Rapporten giver referencer til de tidligere publicerede arbejder fra området: Thomsen et al. (1983), Thomsen et al. (1987), Michelsen (1989b) og Nielsen et al. (2000). Derudover har upublicerede data været til rådighed. Disse tidligere analyser er gennemgået og påideligheden af dem er vurderet. Tvivlsomme målinger er målt om og intervaller uden målinger er analyseret i den udstrækning, der har været materiale til det. Rapporten opsummerer således resultatet af mere end 4700 udførte analyser, og konklussionerne vedrørende source rock bygger således på et meget omfattende materiale.

- Er der fundet oil /gas / shows i nogle boringer indikerende at der er en fungerende source rock? (hvad er baggrunden for projektet??)

Svar: Der er, jævnfør afsnittet om perme kildebjergarter i GEUS´ oprindelig ansøgning, fundet enkelte kulbrinteindikationer i præ-mesozoiske lag nord for Ringkøbing-Fyn Højderyggen. Desværre blev denne del af projektet skåret væk på foranledning af Energistyrelsen. Aspektet er dog kort resumeret i rapporten. Med hensyn til dit spørgsmål om baggrunden for projektet, er baggrunden ~~vel, at Energistyrelsen~~et ønske om~~de~~ at fremme kulbrinte efterforskningen i det østlige Danmark. Baseret på den omfattende geologiske forskning GEUS gennem årene har udført og som er dokumenteret i adskillige publikationer og rapporter, og endvidere indgår i adskillige notater fra GEUS i.f.m. vurdering af ”Åben Dør ansøgninger” har det været indlysende, at det er forekomsten af egnede modne kildebjergarter, der udgør hovedrisikoen i Østdanmark. Projektet, der har haft kildebjergarts problematikken som hovedemne, blev formentlig godkendt på denne baggrund.

- Generel historik

Svar: Det Danske Bassin og Den Fennoscandiske Randzone har været genstand for talrige geologiske forskningsprojekter siden det klasiske arbejde af Sorgenfrei og Buch (1964). Det ville føre alt for vidt at bringe en generel historisk oversigt over alle disse arbejder, og det ville være en dårlig udnyttelse af den tilmålte tid for projektet. I stedet er der givet en introduktion og en ganske grundig og ”up-to-date” beskrivelse af områdets geologiske udvikling med henvisning til relevante referencer. Via den fyldige referenceliste kan den interessede læser finde frem til yderligere referencer, hvis det måtte ønskes.

Figur 18: Er denne figur fra en pub~~p~~likation, reference? Hvis ikke ville det være meget brugbart at have den i farver.

Svar: Figuren er modificeret efter en artikel, der er under trykning; referencen står i figur teksten og i reference listen (Petersen et al. in press.; udkommer 1.11.03). Figuren er ikke i farver og dette er ikke skønnet nødvendigt hverken her eller i Petersen et al. Figuren er konstrueret for at få en brugbar modenheds gradient, og dens styrke er, at et meget stort antal prøver indgår samt at deres dybder er korrigeret for Sen Kridt–Neogen hævning bedømt ud fra uafhængige data (seismiske hastighedsanomalier, jf. diverse arbejder af Peter Japsen, GEUS). Det er således trenden, der er interessant og ikke de enkelte målepunkter. Derudover viser figuren, som omtalt i figurteksten, at de gode kildebjergartsintervaller generelt ligger over olievinduet. Der er, som angivet i figuren, kun ganske få boringer, hvor potentielle mesozoiske kildebjergarter ligger under olievinduet. Desværre er disse af dårlig kvalitet og derfor uinteressante som olie kildebjergarter.

- Figurer 19-21: Hvad er akserne? Dybde i meter eller fødder?

Svar: I figur teksten (angivet på figuren) står der ” TWT. Depth to center of formation and interval velocity” : M.a.o. seismisk løbetid og hastighed. De originale data fremgår i øvrigt af table 1 som der er referet til i samme sætning som omtaler figurerne.

- I " Source rock evaluation of the Danish Basin and Fennoscandian Border Zone ", bedes sidebladene vise navnene på brøndene, således at man ikke skal bladre frem og tilbage hele tiden.

Svar: Det er rigtigt, at det ville have været en ekstra service for læseren, hvis fanebladene havde vist boringsnavnene. Rapporten er færdig og distribueret, og det vil være for resourcekrævende på nuværende tidspunkt at tilbagekalde eller eftersende sådanne faneblade.

Introduction:

Side 3: A variety of hydrocarbon plays have been tested including structural traps with Rotliegendes sandstone, Zechstein carbonate or Triassic sandstone **reservoirs sourced from Carboniferous coal beds or Zechstien mudstones and Marls. Additional speculative plays may include Cambrian sandstones and carbonates sources by Lower Paleozoic shales "** Mener GEUS at man på basis af basin modelleringen beskrevet side 7 fuldstændigt kan udelukke en Paleozorisk source? Hvad med migration?

Svar: GEUS mener ikke, at man kan udelukke paleozoiske kildebjergarter. I det oprindelige projektforslag indgik perme kildebjergarter; men denne del af projektet blev fjernet på foranledning af Energistyrelsen i forbindelse med en kraftig reduktion af projektet. Karbone kildebjergarter er ikke fundet i det Norsk-Danske Bassin; øvre karbone redbeds findes formentlig i Hans-1 og karbone intrusiver findes i Terne-1 (Michelsen og Nielsen 1991, 1993). Hvad angår kambriske kildebjergarter, som f.eks. Alun~~m~~ Skiffer er disse kun fundet på dansk område med en vitrinite reflektans på mere end 2.5 og er derved overmoden (Thomsen et al. 1987, Buch~~k~~ardt et al. 1997). Modellering viser i øvrigt, at Alum Skifferen formentlig er brændt af før Perm, og derfor er irrelevant for mesozoiske strukturer. Lang distance migration fra karbone gas-generende kullag fra Det Nordtyske Bassin er bestemt en mulighed i nogle områder, men lå desværre uden for projektets emne.

Sample material and methods:

- Er analyserne foretaget på GEUS – standard? Sammenlignelighed med andre laboratorier?

Svar: Screeninganalyserne er velkendte metoder udført på standardudstyr (Rock-Eval: ældre data på Rock-Eval-2 og TOC undertiden vha. LECO IR-212; nyere og nyanalyserede data på Vinci Rock-Eval 5 og Vinci Rock-Eval 6; TOC: ~~Leco~~ LECO CS 200). Rock-Eval instrumentet kalibreres først med ekstern standard (IFP-55000 standard) leveret af producenten. Rock-Eval analyserne køres endvidere med en laboratorie-intern standard (kalibreret i.fh.t. ontalte IFP-55000 standard), som værdierne skal ligge indenfor med bestemte acceptgrænser, defineret udfra de i original-literaturen angivne måleusikkerheder. Der analyseres sæt af standard og blank for hver 10 prøver. TOC instrumentet kalibreres med ekstern kommerciel standard og bliver kontrolleret for hver 10. analyse. Kvaliteten af analyserne lever således helt op til international standard og kan sammenlignes med tilsvarende analyser. Der er ikke angivet referencer til metoden idet denne normalt anses for så udbredt at det kan antages, at hvor intet andet er anført, er analyserne udført i overensstemmelse med gældende standard. Relevante referencer er Espitalié et al. (1985) og Bordenave et al. (1993) –

begge fremsendes gerne i kopi hvis det skulle ønskes. GEUS har i forbindelse med andet arbejde desuden lagt et stort arbejde i at finde frem til de rette mængder prøvemateriale i relation til indholdet af kulstof i prøven. Dette har yderligere optimeret analysekvaliteten. M.h.t. vitrinitmålingerne er source rock laboratoriet akkrediteret af International Committee for Coal and Organic Petrology (certifikatnr. ICCP/RA/33.1/0131AB og ICCP/RA/33.2/0132AB). Det kan tilføjes, at det er af afgørende betydning for GEUS som en international anerkendt forskningsinstitution, at vores laboratorier er mindst på niveau med international standard.

- I projektbeskrivelsen står der at : "Afhængig af prøvetype og den enkelte prøvetypes relevans vil de anvendte metoder omfatte:
  1. Palynostratigrafiske/palynofacies (datering og kerogen type)
  2. Organisk petrografi / maceralanalyse, vitrinitereflektans (modenhed og kerogentype)
  3. Organisk geokemisk analyse (Rock-Eval pyrolyse, TOC, TS, biomarkers, aktiveringsenergibestemmelser, pyrolyse-GC. IR-spektrometri / IR-mokroskopi, vårpyrolyse, ect.)

Der er kun foretaget TOC og Rock-Eval. Der er ingen beskrivelse af hvorfor intet andet er foretaget?

Svar: Biomarker-analyser, aktiveringsenergibestemmelser, pyrolyse-GC o.s.v. er meget tids- og ressourcekrævende analyser. Sådanne analyser vil i denne sammenhæng kun levere relevante data, hvis der under screeningen blev identificeret gode og modne kildebjergarter. Dette var desværre ikke tilfældet, idet modenheden er det store problem på trods af enkelte gode kildebjergarts horisonter. Det ville ~~til en vis grad~~ være meningsløst i et projekt som nærværende at iværksætte et omfattende og dyrt analyseprogram på en række umodne prøver, idet de opnåede resultater ikke ville bidrage med nogen betydningsfuld information i forhold til at besvare de grundlæggende spørgsmål omkring kildebjergartspotentialet i Det Norsk-Danske Bassin. Situationen ville have været væsentlig anderledes, hvis modne kildebjergarter var blevet identificeret. I projektbeskrivelsen var derfor lagt vægt på, at brugen af analyse-metoder kunne prioriteres alt efter projektets resultater og dermed relevansen af metoderne. Generelt anvendes forskellige analysemetoder sekventielt, således at et stort antal prøver "screenes" ved hjælp af mindre resourcekrævende metoder med henblik på at udvælge et mindre antal prøver af en kvalitet og beskaffenhed, der bedømt udfra et givent projekts formål, retfærdiggør gennemførelsen af mere omfattende og omkostningstunge analyser. Bedømt udfra dette kriterium har dette projekt ikke identificeret sådanne prøver, hvorfor de omtalte analyser ikke er gennemført. At dette ikke eksplicit er fremhævet i rapporten kan hævdes at være ~~uheldigt, men det omtalte forhold vil være implicit for den geokemisk funderede læser, som denne del af studiet primært henvender sig til~~. Det skal i øvrigt nævnes at konservativt estimeret repræsenterer de rapporterede analyser en kommerciel genanskaffelsesomkostning i omegnen af 1,5 millioner D.Kr.

~~Dette svar er det vigtigste da der her er noget at komme efter.~~

- Sample interval? Tabel over fordeling mellem brøndene og i formationerne!

Svar: Samtlige analyser er listede i data dokumentations rapporten GEUS 2001/128 med angivelse af dybde, dybder til formations grænser og max., min. og gennemsnit for formationerne.

- Side 12: *"The nine S_2 based definitions shows in Enclosure 1 constitute the criteria for evaluation of the source quality"*. Hvad er dette baseret på ? Referencer?

~~Svar: Jønne~~

Cut-off værdier for bedømmelse af kildebjergartskvalitet er et emne der jævnligt diskuteres i geokemiker-kredse, og iblandt olieselskaber er der en vis tendens til at hvert selskab har deres egen variant, idet hovedlinierne dog i store træk er ens. Den anvendte klassifikation tager sit udspring i den uofficielle inddeling, der (såvidt vides) er defineret af Chevron, da Rock-Eval instrumentet begyndte at blive udbredt. Chevron dannede tidligere i mange geokemiske henseender skole. Klassifikationen vil af nogle blive anset for at være noget for positiv, men ikke desto mindre noget lignenede jævnligt anvendt. Da systemet såvidt vides aldrig er formelt publiceret kan der ikke anføres reference. Eftersom der ikke eksisterer nogen universelt anerkendt inddeling er det således tilladt for enhver at anvende en given klassifikation, når blot denne defineres, således som det sker i rapporten. Tilsvarende er det tilladt for enhver at være uenig og anvende en alternativ inddeling, hvilket med overlæg lettes ved at vedlægge alle rådata i elektronisk form (CD-ROM), således som det er sket.

- Side 12*: "This approach may in cases lead to some ambigulity, in paticular if compared to calculated HI values. Utilisation of other information is therefore recommended in order to optimise the utility of the Rock Eval. Data"* Er det op til læseren at gøre dette? Er det ikke projektes opgave?

~~Svar: Jønne~~

Den citerede passus er ment som en advarsel mod den, bedømt udfra en alt for rigelig erfaring, udbredte hovedløse brug af geokemiske screening-data. Mange andre typer geologiske special-data anvendes givetvis ligeledes på tvivlsom måde, men problemet synes særlig akut for såvidt angår geokemiske data, idet sagkundskaben i det overordnede geologiske miljø på dette område generelt er ringe. Den omtalte supplerende information vil være kontekst-afhængig og de fremlagte data leverer svar på projektets hovedspørgsmål. Derimod leverer de ikke nødvendigvis fuld oplysning i forhold til de mulige spørgsmål en efterfølgende bruger af data måtte ønske at uddrage svar på. Derfor denne advarsel, og derfor er det læserens/brugerens opgave, ikke projektets, at finde og anvende supplerende information til det ukendte formål en senere bruger af rapporten måtte have.

Results of the source rock evaluation

- Felicia-1: Energistyrelsen har tidligere gjort GEUS opmærksom på at Felicia-1a (sidetrack) når en dybde på 5330m in Rotligendes? Cuttings fra denne boring indikere tilstedeværelsen af særdeles interessant source rock. Disse data er ikke medtaget i rapporten, hvorfor ikke??

Sidetracket kicker off i 2175m

Svar: Som det er blevet nævnt tidligere i. f. m. præsentation af projektets resultater indgik undersøgelse af perme kildebjergarter ikke i projektet. Foranlediget af styrelsen er prøver fra Felicia-1a efterfølgende undersøgt finansieret over GEUS´ bassismidler. En rapport med resultaterne samt en diskusion af resultaterne er fremsendt til Energistyrelsen (Source rock investigation of part of the Rotliegende succession of the Felicia-1a well af Petersen, Bojesen-

Koefoed & Nytoft, GEUS 2003/55). Rapporten kan desværre ikke bekræfte tilstedeværelse af kildebjergarter.

- Forståelsen af teksten formindskes stærkt af at resultaterne kun behandles i skreven tekst. Grafiske fremstillinger som kort for de enkelte formationer der viser de fundne resultater vil give læseren et overblik. Det vil ligeledes give et overblik om TOC og HI evt. kan konstrueres.

Svar: Det ville føre for vidt – i betragtning af projektets resourcer samt de negative konklusioner vedr. kildebjergarts potentiale – at vise kort e.l. for de undersøgte formationer. Forskellige typer af grafiske afbildninger er forsøgt for F-III og F-IV, og det mest illustrative er vist i Fig. 49 og Fig. 52.

- Rønde-1: Vil konta~~er~~minerende boremudder (ligesom fluide hydrocarboner) blive brændt af i S1, således at resultater giver en indikation af source rock kvaliteten?

Svar: Nej. Noget af boremudderet vil optræde under S1 men desværre langt fra det hele. De tilsatte fluide hydrokarboner vil også trække over i S2-delen, og derved både forårsage et kunstigt højt kildebjergartspotentiale samt vanskeliggøre adskillelsen af S1 og S2. Derved kan Tmax også blive målt forkert, hvorved denne modenhedsparameter bliver uanvendelig. Dette er desværre et alment kendt problem med prøver kontamineret med olie-tilsat boremudder. ~~Jønne?.~~ Kontamineringsproblemet vedrører ikke alene olie (i ældre brønde typisk diesel-lignende substanser), men også andre additiver, der undertiden i kraft af olien, mobiliseres med tid gennem prøvens opbevaring. Herudover vil mængden af tilsat olie gerne føre til en koncentration i prøven, der langt overstiger den apparatet er designet til at kunne kapere, hvorfor en general overbelastning gerne forekommer med værdiløse data til følge. Ofte ses S1 og S2 toppene at være dårligt adskilte, og mere eller mindre sammenflydende, således at kontamineringen påvirker begge målte parametre såvel som definitionen af S2's toppunkt og dermed Tmax.

Seismic Mapping:

- Mangler kort over seismisk database

Svar: I indledningen til afsnittet om seismisk tolkning står der, at kortene er fremstillet ved at kombinere tidligere kort med tolkning af nye digitale linier og enkelte ældre analog linier. I denne forbindelse er der refereret til de gamle kort og her er der kort, der viser datadækningen i stort set hele det område, hvor datadækningen kan være et problem. Vest for Jyllands kyst er der en høj datadækning af nye gode data. Det gælder således kun for Sjælland og et lille område mellem Sjælland og Jylland, at der kan være et problem. Der findes ikke en hurtig genvej til et kort der illustrerer linier tolket i Landmark systemet sammen med linier, der er hånd tolket og hånd aflæst. Igen har det været nødvendigt at priortere arbejdsopgaverne inden for projektets budget.

- Hvad er dybdekonverteringen baseret på ? Check shot points eller VSP i boringerne? I alle boringer?

Svar: I afsnittet om dybdekonvertering er der henvist til tabel 1, hvoraf det fremgår hvilke boringer og hvilke intervaller, der indgår i dybdekonverteringen. Da de benyttede boringer alle er af ældre dato (jf. Nielsen & Japsen 1991) er konveteringen baseret på "Check shot surveys". I regional målestok skulle det ikke betyde noget om det er VSP eller Check shot, der anvendes.

- Liste over estimerede dybder og faktiske dybder i brøndene. Så læseren kan få et indtryk af dybdekonverteringens kvalitet.

~~**Svar:** Torben~~

- Side 25: "It has not been attempted to fit the maps exactely to the well data" Hvad er den største afvigelse? Hvorfor er der ikke gjort et forsøg på dette?

Svar: Konceptet for dybdekonverteringen har i dette tilfælde været lidt anderledes end i normale dybdekonverteringer, hvor man fokusere på strukturer og dermed på placeringen af boringerne. I dette tilfælde, hvor det er den dybe del af bassinet, der er interessant, ville en korrektion der fik kortet til at passe præcist i boringerne meget nemt kunne gøre kortet dårligere i de dybe dele af bassinet. Derfor er det valgt at fokusere på hastighedsfunktionen, der jo beskriver ekstrapolationen ud i den dybe del af bassinet. Derfor er det også valgt at vise afvigelsen mellem hastighedsfunktionen og målte hastigheder og ikke afvigelsen mellem beregnede dybder og målte dybder.

- Er der benyttet brønddata til at konstruere isochore kortene? Alle brøndene?

Svar: Ja, i og med de indgår i dybdekonverteringen og som identifikation af de seismiske horisonter.

- Hvad svarer de tolkede horisonter i figurerne 46, 47, 48 til ?

Svar: Afsnittet omhandler Gassum Formationens placering i forhold til salthorstenes udvikling, og Gassum Formationen er vist på sektionerne. De andre horisonter er hjælpehorisonter, der er medtaget for at gøre det lettere for læseren at genkende salthorstens udvikling. Hjælpehorisonterne illustrerer top og bund af salt, bund primær randsænke og top sekundær randsænke.

Relations between the occurence of potential source rocks and sea-level changes in the Danish Basin and Fennoscandian Border Zone.

- Side 43-44: "at least the two lower levels of organic-rich mudstones in the Fjerritslev Formation seem to correlate very well with the organic-rich shales of the Falciferum and Bifrons Zones of the Posidonian shales" – korrelation af hvad?

Svar: Den sekvensstratigrafiske analyse viser, at det er sandsynligt, at to af de tre påviste stratigrafiske niveauer med organisk-rige lersten indenfor lagene af Toarcien alder i Fjerritslev Fm. kan korrelleres med de organisk-rige skifre, der findes i Falciferum og Bifrons zonerne i Posidonia skiferen. Dette er interessant, fordi Posidonian skiferen er velkendt som værende den bedste nedre jurassiske kildebjergart, den er af regional "europæisk" udbredelse, og dannelsen af de organisk-rige horisonter er knyttet til en regional anoxisk hændelse. M.a.o. taler korrelationen for, at to af de tre "gode" horisonter i Fjerritslev Formationen kan have en regional årsag og dermed stor udbredelse i det danske område.

Distribution of the stratigraphic units with potential source rocks

- Kort visende referede saltdomer:
  - Page 45 Vejrum saltdome
  - Page 46, figure 50 og 51: "This stratigraphic interval probably correlates to a high amplitude seismic reflector in the area around the Vejrum, Sevel, and Mønsted salt domes, which may be interpreted as an indication of organic rich mudstones (figs, 50 – 51)" . Intet kort der viser disse salt domer.

Svar: Der er i alle figurtekster til de viste seismiske eksempler refereret til fig. 54, der viser placeringen af de seismiske eksempler og omtalte boringer, og dermed indirekte viser placeringen af salt domerne. Et omrids af saltdomerne fremgår af dybdekortene.

Afsluttende kommentar: I et projekt som dette, hvor flere forskellige discipliner har indgået og hvoraf nogle er særdeles ressourcekrævende, har det været nødvendigt at prioritere indsatsen indenfor de økonomiske og tidsmæssige rammer, som har været bestemt af bevillingen fra Energistyrelsen. Derfor er valg af analysemetoder og omfanget af de enkelte undersøgelser blevet nøje prioriteret i forhold til de resultater, der blev opnået undervejs i projektet. Det er min opfattelse at dette er blevet gjort så godt, som det har været muligt inden for de givne rammer. Desværre har det ikke været muligt at inkludere analyser af perme kildebjergarter, analyse af mulige kildebjergarter i Farsund bassinet og modellering af saltstrukturernes randsynker. Resultatet af det udførte projekt peger entydigt på, at en succesfuld eksploration af hydrokarboner i Det Danske Bassin og Den Fennoskandiske Randzone er afhængig af forekomst af modne kildebjergarter i præmesoziske lag, modne nedre jurassiske lag i randsynker, eller migration fra Farsund Bassinet eller det Nordtyske Bassin. At resultatet af projektet således ikke umiddelbart er positivt for en yderligere efterforskning i området synes vi heller ikke er opmuntrende, men vi har ikke i data fundet grundlag for en mere optimistisk konklusion.

Med ovenstående svar er eventuelle misforståelser eller uklarheder forhåbentlig afklaret, og det er det min opfattelse, at sagen må betragtes som afsluttet.

Med venlig hilsen,
Torben Bidstrup.

Til
Aksel Mortensgård
Energistyrelsen

Udkast

Vedrørende: EFP projekt 1313/00-0005

Det 10 kontor i Energistyrelsen har følgende kommentarer til afrapporteringen af EFP projektet 1313/00-0005 om "kulbrintepotentialet i det Norsk- Danske Bassin".

I vurderingen af hydrokarbonpotentialet i det Dansk – Norske Bassin er der ikke inkorporeret Felicia-1A boringen. Statoil finder i deres rapport af februar 1988 "Geochemical evaluation of the Statoil Danmark's 5708/18-1 well, Norwegian-Danish Bassin", at de penetrerede Perme sedimenter er modne, men er af dårlig kvalitet. Anschutz som er den nuværende koncessions indehaver har defineret en Rotliegendes moderbjergart med TOC værdier på 1,5% - 4% i Felicia-1A brønden. Det vurderes at udeladelsen af disse afgørende oplysninger fra vurderingen i EFP projektet 1313/00-0005 er en meget alvorlig mangel. Energistyrelsen vurderer at Felicia-1A brønden kan have afgørende indflydelse på studiet, og finder det uforståeligt at brønden ikke er medtaget i EFP projektet.

Energistyrelsen har yderligere samlet en liste af spørgsmål og kommentarer til afrapporteringen, som fremgår af det følgende. Spørgsmål og kommentarer er samlet under de enkelte kapitler af rapporten.

Energistyrelse kan ikke godkende projektet som afsluttet før Felicia-1A brønden er medtaget i studiet, samt at der er taget stilling til de nedenfor listede spørgsmål til rapporten.
Energistyrelsen ønsker yderligere hele projektet afsluttet med en præsentation af resultaterne.

Generelt:

- Figurtekst i liste for sig selv ? Figurteksterne bedes fremgå af figurerne
- Hvad er boringernes alder?
- Er der tidligere foretaget geokemiske / source rock evalueringer (analyser) af området eller brøndene? I projektbeskrivelsen står der : "Gennemføre analyser af hidtil ikke analyseret materiale for at komplimentere eksisterende undersøgelser"
- Er der fundet oil /gas / shows i nogle boringer indikerende at der er en fungerende source rock?
- I " Source rock evaluation of the Danish Bassin and Fennoscandian Border Zone ", bedes sidebladene vise navnene på brøndene.

Depositional development and stratigraphy of the Danish Basin:

Mener GEUS at man på basis af bassin modelleringen beskrevet side 7 fuldstændigt kan udelukke en Paleozorisk source? Hvad med migration?

Sample material and methods:

- Er analyserne foretaget på GEUS – standard? Sammenlignelighed med andre laboratorier?
- I projektbeskrivelsen står der at : "Afhængig af prøvetype og den enkelte prøvetypes relevans vil de anvendte metoder omfatte:
  1. Palynostratigrafiske/palynofacies (datering og kerogen type)
  2. Organisk petrografi / maceralanalyse, vitrinitereflektans (modenhed og kerogentype)
  3. Organisk geokemisk analyse (Rock-Eval pyrolyse, TOC, TS, biomarkers, aktiveringsenergibestemmelser, pyrolyse-GC. IR-spektrometri / IR-mokroskopi, vårpyrolyse, ect.)

Der er kun foretaget TOC og Rock-Eval. Der er ingen beskrivelse af hvorfor intet andet er foretaget?

- Sample interval? Tabel over fordeling af prøver mellem brøndene og i formationerne!
- Side 12: "*The nine S_2 based definitions shows in Enclosure 1 constitute the criteria for evaluation of the source quality*". Hvad er dette baseret på ? Referencer?

Results of the source rock evaluation

- Forståelsen af teksten formindskes stærkt af at resultaterne kun behandles i skreven tekst. Grafiske fremstillinger som kort for de enkelte formationer, der viser de fundne resultater vil give læseren et overblik. Det vil ligeledes give et overblik om TOC og HI evt. kan kontureres.

Seismic Mapping:

- Mangler kort over seismisk database
- Er der ikke brugt brønddata i dybdekonverteringen? Check shot points eller VSP
- Side 25: "It has not been attempted to fit the maps exactely to the well data" Hvad er den største afvigelse? Hvorfor er der ikke gjort et forsøg på dette?
- Liste over estimerede dybder og faktiske dybder i brøndene. Så læseren kan få et indtryk af dybdekonverteringens kvalitet.
- Er der benyttet brønddata til at konstruere isochore kortene? Alle brøndene?
- Hvad svarer de tolkede horisonter i figurerne 46, 47, 48 til ?

Distribution of the stratigraphic units with potential source rocks

- Kort visende referede saltdomer:
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Følgende bedes uddybes

- Rønde-1: Vil konterminerende boremudder (ligesom fluide hydrocarboner) ikke blive brændt af under S1, således at resultater giver en indikation af "source rock" kvaliteten? Er der tilsat Lignite til boremudderet som addiktiv?

- Side 43-44: "at least the two lower levels of organic-rich mudstones in the Fjerritslev Formation seem to correlate very well with the organic-rich shales of the Falciferum and Bifrons Zones of the Posidonian shales" – korrelation af hvad?

Hydrocarbon Potential of the Danish Basin and Fennoscandian Border Zone

List of content

Hydrocarbon Potential of the Danish Basin and Fennoscandian Border Zone

Preface

This report is the final report pertaining to the EFP-2000 project entitled "Kulbrintepotentialet i det Norsk-Danske Bassin". ENS j. nr. 1313/00-0005. The project was carried out in accordance with the proposal that placed focus on the Mesozoic succession.

The report thus integrates the results of geochemical analyses, sequence stratigraphic interpretation and seismic mapping of the Mesozoic succession, and discuss the occurrence of potential source rocks, their maturity, distribution and formation in the Danish Basin and Fennoscandian Border Zone with particular emphasis on the Upper Triassic – Upper Jurassic succession. A brief discussion of the potential of the Palaeozoic succession is included, based on data available from previous work at Geus.

In February 2002 the report: "Source rock evaluation of the Danish Basin and Fennoscandian Border Zone" by Jørgen A. Bojesen-Koefoed and Henrik I. Petersen was forwarded to the Energy Agency. The report contains more than 4,700 screening data (TOC and Rock-Eval pyrolysis data) from 33 selected wells in the Danish Basin, Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform. These data are integrated in this report.

GEUS, December 2002.

Summary

More than 4,700 cuttings samples from the pre-Upper Cretaceous succession in 33 wells widely distributed in the Danish Basin and Fennoscandian Border Zone have been analysed (TOC determination and Rock-Eval pyrolysis). The screening data indicate that the only significant potential source rocks occur within the Toarcian (F-III and F-IV members of the Fjerritslev Formation). The Silurian Nøvling Formation and the Lower–Middle Triassic units in the Rønde-1 well are contaminated with drilling mud additives precluding source rock evaluation. The previously reported high TOC and HI values in the Upper Triassic–Jurassic succession in Felicia-1 are not confirmed by new GEUS analyses. In one well the Gassum Formation shows good potential source rocks; their formation seems to have been dependent on local depositional conditions in rim-synclines. Locally in the Fennoscandian Border Zone occur some good to excellent source rocks in the Frederikshavn Formation (Upper Jurassic–Lower Cretaceous), but burial depth is insufficient for thermal maturation.

The Toarcian potential source rocks occur in distinct and local pods at three different stratigraphic levels. Their formation were related to the well-known regional oceanic anoxic event, basin-wide sea-level fluctuations, and local depressions that favoured primary organic production and preservation possibly facilitated by local brines. Their distribution is further limited by post-depositional erosion related to regional early Middle Jurassic uplift of most of the basin.

An optimistic depth to the oil window is set at 3,250 m (corresponding to 0.6 $\%R_o$) based on numerous vitrinite reflectance data corrected for Late Cretaceous–Early Cenozoic inversion and Late Cenozoic regional exhumation. In all the sections drilled sofar, the burial depth of the Toarcian before uplift was less than 3,250 m. The Toarcian is therefore thermally immature, and has not generated hydrocarbons in the known sections. Seismic mapping support the relatively shallow burial depth in the study area.

It is thus concluded that the absence of mature source rocks is the major risk for successful hydrocarbon exploration in the Danish Basin and Fennoscandian Border Zone. A regional, mature source rock has not been found. Exploration should therefore be directed towards areas where an increased subsidence and/or heat flow have occurred, such as local fault-bounded grabens or rim-synclines developed near salt diapirs.

Introduction

The deeply buried Palaeozoic-Lower Cretaceous succession of the Danish Basin and Fennoscandian Border Zone has been the target for exploration activities since 1935 and about 70 deep wells have been drilled for hydrocarbons, geothermal energy or gas storage in the area (Sorgenfrei & Buch 1964; Thomsen *et al.* 1987; Nielsen & Japsen 1991). A variety of hydrocarbon plays have been tested including structural traps with Rotliegende sandstone, Zechstein carbonate or Triassic sandstone reservoirs sourced by Carboniferous coal beds or Zechstein mudstones or marls. Additional speculative plays may include Cambrian sandstones and carbonates sourced by Lower Palaeozoic shales. The most promising and widely tested play type drilled by more than 30 wells is structures and pinch-outs formed by salt movements or faulting with Upper Triassic–Lower Jurassic or Middle Jurassic fluvial and shallow marine sandstone reservoirs sourced by Lower Jurassic marine shales. So far, the exploration activities have failed since none of the wells drilled north of the Ringkøbing–Fyn High have encountered commercial amounts of hydrocarbons. Based on the results from the activities hitherto it is evident that the main exploration risk is the presence of mature source rocks. The scope of this report is therefore to investigate the hydrocarbon potential of the Danish part of the Norwegian–Danish Basin and Fennoscandian Border Zone and to assess the potential of the identified source rock units in terms of quality, maturation and distribution based on the large number of analysed samples from widely distributed well-sections. The report integrates the results of a geochemical investigation of 33 drilled sections (Bojesen-Koefoed & Petersen 2001) with seismic mapping and sequence stratigraphic interpretation. Main emphasis is placed on the Upper Triassic–Jurassic succession as the most promising potential source rocks occur in the Toarcian section, with potential reservoir sandstones occurring in the Rhaetian–Lower Sinemurian and Middle Jurassic. The sequence stratigraphic development of the succession has been investigated in detail (Nielsen in press), and a description of the geological development of the basin is presented here based on this framework. In addition, an analysis of the relation between the sequence stratigraphic development and the occurrence of intervals with some source rock potential is presented, and the possible regional and local causes for the formation of potential source rock units in the Danish Basin and Fennoscandian Border Zone are discussed.

Tectonic Setting

The Danish part of the Norwegian–Danish Basin corresponds to the Danish Basin (Bertelsen 1978; Michelsen 1978; Nielsen in press), which is roughly synonymous with the Danish Embayment (Sorgenfrei & Buch 1964; Larsen 1966; Michelsen 1975), and the Danish Subbasin (Michelsen 1989a & b). The Danish Basin is an intracratonic, Permian–Cenozoic structure that trends WNW-ESE. It is bounded by basement blocks of the Ringkøbing-Fyn High to the south and by the Fennoscandian Border Zone to the northeast (Figs 1, 2). The border zone demarcates the transition to the stable Precambrian Baltic Shield and includes the Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform (Sorgenfrei & Buch 1964; Baartman & Christensen 1975; EUGENO-S Working Group 1988). The Sorgenfrei-Tornquist Zone forms the northern segment of the Tornquist Zone, which is a long-lived fundamental tectonic feature. It converges with the Teisseyre-Tornquist Zone via the Rønne Graben offshore Bornholm (Rø Gr in Fig.1), where the Danish Basin passes into the Polish Trough. The Sorgenfrei-Tornquist Zone is strongly block-faulted, 30-50 km wide, with tilted Palaeozoic fault blocks unconformably overlain by thick Mesozoic deposits that show pronounced late Cretaceous–early Tertiary tectonic inversion. The Skagerrak-Kattegat Platform is a stable area to the northeast where Mesozoic deposits onlap Lower Permian and Lower Palaeozoic sedimentary rocks and Precambrian crystalline rocks in tilted fault blocks and gradually thins out toward the Baltic Shield.

The deepest regional surface mappable by reflection seismic data in the Danish Basin and Fennoscandian Border Zone is the top pre-Zechstein surface, which is a marked unconformity truncating tilted faults blocks in most of the area (Vejbæk 1989, 1997; Britze & Japsen 1991; Michelsen & Nielsen 1991, 1993; Vejbæk & Britze 1994). The unconformity is penetrated by wells which show the occurrence of Precambrian crystalline rocks on the Ringkøbing-Fyn High (Glamsbjerg-1, Grindsted-1, Jelling-1 and Ibenholt-1 wells) and the Skagerrak-Kattegat Platform (Frederikshavn-1) and lower Palaeozoic sedimentary rocks in the Danish Basin and Fennoscandian Border Zone (Nøvling-1, Rønde-1, Slagelse-1 and Terne-1) (Sorgenfrei & Buch 1964; Poulsen 1969, 1974; Christensen 1971, 1973; Larsen 1971, 1972; Michelsen & Nielsen 1991, 1993; Nielsen & Japsen 1991). The wells cut the unconformity on footwall blocks or on hanging block crests, where deep erosion has occurred, thus making an accurate dating of the rifting impossible. In contrast, the Hans-1 and Sæby-1 wells are located in the deep hanging walls of tilted fault blocks close to the footwall fault (Michelsen & Nielsen 1991, 1993). In Sæby-1 in the Skagerrak-Kattegat Platform the unconformity separates Triassic sediments from syn-rift Rotliegende volcanoclastic rocks (Fig. 2). In the Sorgenfrei-Tornquist Zone, Hans-1 penetrates a pre-rift succession of continental clastic sediments and extrusive volcanic rocks, presumable of Late Carboniferous age, the formation of which preceded the rifting of the basin. A thick Rotliegende syn-rift prism with alluvial conglomerates, sandstones and lacustrine mudstones unconformably overlies this succession. The syn-rift succession is overlain by marginal, non-marine Zechstein deposits. In the nearby Terne-1 well Upper Carboniferous intrusive volcanic rocks occur, and the volcanic rocks in Hans-1 and Terne-1 seem to be roughly contemporaneous with the earliest volcanic rocks in the Oslo Graben and the dolerite dykes in southern Sweden (Bergström *et al.* 1982; Ro *et al.* 1990). The principal phase of rifting of the Danish Basin and Fennoscandian Border Zone thus occurred in Late Carboniferous–Early Permian at the same time as or slightly later, than rifting of the Oslo Graben (Ro *et al.* 1990; Michelsen & Nielsen 1991, 1993).

The tilted fault block crests are deeply truncated by the mid-Permian unconformity showing that regional post-rift thermal subsidence was somewhat delayed (Vejbæk 1997). The unconformity defines the base of the post-rift succession which consist of a relatively complete succession of Upper Permian, Mesozoic and Cenozoic deposits that is ca. 5-6.5 km thick along the basin axis and more than 9 km locally in the Sorgenfrei-Tornquist Zone and Himmerland Graben (Fig. 2). Isocore maps of the Triassic and Jurassic–Lower Cretaceous successions show a relatively uniform regional thickness in most of the basin, except for areas influenced by local halokinetic movements, indicating relatively uniform thermal subsidence (Vejbæk 1989, 1997; Britze & Japsen 1991; Japsen & Langtofte 1991). Although the thick Upper Permian–Triassic succession indicates rapid subsidence that exceeds normal thermal contraction, a prolonged or new rifting phase is precluded by the general lack of pronounced extensional faulting in the Mesozoic succession (Vejbæk 1989, 1997). The evaporitic and continental facies show that the basin was never under-filled or starved, and phase-transformations in the deep crust have been proposed to explain the rapid early post-rift subsidence (Vejbæk 1989). Transtensional strike-slip movements in the Sorgenfrei-Tornquist Zone and large-scale salt-movements facilitated the formation of thick Mesozoic deposits in the Himmerland Graben and Fjerritslev Trough (Vejbæk 1989; Christensen & Korstgård 1994; Mogensen 1996). Minor down-to-basin fault displacements occurred locally along the southern basin margin at the northern flank of the Ringkøbing–Fyn High. The thermal subsidence continued into Late Triassic–Early Jurassic time, and the major part of the basin experienced relatively uniform subsidence until the early Middle Jurassic time when uplift completely changed the configuration of the basin (Michelsen 1978; Koch 1983; Nielsen 1995, in press). The Ringkøbing-Fyn High, most of the Danish Basin, the Skargerrak-Kattegat Platform and parts of southern Sweden was uplifted and subjected to deep erosion. Only the Sorgenfrei-Tornquist Zone experienced slow subsidence. Southwest of this zone, the erosional unconformity, the "Base Middle Jurassic Unconformity" shows a progressively deeper truncation toward the Ringkøbing-Fyn High where the Lower Jurassic is deeply truncated (Fig. 3A). On the high the truncation reach into the Triassic succession. In late Middle–early Late Jurassic time subsidence gradually took over again and became more widespread as shown by a progressively younger Upper Jurassic–Lower Cretaceous onlap to the unconformity toward the Ringkøbing-Fyn High (Fig. 3B). A rather uniform succession of chalk, locally up to 2 km thick was deposited on the Ringkøbing-Fyn High, in the Danish Basin and the Fennoscandian Border Zone in Late Cretaceous–Danian time. Late Cretaceous–Early Cenozoic phases of tectonic inversion occurred especially in the Sorgenfrei-Tornquist Zone (Fig. 2), and later a more regional phase of Late Cenozoic uplift and exhumation influenced most of the Danish Basin and the Fennoscandian Border Zone with the largest uplift occurring in the northeastern part of the area (Japsen 1993; Michelsen & Nielsen 1993; Japsen & Bidstrup 1999).

A general shallowing of the basin toward the Ringkøbing-Fyn High is indicated by thinning of the Zechstein–Lower Jurassic and Upper Jurassic–Lower Cretaceous successions although the erosion at the base of the Middle Jurassic and the Cretaceous have obscured the original distribution of the Triassic–Lower Jurassic on the high. The high was probably formed at the same time as the Danish Basin as an area of less stretching (Vejbæk 1997). Marginal facies were developed in Late Permian time along the high, which probably formed a barrier between the Southern and Northern Zechstein basins (Ziegler 1982; Stemmerik *et al.* 1987). In Late Triassic–Early Jurassic time, the high became flooded during periods of high sea-level (Bertelsen 1978; Michelsen 1975, 1978; Nielsen *et al.* 1995). In Middle Jurassic time the high was uplifted and eroded.

Depositional development and stratigraphy of the Danish Basin

Palaeozoic rocks

The fill of the Danish Basin *sensu stricto* comprises the Upper Permian–Cenozoic succession, which unconformably overlies Precambrian crystalline rocks and tilted fault blocks of mainly Lower Palaeozoic sedimentary rocks. The Lower Palaeozoic includes Cambrian-Ordovician sandstones, shales and carbonates, and Silurian shales, siltstones and extrusives (Fig. 4) (Sorgenfrei & Buch 1964; Poulsen 1969, 1974; Christensen 1971, 1973; Michelsen & Nielsen 1991, 1993). The Middle Cambrian–Early Ordovician Alum Shale Formation forms an excellent source rock in the Baltic region including onshore Sweden. The formation is known from tilted fault blocks in the Danish Basin and Sorgenfrei-Tornquist Zone, and from outcrops and shallow wells on Bornholm (Poulsen 1974; Pedersen 1989; Michelsen & Nielsen 1991). However, in the area covered by the Danish Basin these sediments are deeply buried, and maturation modelling indicates that the main hydrocarbon generation occurred prior to or contemporaneously with the Late Carboniferous rifting phase that formed many of the structural traps (Thomsen *et al.* 1987; Andersen & Doyle 1990). Devonian rocks are not present in the area, and Carboniferous coal measures that are well known as source rocks south of the Ringkøbing-Fyn High have not been found north of the high. In contrast, the regional crustal stretching and dextral strike-slip movements along the Tornquist Zone caused formation of extrusive and intrusive Upper Carboniferous rocks, tilting of numerous fault blocks and deposition of thick syn-rift wedges comprising Lower Permian alluvial conglomerates and sandstones and lacustrine shales virtually without organic matter (Fig. 4) (Michelsen & Nielsen 1991, 1993).

Upper Permian–Lower Cretaceous basin-fill

Possible phase transformations in the deep crust and post-rift cooling caused rapid regional subsidence in Late Permian–Early Triassic time (Vejbæk 1989, 1990). The Danish Basin and parts of the Sorgenfrei-Tornquist Zone were transgressed in the Late Permian, and up to 2–3 km of salt and carbonate deposits belonging to the Zechstein Group were formed central in the basin, showing a pronounced thinning toward the Ringkøbing-Fyn High and the northern and eastern basin margin (Sorgenfrei & Buch 1964; Vejbæk 1997). A thin Zechstein succession of shallow-marine and continental clastics, less than 125 m was deposited along the basin margin in the Sorgenfrei-Tornquist Zone (Michelsen & Nielsen 1991). During Early–Middle Triassic time several kilometres of dominantly continental strata were deposited in a hot and arid climate, and these deposits are grouped into the Bunter Shale, Bunter Sandstone, Ørslev, Falster, Tønder and Oddesund formations (Fig. 4) (Bertelsen 1980).

In the Danish Basin, the Bunter Shale Formation forms an up to 200 m thick succession of claystones interbedded with siltstones, sandstones and occasionally thin dolomites, anhydrites and oolitic limestones. Deposition occurred in flat coastal plains, sabkhas and shallow lakes in a oxidising, semi-arid to arid climate. The overlying Bunter Sandstone Formation mainly consists of medium to fine-grained, well sorted sandstones with intraformational claystone clasts (Bertelsen 1980; Pedersen & Andersen 1980). The thickness of the formation varies from more than 900 m thick in northern Jylland (Mors-1) to 200 m in western Sjælland and in the Øresund region. In general, the formation shows a pronounced thinning toward the Ringkøbing-Fyn High, and it is thin or absent on the high and the Stevns Block. The sand was supplied from the Baltic Shield, and was mainly deposited in distal ephemeral braided fluvial channels in a dry dessert environment. Eolian dune sand and lacustrine clay deposited in short-lived lakes constitutes minor proportions of the formation. Toward the northern and north-eastern basin margin it passes into coarser-grained, alluvial deposits of the lower Skagerrak Formation. The Skagerrak Formation comprises interbedded conglomerates, sandstones, siltstones and claystones that mainly occur along the northern and north-eastern margin of the Norwegian-Danish Basin. These deposits are of Early–Late Triassic age and were mainly deposited as alluvial fans along the faulted basin margin. As mentioned above the lower part of the formation is probably contemporaneous with the Bunter Sandstone Formation, while the middle part is contemporaneous with the Ørslev, Falster, Tønder and Oddesund Formations that mainly occur centrally in the basin.

The Ørslev Formation is typically 100–200 m thick and consists mainly of dolomitic limestones interbedded with claystones and marls grading upward to silty mudstones. The formation was deposited in continental sabkhas (Bertelsen 1980). The Falster Formation is typically 100–200 m thick and consists of a lower unit of interbedded claystones and limestones overlain by a middle unit of claystones with thin anhydrite beds, which is topped by an upper unit of claystones with thin beds of dolomitic limestones and anhydrite. The deposition occurred mainly in a shallow marine sea (lower unit) that developed into an extensive sabkha (middle unit), which later was replaced by shallow-brackisk marine conditions (upper unit). The formation corresponds to the German Muschelkalk Formation (Bertelsen 1980). The overlying Tønder Formation is up to 300 m thick in the Danish Basin and consists of interbedded claystones, siltstones and sandstones that were deposited on a flat coastal plain with increasing fluvial activity toward the north. Dessiminated plant material occur in places and indicate hinterland vegetation. The Oddesund Formation is up to 1500 m thick in wells, but shows large variations due to movements of the Zechstein salt during deposition. The formation consists of claystones and siltstones with thin beds of dolomite and marlstones; two prominent units of halite occur central in the basin. To the north siltstones and sandstones occur between the halites. Deposition occurred in brackish to hypersaline environments such as periodically flooded sabkhas and emphemerale lakes along the basin margin whereas more permanent lakes dominated the more rapidly subsiding basin center. Reworking of Zechstein salt plugs may have contributed to the formation of the evaporites.

A gradual change from arid conditions toward more humid took place in the Late Triassic partly due to formation of a large epicontinental sea (Bertelsen 1978, 1980; Parrish *et al.*, 1982; Ziegler 1982; Hallam 1984, 1985; Scotese 1994; Batten *et al.* 1994). Carnian deposition of lacustrine and sabkha mudstones was terminated by the Early Norian marine transgression. A shallow, restricted marine environment was established in central parts of the basin where deposition of oolitic limestones was succeeded by marlstones and fossiliferous claystones of the Vinding Formation, 40–100 m thick and locally up to 200 m (Fig. 4) (Bertelsen 1978, 1980; Nielsen & Japsen 1991; Nielsen in press). Concurrently, alluvial arkosic sandstones and lacustrine claystones of the upper Skagerrak Formation were deposited in the northern and northeastern, marginal parts of the basin. The uppermost Norian–Lower Sinemurian Gassum Formation overlies the Skagerrak Formation along the basin margin, and interfingers with the upper part of the Vinding Formation in the deep part of the basin (Bertelsen 1978; Nielsen *et al.* 1995). The thickness varies from 50-150 m in the central part of the basin to more than 300 m locally in the Sorgenfrei-Tornquist Zone, and the formation consists of interbedded fine to medium-grained, occasionally coarse-grained and pebbly sandstones, heteroliths, mudstones and few thin coaly beds (Bertelsen 1978; Michelsen & Nielsen 1991). An overall fluvio-deltaic, deltaic to tidally-influenced shallow-marine environment has been proposed (Larsen 1966; Bertelsen 1978; Nielsen *et al.* 1989). The presence of several regressive shoreface sandstones of wide lateral distribution shows, however, that the formation was formed under influence of repeated sea-level fluctuations and not by simple deltaic progradation (Hamberg *et al.* 1992;

Nielsen *et al.* 1995; Hamberg & Nielsen 2001; Nielsen in press).

A subtropical to warm-temperate and humid climate characterised the Jurassic period, and large quantities of clay were supplied to the basin from the weathering of Palaeozoic shales, granitic basement of the Baltic Shield and a possible Carboniferous regolith (Ziegler 1982; Pedersen 1983; Schmidt 1985; Norling & Bergström 1987; Nielsen & Koppelhus 1991, Surlyk *et al.* 1995). The basin expanded northeastward against the Baltic Shield during Early Jurassic time owing to the combined effect of eustatic sea-level rise, regional subsidence and local block-faulting caused by transtensional strike-slip movements in the Sorgenfrei-Tornquist Zone (Gravesen *et al.* 1982; Norling & Bergström 1987; Surlyk *et al.* 1995; Nielsen 1995; Mogensen 1996). The Gassum Formation is overlain by the Lower Jurassic Fjerritslev Formation, which is dominated by marine mudstones containing ammonites, bivalves, foraminifers, ostracods and dinoflagellate cysts (Nørvang 1957; Larsen 1966; Michelsen 1975; Pedersen 1986). The formation is subdivided in to four members, F-I (lower), F-II, F-III and F-IV (upper) of which F-I is further divided in to F-Ia (lower) and F-Ib, which both are widely recognised (Fig. 4) (Michelsen 1978, 1989a,b; Michelsen *et al.* in press). F-II is further divided into F-IIa (lower), F-IIb and F-IIc in some wells (Michelsen 1989a,b). The formation shows very variable thickness due to erosional truncation of the upper part in the southwestern and central parts of the basin and above salt structures; a maximum thickness of more than 1000 m is reached in the fault-bounded Fjerritslev Trough (Fig. 1). The formation covers the Early Jurassic time interval, and includes also mudstones of latest Rhaetian and Early Aalenian age (Dybkjær 1991; Michelsen & Nielsen 1991; Poulsen 1996). The transition from the Gassum Formation to the Fjerritslev Formation occurred in several steps ranging from latest Rhaetian in the central parts of the basin to Early Sinemurian at the northeastern margin reflecting the overall Early Jurassic eustatic sea-level rise (Bertelsen 1978; Dybkjær 1991; Michelsen 1978, 1989b; Hallam 1988, 1997; Michelsen & Nielsen 1991; Nielsen 1995, in press).

The Haldager Sand Formation erosionally overlies the Fjerritslev Formation and consists of fine to very coarse-grained, occasionally pebbly sandstones, siltstones, mudstones and coaly beds (Michelsen 1978, 1989a; Koch 1983). Koch (1983) proposed a general braided fluvial to deltaic depositional environment. The formation is absent on and along the Ringkøbing-Fyn High and is thin and patchy in large parts of the basin except for rim-synclines close to salt structures (e.g. Mors-1, Thisted-3; Fig.1). In the southwestern part of the basin, it consists of fine- to coarse-grained fluvial sandstones, 1-10 m thick, and thickens to more than 150 m towards the northeast in the Sorgenfrei-Tornquist Zone, where the formation includes paralic, estuarine and shallow-marine sandstones, mudstones and coaly beds (Nielsen in press). Dating of the formation is generally poor giving a broad Middle Jurassic age (Michelsen 1978, 1989a; Michelsen & Nielsen 1991; Poulsen 1992a, 1996). Transgressive paralic-marine mudstones and sandstones of the Oxfordian Flyvbjerg Formation, which shows roughly the same distribution as the Haldager Sand Formation, overlie the formation. An increased enlargement and deepening of the basin is reflected by the change to the overlying Kimmeridgian–Ryazanian marine mudstones of the Børglum Formation and the Volgian–Ryazanian marine to paralic siltstones, sandstones and mudstones and thin coaly beds of the Frederikshavn Formation that overstep the limits of the Flyvbjerg Formation (Michelsen 1978, 1989a; Michelsen & Nielsen 1991; Poulsen 1996).

The Lower Cretaceous Vedsted Formation consists mainly of marine mudstones with minor proportions of siltstones and sandstones, that increase in abundance toward the northeastern basin margin, where few non-marine intervals maybe present as well (Sorgenfrei & Buch 1964; Larsen 1966).

Source rock evaluation of the drilled successions

Sample material and methods

The hydrocarbon generative potential and the thermal maturity of the pre-Upper Cretaceous succession in 33 wells drilled in the Danish Basin, the Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform have been evaluated (Fig. 1). The majority of the wells are located onshore in the Danish Basin between the Ringkøbing Fyn High to the south and the Fjerritslev Fault to the north; the Fjerritslev Fault demarcates the boundary of the Sorgenfrei-Tornquist Zone with the Danish Basin (Fig. 1). However, two wells are located in the Sorgenfrei-Tornquist Zone in Kattegat and six wells are situated offshore in the western part of the Danish Basin. The penetrated pre-Upper Cretaceous strata are mainly of Early Cretaceous, Jurassic and Triassic age, but in a number of wells Permian and pre-Permian rocks were drilled.

A total of 4700 cuttings samples were analysed for total organic carbon (TOC, wt.%) content by combustion in a LECO induction furnace and for source quality by Rock-Eval pyrolysis (T_{max}, °C; S_1 and S_2 yields, mg HC/g rock; calculated Hydrogen Index (HI), mg HC/g TOC). All raw data from these screening analyses are tabulated for each well in Bojesen-Koefoed and Petersen (2001), which also includes a CD with the raw data presented in a spreadsheet.

Except for elimination of obviously flawed data, no data treatment has been carried out. Average and maximum S_2 yields have been used to assess the source rock potential of the different formations, and the nine S_2-based definitions shown in Enclosure 1 constitute the criteria for evaluation of the source rock quality. This approach may in cases lead to some ambiguity, in particular if compared to calculated HI values. Utilisation of other information is therefore recommended in order to optimise the utility of the Rock-Eval data. For example, based on the source quality criteria listed in Enclosure 1 the Haldager Sand Formation appears in several wells to constitute a good petroleum source rock. However, this upgrading of the source potential of this sandstone dominated formation results from selective sampling of mudstones and the selective loss of sandy lithologies, which commonly occurs when sampling drill cuttings from poorly consolidated sandy and heterolithic strata. Concentration of the coaly and muddy lithologies will artificially increase the source potential.

Results of the source rock evaluation

In the following the source rock potential of the drilled formations are considered in stratigraphic order, starting with the oldest strata.

Pre-Permian units. Pre-Permian strata have been encountered in seven of the investigated wells, but data are only available from five of them (Encl. 1). In the Rønde-1 well the Silurian Nøvling Formation has high average and maximum TOC contents (2.76 wt.% and 33.92 wt.%, respectively) and high S_1 and S_2 yields (up to 108 mg HC/g rock and 40.52 mg HC/g rock, respectively). These deep strata are, however, contaminated by various drilling mud additives, such as diesel, "Black Magic®", and starch-based mud, which precludes assessment of their source potential. In the other wells no source potential is present.

Permian units. The Zechstein and Rotliegende groups are present in eight wells, but from two of the wells no data are available (Encl. 1). No source potential has been observed in any of the analysed well sections. High TOC contents and S_1 and S_2 yield in the Rotliegende Group in the Nøvling-1 well are, as discussed above, an artefact caused by drilling mud additives.

Lower and Middle Triassic units. Lower Triassic strata have been encountered in eight wells, but data are only available from four of them (Encl. 1). None of these deposits have a hydrocarbon generative potential, and similar to the older succession in the Rønde-1 well, the Lower Triassic data are obscured by contamination by oil-based drilling muds in this well. The Middle Triassic was also drilled in eight wells (seven are the same wells penetrating the Lower Triassic); the strata do not possess a source potential in any of the wells.

Upper Triassic units. In contrast to the Lower and Middle Triassic strata, the Upper Triassic succession has been encountered in 32 of the studied wells, however, not all of the Upper Triassic formations are present in all of the wells (Encl. 1). Only Haldager-1 was terminated in Lower Jurassic strata. The Upper Triassic Oddesund Formation in the Rønde-1 and Voldum-1 wells has a marginal source potential in parts of the succession, where the maximum HI values reach 501 and 317 mg HC/g TOC, respectively; however, the average HI values of the formation in the two wells are only 85 and 148 mg HC/g TOC. The Vinding Formation has a minor source potential in the Nøvling-1 and Slagelse-1 wells, whereas in the Mejrup-1 well a good source potential has been observed in parts of the formation (Encl. 1). There, a maximum S_2 yield of 8.57 mg HC/g rock (average S_2: 1.13 mg HC/g rock) and a maximum HI of 697 mg HC/g TOC (average HI: 181 mg HC/g TOC) was recorded. The Skagerrak Formation is generally a poor source rock, and only a very limited source potential (maximum S_2: 4.52 mg HC/g rock;

maximum HI: 107 mg HC/g TOC) has been registered in the Sæby-1 well.

Apart from the C-1 well, where the formation is absent, and the Haldager-1 well, which was terminated in the Lower Jurassic, the diachronous Upper Triassic to Lower Jurassic Gassum Formation has been penetrated by all other wells (Encl. 1). In the Felicia-1 well a single sample with a TOC content of 6.58 wt.%, a S_2 of 13.29 mg HC/g rock and a HI of 202 mg HC/g TOC suggest a generative potential in a very restricted interval. The average HI is only 49 mg HC/g TOC. In the Hans-1 well the average TOC content of the Gassum Formation is 3.01 wt.%, and the maximum content reaches 22.08 wt.%. S_2 yields reach a maximum of 38.65 mg HC/g rock and the HI has a maximum of 175 mg HC/g TOC. Despite these maximum values, the average HI of the formation is only 63 mg HC/g TOC, suggesting a principally terrestrial origin of the organic matter (probably a combination of kerogen types III and IV). However, according to the criteria used in this context a restricted stratigraphic interval in the formation possesses an excellent source potential. The Gassum Formation in the Mejrup-1 well possesses a marginal to good source potential. The TOC content reaches a maximum of 2.76 wt.% and the average TOC content is 1.11 wt.% (Fig. 5). The average S_2 yield is 2.22 mg HC/g rock with a maximum of 11.00 mg HC/g rock, and the average HI value is182 mg HC/g TOC, reaching a maximum value of 534 mg HC/g TOC. In addition to the Felicia-1, Hans-1 and Mejrup-1 wells discussed above, a number of wells in middle and northern Jylland possess a marginal generative potential in parts of the Gassum Formation (Encl. 1).

Lower Jurassic units. The Lower Jurassic Fjerritslev Formation has, apart from in the C-1 well, been encountered in all investigated wells. The four members of the formation (F-I, F-II, F-III and F-IV) are, however, not present in every well (Encl. 1).

The lowermost F-I Member possesses a generative potential in four wells, with the best source potential found in the Mejrup-1 and Skagen-2 wells, and a more overall marginal potential present in the Sæby-1 and Års-1 wells. In Mejrup-1 the maximum TOC content is 2.39 wt.% (average TOC: 0.86 wt.%), and maximum S_2 yields and HI values reach 9.83 mg HC/g rock and 411 mg HC/g TOC, respectively (Fig. 5). Average S_2 yields of 0.70 mg HC/g rock and an average HI of only 71 mg HC/g TOC indicate, however, that the good source potential only is restricted to parts of the member. The F-I Member in the Skagen-2 well has a maximum TOC content of 3.45 wt.% (average 1.49 wt.%), a maximum S_2 yield of 9.38 mg HC/g rock and a maximum HI value of 272 mg HC/g TOC. Although the average S_2 and HI values are higher than in Mejrup-1, namely 2.88 mg HC/g rock and 132 mg HC/g TOC respectively, the overall source potential is still restricted. Average HI values of 111 and 155 mg HC/g TOC recorded for the F-I Member in the Sæby-1 and Års-1 wells also stress the marginal source potential in these wells.

A good source potential is more common in the F-II Member. A good to excellent generative potential has been recorded in the Hobro-1 well, whereas parts of the member have a good source potential in the Hyllebjerg-1 well (Encl. 1). In Hobro-1 the F-II Member has a maximum TOC content of 5.36 wt.% (average TOC content of 2.41 wt.%) and a maximum S_2 yield of 18.20 mg HC/g rock, with an average S_2 yield of 6.89 mg HC/g rock. The generally good source rock potential is emphasised by a maximum HI value of 340 mg HC/g TOC and an average HI of 185 mg HC/g TOC. In the Hyllebjerg-1 well the average TOC content and S_2 yields are 1.08 wt.% and 1.45 mg HC/g rock, respectively. The average HI is 128 mg HC/g TOC, but a maximum HI value of 321 mg HC/g TOC shows that parts of the F-II Member possesses a good source potential in this well (Fig. 6). In the Farsø-1, J-1, Mors-1, Rønde-1, Vested-1 and Års-1 wells the F-II Member has a very limited source potential.

The overlying F-III Member is in general a moderately good source rock, and in some wells it is an excellent source rock. This is the case for the Kvols-1 and Rønde-1 wells, where the generative potential is determined to be good to excellent (Figs 7 & 8; Encl. 1). The maximum TOC content is 3.92 wt.% (average TOC: 1.68 wt.%) and the maximum S_2 yield is 20.75 mg HC/g rock (average S_2 yield: 5.20 mg HC/g rock) in the Kvols-1 well. The excellent generative potential is emphasised by a maximum HI of 529 mg HC/g TOC and an average HI of 230 mg HC/g TOC (Fig. 7). Similar to the Kvols-1 well, the Rønde-1 well contains a petroleum-prone F-III Member (Fig. 8). The TOC content does not exceed 2.95 wt.% in the member in this well, and the average S_2 yield and HI value for the F-III Member are 3.38 mg HC/g rock and 174 mg HC/g TOC, respectively. However, the maximum S_2 yield and HI value reach 12.62 mg HC/g rock and 428 mg HC/g TOC, respectively. Apart from the good source potential in these two wells, parts of the F-III Member possesses a marginal to good ability to generate hydrocarbons in numerous wells (Børglum-1, Farsø-1, Felicia-1, Fjerritslev-2, Frederikshavn-2, Haldager-1, Hobro-1, Hyllebjerg-1, J-1, Mors-1, Terne-1, Voldum-1, Års-1; Encl. 1). Particularly, in the Farsø-1 well the maximum S_2 yields and HI value are 8.72 mg HC/g rock and 298 mg HC/g TOC, respectively, whereas the corresponding average values are 4.42 mg HC/g rock and 214 mg HC/g TOC. The J-1 well shows a maximum HI value of 303 mg HC/g TOC, whereas the average HI amounts to 184 mg HC/g TOC. The S_2 yields do not exceed 6.22 mg HC/g rock and the average yield is 2.68 mg HC/g rock. In the Frederikshavn-2 well the maximum S_2 yields amount to 7.15 mg HC/g rock, but the maximum HI obtained from the F-III Member is only 108 mg HC/g TOC. In contrast, the maximum S_2 yields in the Haldager-1 well is 5.83 mg HC/g rock (average S_2: 1.69 mg HC/g rock), but due to a maximum TOC content of only 1.67 wt.% the HI value reaches 425 mg HC/g TOC (average HI for the member is 169 mg HC/g TOC). In the Hyllebjerg-1 and Mors-1 wells the maximum S_2 yields are around 4 mg HC/g rock, and the maximum HI values are 257 and 266 mg HC/g TOC, respectively. Average S_2 yields just below 3 mg HC/g rock and HI values just above 200 in both wells indicate a uniformly distributed moderate source potential of the F-III Member in these wells. All the other wells may have a maximum HI value above 200 mg HC/g TOC, but the average values are low. Likewise the maximum S_2 yields range from only 2.13 to 3.86 mg HC/g rock.

Similar to the underlying F-III Member, the uppermost F-IV Member has an overall moderate source potential with a good to excellent potential in a few wells, namely the Børglum-1 and Rønde-1 (Fig. 8, Encl. 1). The former well has a maximum TOC content of 29.75 wt.% (average TOC: 4.07 wt.%) and maximum S_2 yields of 32.21 mg HC/g rock (average S_2: 3.10 mg HC/g rock). The maximum HI value is 161 mg HC/g TOC, and the average HI only 44 mg HC/g TOC. However, due to the S_2-based quality criteria used in this context, the source potential is determined to be good to excellent. The F-IV Member of the Rønde-1 well is an excellent source rock. The TOC content is generally high, having a maximum value of 5.81 wt.% and averaging 3.58 wt.%. S_2 yields reach a maximum of 31.56 mg HC/g rock and the average yields are as high as 16.09 mg HC/g rock. This results in a maximum HI value of 543 mg HC/g TOC and an average HI of 435 mg HC/g TOC (Fig. 8). A marginal to good source potential is registered in the Hyllebjerg-1, Mors-1, Skagen-2 and Sæby-1 wells (Encl. 1). In particular, the Hyllebjerg-1 well shows a marginal to good generative potential. The average TOC content is 1.20 wt.% (maximum: 1.94 wt.%), and the maximum S_2 yields and HI value are 7.20 mg HC/g rock and 371 mg HC/g TOC, respectively, and the corresponding average values are 2.47 mg HC/g rock and 194 mg HC/g TOC. The Mors-1, Skagen-2 and Sæby-1 wells have average S_2 yields from 1.96–3.53 mg HC/g rock and maximum S_2 yields from 6.20–11.23 mg HC/g rock. However, average HI values range only from 60–103 mg HC/g TOC, although in the Sæby-1 well the maximum HI value is 261 mg HC/g TOC. Also, in the Sæby-1 well the average TOC content is rather high, 3.12 wt.% (maximum: 9.17 wt.%). Five wells (Fjerritslev-2, Frederikshavn-2, Hobro-1, Kvols-1, Års-1) contain a restricted generative potential in parts of the F-IV Member (Encl. 1). In these wells the average TOC contents are ranging from 0.93–1.42 wt.% and the average S_2 yields range from 0.39–1.28 mg HC/g TOC. Maximum S_2 yields are not exceeding 4.71 mg HC/g rock in any of the wells. Average HI values range from only 19–103 mg HC/g TOC, but in the Hobro-1 and Kvols-1 wells maximum HI values of 215 and 211 mg HC/g TOC have been recorded.

Relatively high HI and TOC values recorded by Geochem in the Felicia-1 well, in particular in the F-II and F-III members, could not be confirmed by re-analysis of numerous samples by GEUS (Nielsen *et al.*, 2000). The Geochem data are above the regional trend, and the high values are probably caused by contamination from oil-based mud. The GEUS data do not indicate a source potential of the Fjerritslev Formation in Felicia-1.

Middle Jurassic units. Based on the criteria used in this study, the Middle Jurassic Haldager Sand Formation constitute an excellent source rock in the Terne-1 well (Fig. 9; Encl. 1; note comments on the Haldager Sand Formation in the "Sample material and methods" section, and discussion below). The mean TOC content is 10.31 wt.%, and the maximum value 25.63 wt.%. Likewise average S_2 yields are high, 25.27 mg HC/g rock, with a maximum S_2 yield of 65.59 mg HC/g rock. Combined with the high TOC contents, however, the HI values only average 191 mg HC/g TOC (maximum HI of 262 mg HC/g TOC). A marginal to good generative potential is noted for the Fjerritslev-2, Haldager-1 and Vedsted-1 wells (Encl. 1). In particular the Haldager-1 well possesses a very good potential in a narrow interval within the formation: the TOC content is 1.29 wt.%, S_2 yields are 8.22 mg HC/g rock and the HI value is 637 mg HC/g TOC. Average TOC, S_2 and HI values of the Haldager Sand Formation in the well are only 0.38 wt.%, 0.98 mg HC/g rock and 157 mg HC/g TOC, respectively. The two other wells, Fjerritslev-2 and Vedsted-1, have maximum S_2 yields of 7.29 and 6.50 mg HC/g rock, respectively, and average S_2 yields of 2.97 and 1.45 mg HC/g rock. The average HI values, however, are low, namely 88 mg HC/g TOC for Fjerritslev-2 and 47 mg HC/g TOC for Vedsted-1. A maximum HI value of only 143 mg HC/g TOC is recorded in the former well. Several wells (Børglum-1, F-1, Flyvbjerg-1, Hobro-1, J-1, Mors-1, Skagen-2, Sæby-1; Encl. 1) possess a marginal source potential and generally only in parts of the formation. Apart from the F-1 well, where the mean TOC content is 3.43 wt.%, the average TOC content of these wells range from 1.43–2.45 wt.%. In general, maximum TOC contents are <5 wt.%. Average S_2 yields are mainly between 1.05 and 1.69 mg HC/g rock, and the average HI values range from 38–100 mg HC/g TOC, except for the J-1 well where it is 159 mg HC/g TOC.

Upper Jurassic units. The Flyvbjerg and Børglum formations possess only a limited source potential in parts of the successions in a few wells (Encl. 1). In the Skagen-2 well the upper part of the Flyvbjerg Formation shows S_2 yields of 5.82 mg HC/g rock and HI values up to 318 mg HC/g TOC indicating a source potential in a very restricted interval. The Flyvbjerg Fm in the Terne-1 well has a quite high average TOC content (2.27 wt.%), but the average S_2 yield is only 1.65 mg HC/g rock and the average HI value only 70 mg HC/g TOC, with a maximum HI value of 84 mg HC/g TOC. This indicates a very limited generative potential. Although the Børglum Formation in the Fjerritslev-2 well shows a maximum S_2 yield and HI value of 4.82 mg HC/g rock and 155 mg HC/g TOC, respectively, average values of only 1.18 mg HC/g rock and 51 mg HC/g TOC indicate an overall very poor generative capacity. In the Voldum-1 well a single sample from the Børglum Formation suggests a marginal source potential (TOC 1.48 wt.%; S_2: 2.22 mg HC/g rock; HI: 150 mg HC/g TOC). In contrast to the Flyvbjerg and Børglum formations, a good to excellent source potential has been recorded in the Frederikshavn Formation in a couple of wells, namely Skagen-2 and Terne-1 but in particular in the latter (Encl. 1). The average TOC content of the Frederikshavn Formation in Terne-1 is 4.39 wt.%, and the maximum value reach 13.85 wt.%. Average S_2 yields are 23.78 mg HC/g rock and maximum yields as high as 80.24 mg HC/g rock. This results in a high average HI value of 471 mg HC/g TOC and an exceptional high maximum HI value of 1125 mg HC/g TOC (Fig. 9). Overall this classifies the Frederikshavn Formation in the Terne-1 well as an extraordinarily good source rock. The Skagen-2 well has a mean S_2 yield of 2.20 mg HC/g rock, the maximum S_2 yield reaching 11.28 mg HC/g rock. The average HI value is 151 mg HC/g TOC with a maximum value of 346 mg HC/g TOC. However, TOC contents may be very low (average TOC content of 1.01 wt.%) and some of the higher HI values may to some extent be 'artificial' due to these low values. A good source potential is recorded in parts of the Frederikshavn Formation in the Gassum-1 well (Encl. 1). Maximum S_2 yields reach 8.63 mg HC/g rock (average S_2: 1.74 mg HC/g rock) and the maximum HI value is 378 mg HC/g TOC (average HI only 120 mg HC/g TOC). A few wells, Hyllebjerg-1, Sæby-1 and Voldum-1, contain a marginal source potential, mainly only in parts of the Frederikshavn Formation. The Hyllebjerg-1 and Sæby-1 wells have average S_2 yields and HI values of 0.94 and 0.73 mg HC/g rock and 110 and 69 mg HC/g TOC, respectively. The mean TOC contents are <1 wt.% and the maximum recorded content is 1.71 wt.%. The Voldum-1 well has an average S_2 yield and HI value of 2.08 mg HC/g rock and 178 mg HC/g TOC, respectively, and maximum values of 5.71 mg HC/g rock and 348 mg HC/g TOC are recorded. These data suggest a marginal source potential of the formation.

Discussion of the regional hydrocarbon generation potential and maturity

No source potential has been detected in the pre-Permian and Permian units penetrated in the Danish Basin and the Fennoscandian Border Zone. The high source potential recorded in the Rønde-1 well is artificial and caused by contamination by various drilling mud additives.

Similarly, the Lower Triassic in the Rønde-1 well is contaminated by oil-based drilling mud and source rock data are therefore obscured. In none of the other wells, where the Lower and Middle Triassic have been encountered, these strata possess a source potential. Upper Triassic units were drilled in all studied wells apart from the Haldager-1 well. Strata of the Upper Triassic Oddesund and Vinding formations have a marginal source potential in only four wells, whereas a single well (Mejrup-1) possesses a good generative potential in parts of the Vinding Formation. In contrast the Skagerrak Formation is generally a poor source rock in the study area. The Upper Triassic to Lower Jurassic Gassum Formation represents the first unit with a more widely distributed source potential, however, the generative capacity is mainly marginal. In a few wells, Felicia-1 and Hans-1, a better generation potential is indicated in a restricted part of the formation by for example maximum HI values of 202 and 175 mg HC/g TOC, respectively. The best overall source potential of the Gassum Formation is observed in the Mejrup-1 well, where the average HI is 182 mg HC/g TOC and a maximum value of 534 mg HC/g TOC is recorded (Fig. 5). These results indicate that in the Danish Basin and Fennoscandian Border Zone generally no parts of the pre-Permian to Upper Triassic sedimentary package constitute a rich source rock. The sporadic occurrence of intervals with a limited generation potential is considered economically insignificant in an exploration context.

The Lower Jurassic Fjerritslev Formation is regionally present in the Danish Basin and Fennoscandian Border Zone, however the four members (F-I to F-IV) of the formation are not present in all wells (Encl. 1). The F-I Member is the regionally most widespread, being present in all but one well, whereas the uppermost F-IV Member is only present in about 60% of the wells encountering the Fjerritslev Formation. The F-II and F-III members are present in about 80% of the wells. The source potential is not similar for the members, and an increasing hydrocarbon generative capacity is observed from the lowermost F-I Member to the upper members (Figs 10–13). The difference in source potential has been attributed to different depositional conditions by Thomsen *et al.* (1987). The lower generative potential of the F-I and F-II members were related to a more oxic depositional environment and a dominance of kerogen type III in the mudstones, whereas the F-III and F-IV members were considered to have been deposited during more reducing conditions and the higher source potential related to an increased content of kerogen type II (Figs 14–17). Thus, the widespread F-I Member only has a limited source potential (average HI values of 71–155 mg HC/g TOC) in a restricted number of wells, and in general only part of the member possesses a potential.

An overall marginal source potential is also recorded for the F-II Member, but a good hydrocarbon generation potential is sporadically present. Such an exception is the Hobro-1 well in which the member is quite organic-rich (2.41 wt.% TOC in average), and the mean HI of 185 mg HC/g TOC indicates a fair quality of the kerogen throughout the member. Likewise, a maximum HI of 321 mg HC/g TOC in the Hyllebjerg-1 well is promising, but an average HI of 128 mg HC/g TOC shows that the high values are restricted to parts of the member only. In a number of additional wells a very limited source potential is present.

In contrast, the overlying F-III Member is in general a moderate good source rock, and in a few wells (Kvols-1, Rønde-1) it is an excellent source rock. In the Kvols-1 well HI values up to 529 mg HC/g TOC are recorded, and the mean HI for the member is 230 mg HC/g TOC. These values suggest an overall good to excellent source potential, but in reality the upper part of the F-III member is considerably more oil-prone than the lower part (Fig. 7); the uppermost 40 m display continuously HI values >300 mg HC/g TOC and yield an average HI of 439 mg HC/g TOC. An average HI of 174 mg HC/g TOC for the F-III Member is recorded in the Rønde-1 well, but again the uppermost part (~20 m) is most rich, displaying an average HI value of 355 mg HC/g TOC, with a maximum HI of 428 mg HC/g TOC (Fig. 8). Numerous other wells, in particular Farsø-1, Haldager-1, Hyllebjerg-1, J-1 and Mors-1 with mean HI values from 169–214 mg HC/g TOC, possess some ability to generate hydrocarbons stressing that the F-III Member constitute the oldest more regionally distributed and important potential source rock unit.

Similarly to the F-III Member the F-IV Member, the uppermost unit of the Fjerritslev Formation, may also constitute an highly oil-prone potential source rock. Based on S_2 yields the Børglum-1 well seems to contain a rich F-IV Member, but associated high TOC values and thus low HI values point to a principally kerogen type III/IV content in the member in this well. In contrast, the member possesses a significant generative capacity in the Rønde-1 well. Both the

TOC content and S_2 yields are high, and the HI reaches a maximum of 543 mg HC/g TOC, while the mean HI for the member is 435 mg HC/g TOC (Fig. 8). These results points to the presence of a highly prolific marine kerogen type II source rock, and the F-IV Member in Rønde-1 qualifies as the most promising source rock interval of the Fjerritslev Formation observed for all wells. Other wells show a marginal to good source potential, particularly the Hyllebjerg-1 well which has an average HI of 194 mg HC/g TOC.

In the post-Lower Jurassic strata potential oil-prone source rocks are locally present, but in general the hydrocarbon generative capability is limited and is mainly restricted to parts of the successions. A few exceptions occur. The Middle Jurassic Haldager Sand Formation constitutes a good source rock in the Terne-1 well. An average HI of 191 mg HC/g TOC and maximum values not exceeding 262 mg HC/g TOC combined with high TOC contents suggest a mainly terrestrial kerogen type III source rock. In contrast, a narrow interval of the formation in the Haldager-1 well yield a HI value of 637 mg HC/g TOC, which could suggest the presence of kerogen type I. The overall generative ability of the Haldager Sand Formation in this well is, however, restricted. A highly oil-prone kerogen type I source rock is also present in the Upper Jurassic Frederikshavn Formation in the Terne-1 well. An average HI value of 471 mg HC/g TOC and a maximum value reaching 1125 mg HC/g TOC classifies the Frederikshavn Formation in this well as a highly rich potential source rock with exceptional oil-prone lacustrine kerogen type I intervals. The Frederikshavn Formation also possesses a limited generation potential (maximum HI values from 346–378 mg HC/g TOC) in the Gassum-1, Skagen-1 and Voldum-1 wells.

The lacustrine-influenced Frederikshavn Formation in the Terne-1 well constitutes the most prolific potential source rock in the Danish Basin and Fennoscandian Border Zone, however, the occurrence is very local, which reduces its importance significantly in a basin-wide exploration context. Therefore, despite this rich interval and other sporadic more or less prolific source rock intervals in the Upper Triassic to Upper Jurassic succession in the study area, the more regionally distributed Lower Jurassic Fjerritslev Formation qualifies as the only promising source rock in the Danish Basin and Fennoscandian Border Zone; this in particular is valid for the two upper members, F-III and F-IV (Figs 12, 13, 16, 17), but as already mentioned this part of the Fjerritslev Formation is the least widespread.

Apart from the obvious lack of a basin-wide continuous, prolific source rock in the Danish Basin and Fennoscandian Border Zone, the most crucial factor for hydrocarbon generation in the area seems to be maturity. This was also recognised by Thomsen *et al.* (1983, 1987). As maturation of organic matter, and thus vitrinite reflectance ($\%R_o$), is an irreversible process the measured vitrinite reflectance values will record the maximum temperature the organic matter has been subjected to, which under most geological conditions is equivalent to the maximum burial depth; thus, in the Danish Basin and Fennoscandian Border Zone measured vitrinite reflectance values will be related to the maximum burial depth of the strata. Vitrinite reflectance data from undisturbed strata will form a maturity trend, which intercepts the surface at a vitrinite reflectance value of approximately 0.20–0.25$\%R_o$, the reflectance of immature organic matter (e.g. Suggate 1998). Most strata penetrated by the wells in the Danish Basin and Fennoscandian Border Zone have, however, experienced a post-Cretaceous exhumation (Jensen and Michelsen 1992; Jensen & Schmidt 1992; Japsen 1993; Michelsen & Nielsen 1993; Japsen & Bidstrup 1999), which for example is manifested by vitrinite reflectance versus depth trends intercepting the surface at $\%R_o$-values much higher than the expected 0.20–0.25$\%R_o$. The measured vitrinite reflectance trend in the Mors-1 well, for example, intercepts the surface at 0.35$\%R_o$ (Bojesen-Koefoed & Petersen 2001). Based on the analysis of sonic velocities of shales Japsen (1993) estimated the post-Early Cretaceous net exhumation for numerous wells in the study area. Petersen *et al.* (in press) used these exhumation values to correct the burial depth of 249 reflectance measurements from 15 wells before the $\%R_o$ values were plotted against depth. Due to the generally low $\%R_o$-values ($<0.6\%R_o$) the vitrinite reflectance versus depth trend is approximated by a linear regression line defining a regional coalification curve (maturation gradient) (Fig. 18). This maturity gradient can be used to estimate the depth of the start of the oil window for the Danish Basin and Fennoscandian Border Zone.

The regional maturity gradient intercepts the surface at a vitrinite reflectance of 0.21$\%R_o$, and it has a gradient of 0.12$\%R_o$/km (Petersen *et al.*, in press). This is slightly higher than the 0.09$\%R_o$/km calculated by Thomsen *et al.* (1983, 1987), who did not consider the effects of post-Early Cretaceous exhumation, and who attributed the low maturity gradient to a geothermal gradient in the area not higher than 28°C/km (Madsen 1975, 1978). Thomsen *et al.* (1983, 1987) expected the start of the oil window (set to 0.6$\%R_o$) to be located at depths of 2700–3000 m. Using the same vitrinite reflectance value, Petersen *et al.* (in press) estimated the start of the oil window to be located at approximately 3250 m depth. The burial depth of potential source rocks must therefore exceed about 3250 m for hydrocarbon generation to take place. The uplift-corrected maturity profile by Petersen *et al.* (in press), which is based on Lower Jurassic–Lower

Cretaceous samples, demonstrates that the most promising Jurassic source rocks in the 15 wells in general have not been buried sufficiently to generate hydrocarbons. In Mors-1 the F-I Member has been buried deeper than 3250 m, and in Års-1 the F-I and F-II members and part of the F-III Member have been buried below 3250 m (Fig. 18). However, in both the wells these units constitute a poor source rock. In addition, it can be argued that the conventional start of the oil window at ~0.6%R_o is too optimistic. Furthermore, the assumption that a single %R_o-value can be used as an indication of the start of the oil window for the different kerogen types is also a very simplistic approach since several studies indicate not only a higher maturity (%R_o-value) for the start of the oil window for the various kerogen types, but also different vitrinite reflectance ranges of the oil window for each kerogen type (e.g. Powell & Snowdon 1983; Tissot *et al.* 1987; Tegelaar & Noble 1994; Ruble *et al.* 2001; Petersen 2002; Petersen *et al.* submitted). Petersen (2002) estimated the oil window for kerogen type III and humic coals to extend from 0.85–1.8%R_o, and kerogen type I has been determined to start hydrocarbon generation between about 0.75%R_o and 1.1%R_o (Tegelaar and Noble 1994; Ruble *et al.* 2001; Petersen *et al.* submitted). For all kerogen types the incorporation of sulphur causes an earlier hydrocarbon generation due to the weaker C-S bonds. Thus, for marine kerogen type II Tegelaar and Noble (1994) differentiated between the content of sulphur, and only for high sulphur kerogen type II they estimated the onset of hydrocarbon generation to occur from approximately 0.57–0.66%R_o, which is close to the conventional start of the oil window. For marine kerogen with lower sulphur contents the onset of hydrocarbon generation occurred at higher maturities.

In the studied wells the base of the most promising source rock unit, the F-III and F-IV members of the Fjerritslev Formation, is at present in general buried to less than approximately 2400 m. The wells corrected for post-Early Cretaceous exhumation show (Petersen *et al.* in press), that the base of the F-III Member in general not has been buried deeper than approximately 2900 m before uplift. Of the studied wells by Petersen *et al.* (in press) the Års-1 is an exception (Fig. 18), but as already discussed the source potential of F-III in this well is poor.

Seismic mapping

Introduction

The distribution and depths of the stratigraphic units with potential source rocks have been mapped by means of seismic data. The mapping was originally intended to be carried out on interactive interpretation facilities. Unfortunately, some of the old data is not available in digital format, and the mapping has therefore been performed by combining interpretation of digital data on the Landmark system, re-interpretation of some old analog data and utilization of existing maps (Japsen & Langtofte 1991a&b). This approach has caused some problems as the integration of hand-contoured and machine contoured data in structurally complex areas is difficult. When complex areas and areas with uneven data distribution is hand-contoured, support to the contouring is lend from a likely geological model. In contrast, a machine contouring is a strictly mathematical process; from this difference in approach some difficulties arises, which are especially critical when isochore maps are constructed. Thus, some of the minor details of the maps may therefore be artificial effects due to the integration of various data sources.

Database and data quality

In the offshore part of the Danish Basin most of the public domain seismic data are in digital form and available on the GEUS Landmark system. In areas where the seismic coverage has been sufficient only the newest data have been used. Close to the west coast of Jylland and in the Danish inner waters, digital data are absent in some areas and here old analogue data have been integrated in the interpretation. Onshore Denmark the available digital data have been integrated with old analogue data and existing maps. The seismic data vary in quality from single fold analogue sections to modern high-resolution marine data. In general onshore data from before 1970 are of relatively poor quality, but also newer data are of poor quality in certain areas. The following maps have been constructed by integrating new interpretation with existing maps: the Base Upper Cretaceous, Base Middle Jurassic Unconformity (Base Haldager Sand Formation) and Top Triassic (Top Gassum Formation).

Depth conversion

A layered velocity model has been used to convert time structure maps to depth maps. Each layer except for the Tertiary is assigned a velocity function of the form:

$V_{int} = Vo + K*t$

where V_{int} is the interval velocity of the layer Vo and K is a constant, which is fitted from well data, and t is the seismic two-way time to the center of the layer. In the Tertiary section a constant velocity of 2000 m/sec has been applied. For the Chalk Group an interval velocity function $V_{int} = 2729 + 0.902*t$ has been applied. For the interval Lower Cretaceous and Upper Jurassic the function is $V_{int} = 2299 + 0.5186*t$, and finally the function for the Fjerritslev Formation is $V_{int} = 2046 + 0.7482*t$. The data and the fit are shown in Table 1 and figures 19 – 21. This approach is somewhat simplistic, but is considered to be sufficient for a general analysis of the development of the basin, and for the mapping of the distribution of potential source rocks. It has not been attempted to fit the maps exactly with depths information from the wells.

Structural depths maps

The main results of the seismic mapping have been the construction of regional maps delineating the main stratigraphic units with potential source rocks. The top of the succession investigated by geochemical analyses corresponds to the base of the Upper Cretaceous, and a depth structural map of this surface is included (Fig. 22). The next important surface below is the base of the Middle Jurassic ("MCU"; Fig. 23). This surface approximates relatively well the base of the Upper Jurassic–Lower Cretaceous succession in most of the area, as the Middle Jurassic is thin except for the Sorgenfrei-Tornquist Zone. The surface also defines the top of the stratigraphic unit with the most promising source rocks in the Lover Jurassic Fjerritslev Formation (F-III and F-IV members). As the best possible regional approximation of the lower base of this interval, the top of the F-I Member was mapped (Fig. 24). These two surfaces are used in the construction of an isochore map that contains the F-II to F-IV interval (Fig. 25). As indicated by the geochemical analyses some limited potential is found in the Gassum Formation, and a depth map of the Top Triassic is also included as this surface corresponds to the top of the Gassum Formation in the area where the formation is present (Fig. 26).

Base Upper Cretaceous

The depth of the base of the Upper Cretaceous is shallowest, less than a few hundred meters, in the northeastern part of the area in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform, where it is truncated by the Quaternary. In most of the area a rapid increase in depth to 1,500–2,200 m occurs just southwest of the Sorgenfrei-Tornquist Zone. In the central part of the basin where salt tectonism is prominent, the surface shows that salt movements continued into the Late Cretaceous. The surface gradually deepens towards the west, where it reaches more than 2,500 m (Fig. 22)

Base Middle Jurassic Unconformity ("MCU")

The base Middle Jurassic unconformity is prominent in most of the study area. In the northeastern part of the area, the Skagerrak-Kattegat Platform and Sorgenfrei-Tornquist Zone, where the Haldager Sand Formation is thick and the quality of the seismic data is poor, the mapping has been uncertain. In this area the mapped surface probably occurs within the Haldager Sand Formation rather than at the base of the formation. In the area where the Chalk Group is absent the map has not been depth converted, because of the layered velocity model used. No attempt to use an alternative depth conversion model for this area has been made, since burial depth in this area is insufficient for maturation of any potential source rocks. The surface is most shallow on the Skagerrak-Kattegat Platform, typically less than 1,000 m and gradually deepens and steps down towards southwest across the Sorgenfrei-Tornquist Zone. In the central part of the basin, the surface typically reaches depths of 1,800–2,600. In the areas of significant salt tectonism the surface is locally buried to more than 3,000 m (Fig. 23). The base Middle Jurassic unconformity approximates well the top of the most promising source rock interval in the Lower Jurassic Fjerritslev Formation.

Top of the F-I Member, Fjerritslev Formation

The top of the F-I Member of the Fjerritslev Formation is mapped as it represents the best possible regional approximation of the base of the interval in the Fjerritslev Formation with potential source rocks. The surface is difficult to map especially offshore where well ties to the many separate rim-synclines are missing. The map has not been depth converted where the Chalk Group is missing (see above). The top F-I surface shows the same general picture as the base Middle Jurassic unconformity with the shallowest part toward the northeast, less than 1,600 m, and the deepest part in the west, up to 2,600 m. The surface displays a strong influence by salt tectonism in the central part of the basin, and very locally the surface reaches depths up to 3,400 m (Fig. 24).

Top Triassic (Top Gassum Formation)

As discussed in the section on source rock evaluation, the Gassum Formation is the deepest unit that may comprise some potential source rocks. The immediately underlying Vinding Formation may also have a small local source potential. The map shows the depth to the top of the Gassum Formation in large parts of the study area. In areas where the formation is absent, the map shows the top of the Triassic. In the Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform where the Gassum Formation is diachroneous (Bertelsen 1978; Michelsen 1978; Nielsen in press), the mapped surface occurs within the formation or at the base. The map has not been depth converted where the Chalk Group is absent (see above). The Top Triassic surface shows the same general picture as the base Middle Jurassic unconformity with the shallowest part toward the northeast and the deepest part in the west (Fig. 25). In the central part of the basin the surface is strongly influenced by salt tectonism, and locally in rim-synclines the surface reaches depths of more than 4,000 m.

Isochore map of the F-II, F-III and F-IV members, Fjerritslev Formation

The upper part of the interval from base F-II Member to top F-IV Member contains the most promising source rocks in the study area. The isochore map reveals significant influence by salt movements on the thickness of the unit demonstrating the importance of local conditions for the formation of source rocks (Figure 26).

Relation between the sequence stratigraphic development and the occurrence of potential source rocks

As discussed previously, possible potential source rocks are only found within the Upper Triassic-Jurassic succession. In the following section emphasis is therefore placed on the sequence stratigraphic development of the Norian (Upper Triassic) to Rhyazanian (Lower Cretaceous) as sea-level changes is one of the main factors that influence formation and preservation of source rocks (see later discussion). A schematic time stratigraphic summary is given in figure 27 displaying time, lithostratigraphy, depositional sequences and environment. A selected series of detailed well-log panels displaying identified sequence stratigraphic key-surfaces and the development of the depositional environment through time are further provided (Figs 29, 33, 36, 40, 42; their position is given Figs 28, 32, 35, 41). In order to investigate the relation between the depositional environments and the formation of potential source rock units, a series of well-log panels have been constructed showing Gamma Ray or SP logs, TOC contents and HI values together with the sequence stratigraphic key-surfaces (Figs 30, 31, 34, 37, 38, 42, 43, 45). Only well-sections that are discussed in the section on source rock evaluation are included in the panels. It has to be noted that the geochemical analyses were carried out on cuttings samples, which causes some problems in relating anomalies to sequence stratigraphic surfaces, as sample depths are encumbered with some uncertainty due to caving and calculation of lag time. For wells drilled before the Rønde-1 well, drilled August 1966, lag time was not estimated (i.e. Fjerritslev-2, Flyvbjerg-1, Frederikshavn-2, Haldager-1, Horsens-1, Skagen-2 and Slagelse-1, among others).

Sequence boundaries are abbreviated as SB, regional transgressive surfaces are termed TS, and regional maximum flooding surfaces are abbreviated as MFS. Lowstand systems tracts bounded below by a SB and topped by a TS are termed LST, transgressive systems tracts bounded below by a TS and topped by a MFS are termed TST, and highstand systems tracts bounded below by a MFS and topped by a SB are termed HST. Forced regressive systems tracts, FRST are, in general not differentiated from the HST in this study, as they both form parts of the progradational wedges that were formed during phases of decreasing rate of sea-level rise (HST) followed by falling sea-level (FRST) (e.g. Hamberg & Nielsen 2001). The surfaces are numbered in ascending order beginning with TS 1, which is regarded as a regional transgressive surface defining the shift from the Oddesund Formation to the overlying Vinding Formation (Nielsen in press). The uppermost regional surface numbered is the TS 22, which coincides with the boundary between the Flyvbjerg and Børglum formations. A number of higher-order sequences and their related surfaces have been identified in the Vinding and Gassum formations, but are not considered further here. They are, however shown on figure 29.

Late Triassic marine flooding, subsequent coastal progradation and fluvial incision (TS 1 – SB 9; Vinding and Gassum formations)

The deposition of lacustrine and sabkha mudstones in Carnian time was terminated by an Early Norian marine transgression that probably came from the south (marked as TS 1 in Fig. 29). The transgression led to deposition of a backstepping set of parasequences of oolitic limestones, marlstones and fossiliferous claystones belonging to the Vinding Formation (Bertelsen 1978, 1980; Nielsen *et al.* 1995). During peak time in late Norian (marked as MFS 1, Fig. 29), the shallow sea covered most of the Danish Basin and the Ringkøbing-Fyn High, while fluvial arkosic sands and lacustrine muds were deposited in the Sorgenfrei-Tornquist Zone, Skåne, Rønne Graben and along the northern basin margin. These deposits are included in the Skagerrak and Kågeröd Formations (Bertelsen 1980; Gravesen *et al.* 1982; Sivhed 1984; Ahlberg 1994; Nielsen 1995, in press).

After the maximum transgression, a phased regression followed, and shoreface and fluvial sands of the lower Gassum Formation were deposited in stepwise more basin-ward positions intercalated with clays of the upper Vinding Formation in the basin centre (Fig. 29). In the Fjerritslev Trough, alternating units of arkosic fluvial sand and variegated lacustrine mud belonging to the uppermost part of the Skagerrak Formation were deposited, reflecting repeated base-level changes controlled by the short-term sea-level fluctuations. The regression culminated in the early Rhaetian with formation of an extensive, fluvially incised sequence boundary (marked as SB 5, Fig. 29). At this time the Ringkøbing-Fyn High was exposed to erosion and fine-grained sand was shed to the basin from the high. Non-deposition or erosion probably occurred on the Skagerrak-Kattegat Platform, in Skåne and on Bornholm east of the Rønne Graben.

After termination of the early Rhaetian sea-level fall, sea-level slowly rose again and fluvial-estuarine deposits, up to 30 m thick were deposited above the sequence boundary before widespread marine flooding occurred; the flooding is marked by the TS 5 surface on figure 29. The transgression was punctuated by two short-term, forced regressions that led to deposition of widespread shoreface sandstone sheets encased in marine mudstones before it reached its maximum in the latest Rhaetian, when the Danish Basin, the Sorgenfrei-Tornquist Zone, the Skagerrak-Kattegat Platform, the North German Basin, and the Ringkøbing-Fyn High were covered by the sea (marked as MFS 7, Fig. 29). The increasing amount of macro-plant fossils, rootlets, coal seams and more mature sandstones testify that the climate became more humid during the Late Rhaetian transgressive phase.

An overall sea-level fall commenced and two phases of coastal progradation at the Rhaetian–Hettangian boundary and in the earliest Hettangian, respectively, caused deposition of two thin regressive shoreface sand sheets that constitute the upper part of the Gassum Formation in much of the Danish Basin. The regression culminated with coastal progradation far into the basin accompanied by fluvial erosion and incision in the Himmerland Graben, Fjerritslev Trough and along the southern basin margin, where parts of the Ringkøbing-Fyn High were exposed and supplied sand to the basin (marked as SB 9; Fig. 29).

Geochemistry and key-surfaces. The geochemical analyses of the sections between the TS 1 and SB 9 surface show that, in general the source rock potential is very limited. Only 8 of the analysed well-sections show some limited potential with the Mejrup-1 well as the most notable exception. Two log-panels, a strike section including Slagelse-1, Nøvling-1, Mejrup-1, Mors-1 and Felicia-1, and a dip-section with Nøvling-1, Mejrup-1, Hyllebjerg-1, Års-1 and Sæby-1 have been constructed (Log-panel Figs 30 & 31; refer to Fig. 28 for position). None of the wells show any systematic change of TOC or HI in the transgressive systems tracts TS 1 to MFS 1; only Nøvling-1 shows a weak increase in HI. Two wells, Slagelse-1 and Sæby-1 show a slight increase close to the MFS 1. Three wells show a weak tendency of increased TOC and HI at the regional MFS 7 flooding surface, namely Mors-1, Felicia-1 and Sæby-1. The two latter wells are located relatively close to the basin margin, where the flooding caused a significant change in the depositional environment from various sandstones to marine mudstones. In the deeper parts of the basin, e.g. Nøvling-1 and Mejrup-1 this relation is not indicated, rather the inverse relation is suggested by the data from Mejrup-1, where upward decreasing values of TOC and HI are indicated below MFS 7 and increasing values above. Three well-sections, Mejrup-1, Hyllebjerg-1 and Års-1 show distinct levels with somewhat increased values, that are related to MFS in higher order sequences or minor flooding surfaces topping parasequences.

Early Jurassic basin expansion (SB 9 – SB 13; Upper Gassum Formation, F-Ia and F-Ib Members)

A Hettangian–Early Pliensbachian transgression commenced with the early Hettangian Planorbis Zone, and fully marine mudstones belonging to the F-Ia member of the Fjerritslev Formation overlie the sandy Gassum Formation in most of the Danish Basin (Fig. 33). The mudstones have a low content of ostracods, foraminifers and infaunal bivalves, but a high content of land-derived organic matter. In the northeastern part of the Sorgenfrei-Tornquist Zone aggrading parasequences of fluvial and shoreface sands with subordinate offshore muds were deposited, while lagoonal parasequences were formed on the Skagerrak-Kattegat Platform. The transgression peaked in the early and late Hettangian (marked as MFS 9 and MFS 10, Fig. 33) interrupted by a short-term regression in the mid-Hettangian (SB 10, Fig. 33). The large increase in accommodation space governing deposition of transgressive paralic deposits along the basin margin was interrupted briefly by a fall in sea-level closely after the Hettangian–Sinemurian boundary. This resulted in fluvial incision on the Skagerrak-Kattegat Platform, while regressive shoreface sand was deposited in the Fjerritslev Trough (marked as SB 11, Fig. 33). Farther basin-ward, heteroliths and silty mudstones were deposited above the conformable part of the sequence boundary. A rapid sea-level rise followed in the earliest Sinemurian (marked as TS 11, upper part of the Bucklandi Zone) and transgressive marine mud of the F-Ib member finally overstepped fluvial and marine sand of the Gassum Formation in the Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform. In the basin, up to 150 m of uniform mudstones were deposited, showing a marked thinning toward the northeastern basin margin (Fig. 33).

In the Late Sinemurian, a minor sea-level fall caused a slight basin-ward progradation of coastal parasequences on the Skagerrak-Kattegat Platform and in parts of the Sorgenfrei-Tornquist Zone (marked as SB 12, Fig 33). In the deeper parts of the basin where deposition of marine mud prevailed this progradational event is difficult to reveal. After this minor excursion, the overall Early Jurassic sea-level rise continued, and reached a maximum in the latest Sinemurian possibly close to the Oxynotum–Raricostatum Zone boundary (marked as MFS 12, Fig. 33). In the centre of the Danish Basin, the diversity and abundance of the ostracod fauna decreased and infaunal bivalves and some of the epifaunal bivalves disappeared due to reduced oxygenation (Pedersen 1986; Michelsen 1989b).

Geochemistry and key-surfaces. The geochemical analyses of the sections between the SB 9 and SB 13 surfaces suggest that the source rock potential is very limited. Only three wells show a very limited potential and a dip section displaying these wells has been constructed (Fig. 34; refer to Fig. 32 for position). The samples in Mejrup-1 show very uniform low values of TOC and HI except for two samples closely above MFS 9 and TS 10, which show fairly high HI. Similar changes are not seen at the other transgressive surfaces or the maximum flooding surfaces. In Års-1 the sample closely above MFS 12 shows a small increase in both TOC and HI. In Sæby-1, one sample shows a weak increase in both TOC and HI; the sample seems to represent a minor flooding surface in the HST between MS 10 and SB 11. Except for these small anomalies, TOC and HI seem unaffected by the sea-level changes, that led to the formation of the transgressive surfaces and maximum flooding surfaces.

Pliensbachian sea-level fluctuations and erosion at basin margin (SB 13 – TS 14; F-II Member)

A gradual decrease in the rate of sea-level rise in the Early Pliensbachian Jamesoni Zone caused a distinct basin-ward progradation of shoreface sandstones on the Skagerrak-Kattegat Platform (Fig. 36). The regression culminated in the mid Early Pliensbachian (early Ibex Zone), and the deposition changed from fine-grained mud (F-Ib member) to silty and sandy heteroliths (F-IIa member; SB 13, Fig. 36). On the Skagerrak-Kattegat Platform, deposition of shallow-marine shoreface sand ceased for some time due to submarine or subaerial erosion and bypass. When sea-level started to rise again deposition of fine-grained mud resumed in the Danish Basin (marked as TS 13, lower part of F-IIb beds; Fig. 36), and backstepping parasequences of marine sand was succeeded by transgressive mud on the Skagerrak-Kattegat Platform. Peak transgression was reached in the late Early Pliensbachian Davoei Zone (marked as MFS 13; Fig. 36). Thereafter, rate of sea-level rise decreased and an upward-coarsening succession of mud and fine-grained heteroliths were deposited in the Danish Basin (middle part of F-IIb).

Significant erosion took place on the Skagerrak-Kattegat Platform during a sea-level fall in the early Late Pliensbachian Margaritatus Zone (marked as SB 14, Fig. 36). Basin-ward, in the Fjerritslev Trough and the Danish Basin, deposition changed to silty and sandy mud and fine-grained sand, showing very marked thinning over salt-structures possibly reflecting shallow water depths (upper part of F-IIb and F-IIc beds). The ensuing sea-level rise, which initiated the second Early Jurassic transgression, commenced in the Margaritatus Zone and caused the formation of the transgressive surface TS 14 (Fig. 36).

Geochemistry and key-surfaces. Two well-log panels have been constructed to illustrate the Pliensbachian-Lower Aalenian, a strike section including the wells Rønde-1, Voldum-1, Kvols-1, Hobro-1, Farsø-1, Mors-1, Fjerritslev-2, J-1 and Felicia-1, and a dip section including Kvols-1, Hyllebjerg-1, Års-1, Haldager-1, Børglum-1, Sæby-1, Frederikshavn-2 and Skagen-2 (Figs 37, 38; refer to Fig. 35 for position). The panels display the sequences from SB 13 to SB 19 in order to limit the number of panels. None of these well-sections show any systematic change in the TOC and HI values in the SB 13 to TS 14 succession, and there is no clear relationship between changes in the values and the identified systems tracts. One well, Mors-1, displays an interesting trend, however the HI shows a distinct systematic upward increase in values beginning at TS 13 and continuing upward to some 30 m below MFS 14, apparently without any influence from the sea-level changes that caused the formation of SB 14 and TS 14. Some well-sections clearly show the influence of local salt structures as the thickness of the succession from SB 13 to TS 14 display very significant variations with only thin successions preserved in the Kvols-1, Voldum-1 and Hobro-1 wells. Based on ostracods Michelsen (1989a&b) indicate hiati at this level.

Late Pliensbachian-Early Aalenian sea-level rise and anoxia (TS 14 – SB 19; F-III and F-IV Members)

The second Early Jurassic overall sea-level rise reached a peak in the late Late Pliensbachian (marked as MFS 14, early Spinatum Zone; Fig. 40). Marine silty mud was deposited in the Danish Basin, while marine sand with bivalves was deposited in the Fjerritslev Trough. Deposits from this period are absent on the Skagerrak-Kattegat Platform due to bypass or later erosion. The following sea-level fall culminated in the late Spinatum Zone with the formation of a widespread marine regressive surface of erosion (marked as SB 15, Figs 40 & 42) and progradation of a sandy shoreface into the central parts of the Fjerritslev Trough. The sea-level fall caused erosion of the Lower Pliensbachian strata on the Skagerrak-Kattegat Platform. The ensuing sea-level rise caused marine flooding over the entire basin at the Pliensbachian–Toarcian boundary, including the Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform, and deposition of transgressive marine mud commenced (marked as TS 15, Figs 40 & 42). The transgression reached its maximum in the Early Toarcian Falciferum Zone (marked as MFS 15, Fig. 42). Due to oxygen-poor conditions the ostracod fauna disappeared and an increasing amount of amorphous marine matter is preserved (Michelsen 1989b; Dybkjær 1991). During the remainder of the Early Jurassic period and in the Early Aalenian Opalinum Zone, a succession of up to 150 m of marine mudstones with three shoreface sandstones overlying regressive marine erosion surfaces were deposited in the Sorgenfrei-Tornquist Zone during sea-level falls. In the Skagerrak-Kattegat Platform, where accommodation was much less, thin peat-bearing lagoonal successions were deposited on the subaerial erosion surfaces during ensuing transgressions. The basin gradually shrank and became isolated from the North Sea Basin due to initial uplift, and a poor circulation pattern and possibly brackish conditions at the margin caused impoverishment of the fauna.

Geochemistry and key-surfaces. The two well-log panels in figures 37 and 38 are used to illustrate the TS 14 – SB 19 succession (SB 19 corresponds to the "Base Middle Jurassic Unconformity", which is a composite surface composed of several amalgamated sequence boundaries. In 8–9 wells the TOC and HI show relatively low values in the TST from TS 14 to MFS 14. The low values may be related to diluting effects since this part of the succession is missing in the wells on the Skagerrak-Kattegat Platform (Skagen-2, Frederikshavn-2 and Sæby-1) possibly due to non-deposition and by-pass on the platform, supporting a high rate of sediment influx to the deeper part of the basin.

In several wells, Rønde-1, Voldum-1, Kvols-1, Hobro-1, Mors-1, J-1, and Frederikshavn-2, a weak to very distinct trend of increasing values is found in the TST from TS 15 to MFS 15 with a maximum close to MFS 15. In a few wells a small low occurs at MFS 15, e.g. Felicia-1 and Hyllebjerg-1. The section in Kvols-1, which has excellent values in the discussed succession, shows an interesting trend of a steady upward increase in TOC and especially in HI beginning from MFS 14 and reaching a maximum at or slightly below MFS 15. The steady increase in HI seems un-affected by the change from HST to LST across the SB 15 and from LST to TST across the TS 15 surface. This may be due the distant location of the Kvols-1 well in relatively deep water, where changes in sea-level and thus water depth was of relatively little importance. In the HST above MFS 15, the values show a rapid upward decrease. A similar distinct upward decrease in the HST is also seen in Mors-1 and J-1. In other wells, Rønde-1, Hyllebjerg-1, Børglum-1, Sæby-1 and Frederikshavn-2, maximum values occur in the HST well above MFS 15 in a distinct log interval with minor flooding surfaces. In some wells, e.g. Hyllebjerg-1, Års-1, Haldager-1, Børglum-1 and possibly also Sæby-1 a small maximum occurs above TS 16 and close to the MFS 16. Potential source rocks thus occurs at three stratigraphic levels in the Toarcian.

The MFS 15 is dated to the Falciferum Zone and the two lower occurrences of maximum values of TOC and HI in the Toarcian in several Danish wells fit thus very well with the maxima of organic matter enrichment that have been shown in the Falciferum Zone and the overlying Bifrons Zones of the Lower Toarcian Posidonia Shale in Germany (Röhl *et al.* 2001).

Late Early–Middle Jurassic uplift and erosion (SB 19 – TS 22; Haldager Sand Formation)

The Ringkøbing-Fyn High, most of the Danish Basin and the Skagerrak-Kattegat Platform were uplifted in late Early Jurassic–early Middle Jurassic time, and the Triassic–Lower Jurassic successions were eroded on the highest parts of the Ringkøbing-Fyn High. The Lower Jurassic was deeply eroded in the uplifted area north of the high, whereas erosion did not reach such deep levels closer to the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform (see Figs 36, 45). In the fault-bounded Sorgenfrei-Tornquist Zone, where subsidence still occurred but at a much smaller rate than before, the change in basin configuration resulted in a shift from deposition of homogeneous offshore muds to shallow-marine sands. The sandstones overlie a marine erosion surface dated to the top of the Lower Aalenian Opalinum Zone (SB 19, Fig. 42). Hence, during the rest of the Aalenian, the Bajocian and the early Bathonian, deposition was more or less confined to the narrow zone bounded by the Fjerritslev and Børglum Faults and their southeastward continuation in Kattegat, Øresund and Skåne. Material was supplied from both the uplifted areas to the west and southwest, and from the Baltic Shield. Most of the Haldager Sand Formation and time equivalent units in Skåne from the Fjerritslev Trough in the northwest to Skåne in the southeast, consists predominantly of shallow-marine, paralic and fluvial sediments belonging to lowstand systems tracts with minor proportions of marine and lacustrine muds belonging to transgressive systems tracts. The area of subsidence gradually expanded in Bathonian–Callovian time with deposition of Bathonian(?) braided fluvial sands on the Skagerrak-Kattegat Platform and southwest of the Fjerritslev Trough in the Himmerland Graben.

Geochemistry and key-surfaces. Two well-log panels have been constructed, a strike section including the wells Terne-1, Haldager-1, Vedsted-1, Fjerritslev-2, J-1 and F-1, and a dip section with the wells Mors-1, Hobro-1, Børglum-1, Flyvbjerg-1, Sæby-1 and Skagen-2 (Figs 43 & 44;

refer to Fig. 41 for position). The density of analysed cuttings samples are low in this sandstone-dominated succession compared to the analyses from the Fjerritslev Formation. An increase in TOC occurs in one of the sandstone units in the Vedsted-1, Børglum-1 and Flyvbjerg-1 wells; the HI is low, however, and the analyses reflect probably the presence of transported fragments of coalified plant material in the fluvio-estuarine and shoreface sandstones. In Terne-1 two samples show relatively high TOC and HI values close to the TS 20 and SB 21 surfaces. The two samples are collected close to minor flooding surfaces topping parasequences and consist of marine mudstones and siltstones that only constitute a minor proportion of the otherwise sandstone dominated section (Fig. 42). In Haldager-1 a few samples apparently from fluvial sandstones have yielded relatively high HI ranging from 174-637. It is obvious that there is a problem with the actual sample depth due to missing estimation of lag time or caving; most likely the samples represents the overlying mudstones deposited below and at the MFS 20 surface.

Late Middle–Late Jurassic basin expansion (Flyvbjerg, Børglum and Frederikshavn Formations)

A marine transgression close to the Callovian–Oxfordian boundary (marked as TS 22, Figs 42, 45) influenced most of the basin and accommodation space was also created in the former by-pass zone of the southern part of the basin and the Skagerrak-Kattegat Platform, where fluvial sands were now deposited. During the Oxfordian, the sedimentation area was further enlarged and a northeastward-thickening wedge of marine transgressive, fossiliferous sand and mud was deposited above lagoonal deposits on the Skagerrak-Kattegat Platform, while lagoonal deposition apparently dominated to the southwest (Flyvbjerg Formation), where the structural high was still present, albeit with much reduced relief. The transgression culminated in the late Oxfordian with widespread deposition of marine mudstones (Fig. 42). A latest Oxfordian sea-level fall resulted in coastal progradation on the Skagerrak-Kattegat Platform and in the Fjerritslev Trough; fluvial and shallow-marine sands were deposited, and a southwest prograding wedge was formed (Fig. 42). Extensive marine flooding occurred in the Kimmeridgian, and sedimentation of marine mud belonging to the Børglum Formation characterised the entire area, although the marked thinning toward the southwest emphasises the reduced accommodation here. During Volgian–Ryazanian time the depositional environment was dominantly a shallow shelf with three–four major phases of coastal progradation (Sequence Fr 1, Fr 2 and Fr 3, Fig. 27). Coastal and deltaic sandy deposits (Frederikshavn Formation) were formed in the Skagerrak-Kattegat Platform and parts of the Sorgenfrei-Tornquist Zone, while marine mud was deposited in much of the basin. The occurrence of sandy beds in the southwestern-most parts of the basin indicates, that during low sea-level the Ringkøbing-Fyn High still supplied some sand.

Geochemistry and key-surfaces. The geochemical analyses show that potential source rocks units only occur locally in the marine mudstones of the Børglum Formation and in lacustrine mudstones in the Frederikshavn Formation. The lacustrine units have only a very local distribution (Nielsen in press). Since these few outliers are highly immature with a local presence only, the study has not attempted to carry out a thorough sequence stratigraphic analysis at this stratigraphic level.

Sedimentology of organic matter in the marine environment: formation of marine petroleum source rocks

The conducted geochemical analyses clearly indicate that the most promising potential source rocks are the marine mudstones of the Fjerritslev Formation. Before continuing with a discussion of the possible relation between source rock formation and the changes in sea-level and depositional environments that influenced the Danish Basin and Fennoscandian Border Zone as described above, it may be suitable to review the current understanding of the processes that govern formation of marine source rocks. Petroleum source rocks are deposits having an organic matter content that allows them to generate and expel commercial quantities of petroleum under adequate conditions of thermal maturation. Organic richness and the type of organic matter are critical features, that are determined by a complex interplay of a number of factors that fall under one or more of the following headings: *supply, preservation* and *decomposition* of sedimentary organic matter. The "principal causes" for organic matter enrichment in marine sediments have previously been the subjects of a rather heated debate, and two "schools" emerged, *"productionists"*, principally represented by Tom Pedersen and Stephen Calvert, advocating the importance of primary production over other factors (e.g. Pedersen & Calvert 1990, Calvert & Pedersen 1992), and *"preservationists"*, principally represented by Gerard Demaison & Richard Tyson (e.g. Demaison & Moore 1980, Tyson & Pearson 1991), emphasizing the importance of anoxia in organic matter preservation. Over the last decade, the obvious futility of the debate appear to have been realized by the combatants, and the concept of principal factors seems to have given way to more balanced views, acknowledging the complexity of the matter (e.g. Tyson 1995). However, for practical purposes a number of controls on organic matter enrichment in sediments can be identified, although the effects of each individual factor cannot be fully resolved:

Sediment texture

Petroleum source rocks are generally fine-grained rocks, containing reduced (i.e. hydrogen-rich) organic matter. Organic matter is hydro-dynamically equivalent to clay-grade clastics, that tend to settle in quiescent low-energy depocentres. Organic particles in seawater behaves non-Stokesian due to the very low difference in density between the particles and the medium in which they sink, and organic particles tend to become adsorbed to active (i.e. charged) surfaces, further promoting their association with clays. Conversely, coarse-grained sediments are generally associated with high-energy environments that are bypassed by clay-grade material. Physical wear, bioturbation, and the continuous replenishment of oxidants in such environments are further detrimental to the inclusion of significant proportions of reduced organic matter in coarse-grained sediments.

Bathymetry

Although the exact relationship is not clear a number of studies in oceanic settings have shown that the flux of organic carbon from the photic zone decreases with increasing water depth (e.g. Suess 1980; Betzer *et al.* 1984). However, the effect of bathymetry is probably of little importance in a shallow shelf setting where most petroleum source rocks have been deposited.

Primary productivity

A certain level of primary productivity in the photic zone is required in order to produce organic enrichment in the underlying sediments, but the relationship is not simple. High levels of primary productivity and organic enrichment in underlying sediments may be coeval, primarily in settings with extensive upwelling of deep-ocean nutrient-rich waters, serving to compensate the negative feedback resulting from the sequestering of nutrients in sediments underlying the photic zone. In other cases, efficient recycling of nutrients within the photic zone itself allows high levels of primary production to be maintained without the introduction of nutrients from external sources. Such systems are effectively closed, and little preservation of organic matter in the underlying sediments will take place, see e.g. Húc (1988). However, high levels of primary productivity have derived effects that may enhance organic matter export from the photic zone. These include increasing feacal pellet size, resulting in higher sinking velocity, and thus more efficient export of OM (organic matter), and inefficient grazing by the zoo-plankton under conditions of excess food supply, leading to disproportional increasing OM flux from the photic zone (Dagg *et al.* 1986; Betzer *et al.* 1984).

Sediment accumulation rate

A number of studies seem to indicate that within certain limits, proportionality exists between the sediment accumulation rate and the organic carbon content of sediments (e.g. Ibach 1982;

Müller & Suess 1979; Stein 1990). However, most relationships are demonstrated using bilogarithmic plots, which tend to produce linear relationships irrespective of what parameters are plotted. Moreover, no relationship can be demonstrated for anoxic environments, even when using log-log plots. Despite these complications, no doubt exists that the sediment accumulation rate exerts an important control on the amount and type of organic matter preserved in sediments, although the exact nature of the mechanism remains unresolved. At high sedimentation rate, dilution of organic matter will take place, whereas low sedimentation rates will expose organic matter to decomposition near the active sediment-water interface for extended periods of time. A number of other factors are likely to be confounded in the apparent relationship between OM-enrichment and sedimentation rate, including microbial processes, oxygen level, sediment texture, and primary productivity. These factors are in turn more or less related, thus illustrating the complexity of the problem.

Bottom water oxygenation

The bottom water oxygen level is an important control on the amount and type of organic matter eventually included in sediments, but oxygen deficiency does not in its own right lead to organic matter enrichment or development of petroleum source rocks. However, more or less all petroleum source rocks were deposited under conditions of oxygen deficiency, and significant qualitative differences exist between organic matters contained in oxic versus anoxic sediments. Hence, organic matter preserved in anoxic sediments is generally reduced, i.e. rich in hydrogen, which is a prerequisite for petroleum generation. Since largely all marine sediments are anoxic at very shallow depth, and most organic matter in marine settings is supplied from the photic zone, preservation factors and pre-burial processes, taking place near the sediment-water interface must be important for the amount and quality of organic matter preserved in oxic versus anoxic environments. Most organic matter decomposition is undertaken by microbes, and aerobic bacteria are generally very versatile and may carry out complete breakdown of almost any organic substrate whereas anaerobic bacteria are generally limited in substrate utilization, and require commensalistic/symbiotic relationships to other anaerobes in order to carry out complete breakdown of the substrates on which they thrive. Hence, the various classes of the anaerobic community are deeply dependant on each other for substrate preprocessing (i.e. partial breakdown) and removal of "waste" (i.e. preprocessed substrate). Hence, the anaerobic decomposition is vulnerable, since if one critical process is inhibited, wholesale retardation of degradation is likely to result. Moreover, substrate preferences are well documented, and anaerobes are not very efficient for lipid degradation. This feature is very important for the development of source rocks, since lipids are hydrogen-rich, reduced organic components, that may accumulate during anaerobic degradation. Another important effect of oxygen deficiency is the exclusion of bottom-dwelling macro fauna, and hence bioturbation. In general, benthic macro-fauna is responsible for less than 20% of the sediment respiration, but bioturbation is important in catalyzing decomposition of sedimentary organic matter by fragmentation of particles (increasing the surface to volume ratio), ventilation of the surface sediments, and recycling of organic particles between the sediment-water interface and deeper parts of the sediments, thereby expanding the zone of oxic decomposition.

Other factors

Temperature may influence organic matter decomposition at very shallow water locations only – in deeper water settings, bottom water temperatures are fairly constant. Likewise, salinity may influence organic matter preservation. For instance, strong brines may accumulate in depressions on the seafloor, developed in response to dissolution of underlying salt diapirs.

Summary

The amount and character of organic mater included and preserved in sediments is determined by a highly complex interplay of a large number of different factors, the effects of which may seldom be satisfactorily resolved. In general terms, deposition under conditions of oxygenic bottom waters, low primary productivity and sedimentation rate, great water depth and distance from fluvial sources is disfavourable for accumulation of organic matter. Deposition under condition of anoxic bottom waters, moderate sedimentation rate, high primary productivity, moderate water depth and great distance from fluvial sources is favourable for the accumulation of reduced organic matter and hence for source bed deposition. Deposits from areas receiving large amounts of continental runoff may contain high proportions of terrestrial organic matter, without the development of petroleum source potential.

Relation between the occurrence of potential source rocks and sea-level changes recognised in the Danish Basin and Fennoscandian Border Zone

Marine source rocks and sequence stratigraphy

As described above the accumulation and preservation of marine organic matter is related to a complex interplay between various factors. In terms of sequence stratigraphy such conditions are best met in the transgressive systems tract (TST), where black organic-rich shales forming potential source rocks most commonly seem to be related to either the transgressive surface (TS) or the maximum flooding surface (MFS). According to Wignall & Maynard (1993) transgressive black shales are commonly associated with the initial flooding of the lowstand systems tracts and the landward sequence boundary; lateral facies variations are small and the shales are laterally persistent. Transgression over a large, down-eroded area creating sediment-starved, basinal-like conditions in a marginal area has been suggested as an explanation for the development of the transgressive black shales in the basal part of the TST (Wignall 1991). In contrast, the black shales deposited during maximum flooding typically form condensed sections that laterally pass into much thicker nearshore facies. However, a black organic-rich shale source rock may not necessarily form during transgression as all the environmental, depositional and preservation factors discussed above influence the formation of organic-rich shales (see also Herbin *et al.* 1995; Tyson 1996).

Organic-rich black shales associated with the Early Toarcian anoxic event are well-known from Europe and other parts of the world (e.g. Jenkyns 1988), and an example of a Lower Toarcian transgressive black shale is the Jet Rock black shales of northern England. The Lower Toarcian Posidonia Shale is likewise famous for its excellent source rock characteristics, and a detailed analysis of outcrops and shallow cores of southwest Germany has shown that the formation of this unit was governed by a highly dynamic depositional system including water column stratification controlled by sea-level changes (Röhl *et al.* 2001). Well-developed organic-rich source rocks associated with the MFS has been demonstrated for, for example, the Lower Jurassic succession of the Paris Basin (Bessereau *et al.* 1995) and the Upper Cretaceous succession of Egypt (Robison & Engel 1993).

The most oil-prone shales associated with the MFS are not found symmetrically distributed about this surface, but are generally reported to occur below the condensed section in the transgressive systems tract (TST) (Wignall 1991; Pasley *et al.* 1993). Exceptions to this general assumption are known, and in the Cenomanian–Turonian Red Wash section, Curiale *et al.* (1992) determined the best source potential to be present immediately above the condensed section in the highstand systems tract (HST). Also, Robison *et al.* (1996) did not observe a significant change in the kerogen type across the MFS in the Triassic Shublik Formation, Alaska, but due to an increasing content of terrestrial organic matter in the HST the overall source potential is lower than that recorded for the TST.

Source rock formation and sea-level changes in the Danish Basin and Fennoscandian Border Zone

The discussions in a previous section of the correlation between the identified sequence stratigraphic key-surfaces in the Upper Triassic–Jurassic and the results of the geochemical analyses indicate that the basin-wide sea-level changes did not govern the formation of organic-rich marine deposits in a simple way. Hence, a well-defined correlation between sequence stratigraphic key-surfaces (TS and MFS) and organic enrichment cannot be established within the study area. Occasionally, there is a clear correlation between increased TOC and HI and marine flooding surfaces, and the TST may show upward increasing values, and HST the opposite trend as expected. Dybkjær (1988, 1991) found a general positive correlation between the Early Jurassic sea-level changes and the relative variation of the content of marine and terrestrial palynomorhs in some wells. Pedersen (1986) recognised a major change in the sea-bottom fauna at the late Sinemurian–Early Pliensbachian boundary and a disappearance of benthonic fossils in the uppermost Pliensbachian, and related these changes to two phases of sea-level rises. However, from the discussion above it is also evident that the sea-level rises not always led to increased source quality, and that other factors have exerted a stronger control on the production and preservation of organic matter.

The most promising potential source rocks of the Upper Triassic–Jurassic succession occur in the Toarcian part of the Fjerritslev Formation. The sequence stratigraphic framework established by Nielsen (in press) and correlation of log-sequences (Michelsen 1989b) indicate that the potential source rocks occur at three different stratigraphic levels in the Toarcian. As mentioned previously, Lower Toarcian organic-rich marine shales are known from several places in Europe, e.g. Jet Rock in UK and Posidonia Shales in Germany, and at least the two lower levels of organic-rich mudstones in the Fjerritslev Formation seem to correlate very well with the organic-rich shales in the Falciferum and Bifrons Zones of the Posidonia Shales in southwest Germany. The contemporaneous development of organic-rich marine mudstones over such great distances advocate for a common cause related to global or regional anoxia. However, several well-sections contain coeval marine mudstones with a low content of organic matter, which emphasis that it was only parts of the basin, that were favourable for the accumulation of organic-rich mudstones. This clearly indicates a strong local control on the production and/or preservation of the organic matter in parts of the Danish Basin and Fennoscandian Border Zone. In addition, the development of organic-rich mudstones is, in some cases independent of falling sea-level as indicated by the Kvols-1 section at SB 15, possibly due to the distant position of the well in relatively deep water at this time.

Distribution of the stratigraphic units with potential source rocks

Maps showing the distribution and depth of the stratigraphic units with some source rock potential, and the kerogen types in the identified potential source rocks have been produced. The kerogen type has been determined by using the relation between TOC and HI published by Katz (1983).

Gassum Formation

The Gassum Formation is present in most of the study area with a maximum thickness in the Sorgenfrei-Tornquist Zone and closely southwest of the zone. As discussed above, the formation has only a very limited source potential with kerogen type III in Mors-1 (one sample) and Hans-1, and kerogen type II Voldum-1 (one sample), Felicia-1 (one sample) and Mejrup-1 (several samples). The largest potential occurs in Hans-1 well, where an interval with a good kerogen type III is registered in accordance with the presence of several thin coaly beds.

The Mejrup-1 well is the most interesting because it shows a reasonable interval with kerogen type II. The well is drilled in a position where the formation of the secondary rim-syncline of the Vejrum Salt dome was started when the Gassum Formation was deposited (Fig. 46). Thus, the relatively good potential source rocks in the Gassum Formation in Mejrup-1 is probably a phenomena related to these salt movements, which have created favourable conditions at the Mejrup position. The lithology and depositional environment at this position differ from the typical situation, as marine mudstones dominate the succession here in contrast to marine sandstones that are common elsewhere at this level (Fig. 29). This probably reflects larger water depths caused by the salt withdrawal.

The wells Inez-1 and K-1 are situated in a relatively similar position, but these wells do not show any potential, which may be due that the fact that they are located too distant from the secondary rim-syncline to be affected (Figs 47, 48). However, in the rim-syncline close to salt-dome an amplitude anomaly is seen at the level of the Gassum Formation or F-I Member (Fig. 47). The geochemical results from Mejrup-1 and the difference in lithology in this well suggest that the proportions of marine mudstones in the Gassum Formation may increase in the deeper part of rim-synclines, and that these mudstones may posses a source rock potential.

Fjerritslev Formation, F-III Member

The F-III Member is present in the central and northern part of the study area (Fig. 49). It contains kerogen type III in some of the wells on the Skagerrak-Kattegat Platform. In the Sorgenfrei-Tornquist Zone and further southwest kerogen type II dominates. Further to the south and west in the wells Mejrup-1, Skive-1, Røddding-1, F-1 and K-1 the source potential disappears and is marked as kerogen type III in figure 49 following Katz (1983). The upper part of the F-III Member contains excellent source rocks in the Kvols-1 well. This stratigraphic interval probably correlates to a high amplitude seismic reflection in the area around the Vejrum, Sevel and Mønsted salt domes, which may be interpreted as an indication of organic-rich mudstones (Figs 50, 51). In contrast to the situation at Mejrup-1, the transition from primary to secondary rim-syncline development began at the time of deposition of F-I Member (Fig. 51). The deposition of F-III and F-IV members were strongly influenced by the secondary rim-syncline.

F-IV Member, Fjerritslev Formation

The F-IV Member is found on the Skagerrak-Kattegat Platform, in the Sorgenfrei-Tornquist Zone and just southwest of the zone (Fig. 52). The F-IV Member contains kerogen type III in the northern part of the area changing to kerogen type II southwest of the Sorgenfrei-Tornquist Zone. Especially, in the Rønde-1 well the F-IV Member contains some very good potential source rocks, that probably reflects that the deposition of F-IV Member was influenced by the occurrence of a local basin related to deep seated faults and salt tectonism (Fig. 53).

Discussion

The analyses of more than 4,700 cuttings samples from 33 wells widely scattered in the Danish Basin and the Fennoscandian Border Zone, and covering the stratigraphic interval from the Silurian, Permian and Triassic–Lower Cretaceous have shown that the only significant potential source rocks occur within the Toarcian (upper Lower Jurassic; F-III and F-IV members). Very locally in the Fennoscandian Border Zone occur some good to excellent source rocks in the uppermost Jurassic–lowermost Cretaceous (Ferderikshavn Formation), but the burial depth is very shallow.

The formation of the Toarcian source rocks and the scattered potential source rocks with a limited generative potential within other parts of the Norian–Lower Aalenian succession is clearly related to the large-scale changes in the depositional environments determined by, among other factors, the long-term regional or global sea-level changes. On a finer scale, however the formation of organic-rich marine mudstones is relatively poorly related to the sequence stratigraphic development. The lack of detailed correlation to the frequent basin-wide changes of relative sea-level is probably related to the physiography of the basin.

In Late Triassic time the basin constituted a shallow, low-gradient embayment without a shelf-slope break. The basin received a large amount of sand and mud from the basin margins, and due to effective coastal distribution processes and frequent sea-level changes, the clastic material was widely distributed in the basin diluting the organic matter. The shallow water depth and coastal processes prevented the establishment of widespread anoxia.

Due to continued subsidence and a general eustatic/regional sea-level rise, a deeper and fully marine, low-gradient shelf was established in Early Jurassic time. Rivers from the landmasses to the east and north that were exposed to extensive weathering in the humid, warm-temperate to subtropical climate, supplied a high, continuous amount of mud to the basin. Generally, sedimentation kept pace with the formation of new accommodation space, and bio-zones and facies packages are thickly developed, and omission surfaces and condensed sections are poorly developed. Seaward flowing currents carried mud in suspension into the basin, where it was deposited below average storm wave base. Local topography was smoothed out by draping mud, forming widespread uniform and thick mudstone packages with a conformably stratal pattern. Except for a few intervals, at the Sinemurian–Pliensbachian boundary and in the Toarcian, the basin was generally well-oxygenated as testified by the presence of infaunal remains. Poor preservation in combination with clastic dilution probably hindered favourable conditions for formation of organic-rich marine sediments. Locally, coaly beds were formed on the coastal plains at the basin margin in Rhaetian–Early Jurassic times during sea-level rises, but the coals are thin with a large proportion of clastic material.

The Toarcian potential source rocks seem to occur in distinct pods at three different stratigraphic levels. Within the present biostratigraphic resolution these levels correlate with organic-rich marine shales known from other European basins, e.g. Jet Rock in UK and Posidonia Shales in Germany. The contemporaneous development of organic-rich marine mudstones in several basins advocates for a common cause, which have been interpreted as related to a regional oceanic anoxic event asscociated with voluminous and rapid release of methane from gas hydrate contained in marine sediments (e.g. Hesselbo *et al.* 2000). However, the source rocks are not widely present in the Danish Basin as many well-sections contain coeval marine mudstones with a low content of organic matter. This underlines that local factors at these locations probably played a dominant role for the production and preservation of organic matter. These factors probably include relatively short distance to the shoreline, shallow water depths and turbulent water, among others.

The formation of good to excellent source rocks in the Gassum Formation in Mejrup-1, in the F-III Member in Kvols-1 and Rønde-1, and in the F-IV Member in Rønde-1 was probably favoured by local depressions caused by salt-movements and faulting. In these depressions the delicate balance between primary organic production and preservation, and clastic input was more optimal than generally in the basin, and it is further possible that local anoxia or low levels of oxygenation in the depressions due to a stratified water column and development of dense, salty bottom water further favoured the preservation of marine algae (kerogen type II). Occasionally, the seismic data display amplitude anomalies in the rim-synclines to salt-structures at these stratigraphic levels, and these anomalies are interpreted to represent organic-rich intervals corresponding to those drilled in a few wells. It is possible that solution of the neighboring salt-diapirs contributed to the formation of salt brines.

Owing to late Early Jurassic–early Middle Jurassic regional uplift, the Toarcian is erosively truncated outside the Sorgenfrei-Tornquist Zone, limiting the extent of the best potential source rocks. The distribution of the Toarcian interval with the potential source rocks is therefore structurally controlled on a regional scale.

Based on a large number of vitrinite reflectance data corrected for Late Cretaceous–Early

Cenozoic inversion and Late Cenozoic regional uplift and exhumation, an optimistic depth to the oil window is estimated to approximately 3,250 m by accepting 0.6%R as the start of oil generation. In the sections drilled so far, the deepest burial depth of the Toarcian before uplift was less than 3,250 m, and generally less than 2,900 m. The Toarcian is therefore thermally immature, and has not generated hydrocarbons in the known sections. Seismic mapping further indicate that Toarcian deposits within the study area are too shallow buried today and also before the later uplift to be mature.

It is thus concluded that the absence of mature source rocks is the major risk for successful hydrocarbon exploration in the Danish Basin and Fennoscandian Border Zone. A regional, mature source rock has not been found. The search for mature source rocks should therefore be directed towards areas where an increased subsidence and/or heat flow have occurred, such as local fault-bounded grabens or rim-synclines developed near salt diapirs.

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Figure Captions

Fig. 1: Well-locations and principal structural units of the study area. The outline of the Ringkøbing-Fyn High is based on the distribution of Zechstein deposits. The Sorgenfrei-Tornquist Zone merges with the Teisseyre-Tornquist Zone offshore Bornholm in the Rønne Graben (bottom rigth; Rø Gr) (Modified from Michelsen & Nielsen 1991 and Vejbæk 1997).

Fig. 2: A regional SW-NE geosection through the Danish Basin and Fennoscandian Border Zone.

Fig. 3: A: Generalised subcrop contour map of the "Base Middle Jurassic Unconformity". The contours are based on the recognised sequences, lithostratigraphy from Nielsen and Japsen (1991), age determinations from Dybkjær (1988, 1991) and Poulsen (1996), Norling & Bergström (1987) and Erlström *et al* (1997). Sinemurian (Sin.) deposits are preserved NE of the STZ in Skåne, while Toarcian (Toar.) deposits occur in Hanø Bay. B: Generalised contour map showing the onlap to the "Base Middle Jurassic Unconformity". Bajocian (Baj.) deposits occur in Hanø Bay. Both the subcrop contours and the onlap contours parallel the general trend of the Ringkøbing-Fyn High. Modified from (Nielsen in press).

Fig. 4: Lithostratigraphic scheme based on Poulsen (1969, 1974); Bertelsen (1978, 1980), Michelsen (1978, 1989a), Nielsen *et al.* (1995) and Michelsen *et al.* (in press).

Fig. 5: HI versus depth plot for the Mejrup-1 well. A marginal to good source potential is present in the Gassum Formation.

Fig. 6: HI versus depth plot for the Hyllebjerg-1 well. In particular the F-IV Member of the Fjerritslev Formation possesses a marginal to good source potential

Fig. 7: HI versus depth plot for the Kvols-1 well. The F-III Member of the Fjerritslev Formation is an excellent source rock with HI values extending to 529 mg HC/g TOC.

Fig. 8: HI versus depth plot for the Rønde-1 well. The F-III and F-IV members of the Fjerritslev Formation are excellent source rock units with HI values extending to 428 and 543 mg HC/g TOC, respectively.

Fig. 9: HI versus depth plot for the Terne-1 well. The Frederikshavn Formation an extraordinary good source potential with HI values extending to 1125 mg HC/g TOC, indicating the presence of lacustrine kerogen type I source rocks.

Fig. 10: S_2 versus TOC plot of the F-I samples showing that the F-I Member in general is a poor source rock.

Fig. 11: S_2 versus TOC plot of the F-II samples showing that the F-II Member in general is a poor source rock.

Fig. 12: S_2 versus TOC plot of the F-III samples showing that the F-III Member may contain good source rocks and in some wells possesses an excellent source potential.

Fig. 13: S_2 versus TOC plot of the F-IV samples showing that the F-IV Member may contain good source rocks and in some wells possesses an excellent source potential.

Fig. 14: HI versus T_{max} plot of samples from the F-I Member indicating a predominantly kerogen type III and IV source rock and a poor hydrocarbon generation capacity.

Fig. 15: HI versus T_{max} plot of samples from the F-II Member indicating a predominantly kerogen type III and IV source rock and a poor hydrocarbon generation capacity.

Fig. 16: HI versus T_{max} plot of samples from the F-III Member indicating the presence of kerogen type II source rocks. Compared to the F-I and F-II members the overall source potential has increased, and in places a good to excellent hydrocarbon generation capacity is present.

Fig. 17: HI versus T_{max} plot of samples from the F-IV Member indicating the presence of kerogen type II source rocks. Compared to the F-I and F-II members the overall source potential has increased, and in places a good to excellent hydrocarbon generation capacity is present.

Fig. 18: Uplift-corrected maturation gradient for 15 wells in the Danish Basin, Fennoscandian Border Zone and the Skagerrak-Kattegat Platform (n = 249; correlation coefficient = 0.88) (From Petersen *et al.*, in press). The start of the conventional oil window at 0.6%R_o is located at 3250 m depth. In these wells the good source rock units (F-III and F-IV members) are generally lying above the oil window. The Mors-1 and Års-1 wells are the only two wells in which the Fjerritslev Formation is buried below the start of the oil window, but in both wells the source potential is poor.

Figure 19: Upper Cretaceous TWT depth to center of formation versus interval velocity.

Figure 20: Base Upper Cretaceous–Middle Jurassic Unconformity. TWT depth to center of formation versus interval velocity.

Figure 21: Fjerritslev Formation. TWT depth to center of formation versus interval velocity.

Figure 22: Structural depth map of Base Upper Cretaceous.

Figure 23: Structural depth map of Base Middle Jurassic Unconformity ("MCU"; Base Haldager Sand Formation).

Figure 24: Structural depth map of the top of the F-I member of the Fjeritslev Formation.

Figure 25: Isochore map for the interval F-II, F-III & F-IV members of the Fjeritslev Formation.

Figure 26: Structural depth map of the Top Triassic (Top Gassum Formation).

Fig. 27: Schematic time-stratigraphic SW-NE section from Ringkøbing-Fyn High (RKF) across the Danish Basin and Sorgenfrei-Tornquist Zone (STZ) to the Skagerrak-Kattegat Platform (SKP) showing depositional sequences and environments against chronostratigraphy and

lithostratigraphy. Sequence stratigraphic key-surfaces are drawn at their most likely age. Hiati are shown in grey. A deep erosional truncation of the pre-Lower Aalenian strata and an Upper Jurassic onlap younging toward the RKF are indicated. The "base Cretaceous unconformity" merges with the "base Middle Jurassic Unconformity" close to the high. The hiati in the Skagerrak-Kattegat Platform illustrate limited accommodation space here due to relatively slow subsidence in Norian–Callovian time. The duration of the Middle Jurassic hiati is poorly constrained. Time-scale from Gradstein *et al.* (1994).

Fig. 28: Map showing the position of the well-logs panels in figure 29–31.

Fig. 29: SW-NE well-log panel across the Danish Basin, Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform showing two sequences, the Norian–lower Rhaetian Vi 1 bounded by TS 1 and SB 5, and the Rhaetian–lowermost Hettangian Ga 1 bounded by SB 5 and SB 9. The lower part of the Hettangian Fj 1 sequence is shown in the upper part of the panel. The TST of sequence Vi 1 (TS 1–MFS 1) consists of simple backstepping parasequences, while the HST shows a more complex development with three minor sequences bounded by SB 2 through SB 5. Likewise, the Ga 1 sequence consists of four minor sequences bounded by SB 5 through SB 9. The boundaries marked in bold are defined by changes in stacking pattern of the minor sequences which is most clearly seen in distal successions such as Vemb-1, Mejrup-1 and Rødding-1. Modified from Nielsen (in press).

Fig. 30: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession TS 1 to SB 9, corresponding to the Vinding Formation, most of the Gassum Formation and upper part of the Skagerrak Formation; dip section.

Fig. 31: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession TS 1 to SB 9, corresponding to the Vinding Formation, most of the Gassum Formation; strike section.

Fig. 32: Map showing the position of the well-logs panels in figure 33–34.

Fig. 33: SW-NE well-log panel across the Danish Basin to the Skagerrak-Kattegat Platform showing the upper part of the Rhaetian-lowermost Hettangian sequence Ga 1 and the Hettangian–Sinemurian sequences Fj 1, Fj 2 and Fj 3, and lower part of Fj 4. Note the thickly developed HST of sequence Fj 1 in Børglum-1 and Flyvbjerg-1 on the basin-ward side of the Børglum Fault. The interbedding of estuarine sandstones with marine mudstones and sandstones indicates repeated fluctuations of sea level during the formation of the HST and suggest the presence of several minor sequences at this level. Modified from Nielsen (in press).

Fig. 34: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 9 to SB 13, corresponding to the Fjerritslev Formation and the upper part of the Gassum Formation; strike section.

Fig. 35: Map showing the position of the well-logs panels in figure 36–38.

Fig. 36: Well-log panel showing the basinal part of the sequences Fj 1 through Fj 8 from Hyllebjerg-1 (Himmerland Graben) toward more basinal well-sections. An increasing amount

of erosion is seen toward the southwest below the "Base Middle Jurassic Unconformity" consisting of the amalgamated SB 19-22. The log-markers (a–m) recognised by Michelsen (1989b) are defined by subtle changes in lithology, and are interpreted as chronostratigraphic markers that reflect basin-wide changes in the relatively uniform and deep marine environment. Modified from Nielsen (in press).

Fig. 37: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 13 to SB 19, corresponding to the Fjerritslev Formation; dip section.

Fig. 38: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 9 to SB 13, corresponding to the Fjerritslev Formation and the upper part of the Gassum Formation; strike section.

Fig. 39: Map showing the position of the well-logs panel in figure 40.

Fig. 40: Well-log panel showing the development of sequence Fj 5 through Fj 8 from Hyllebjerg-1 to more proximal well-section on the Skagerrak-Kattegat Platform. Note the large amount of truncation at SB 15. Modified from Nielsen (in press).
Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 13 to SB 19, corresponding to the Fjerritslev Formation; dip section.

Fig. 41: Map showing the position of the well-logs panels in figure .

Fig. 42: Well-log panel showing the Toarcian–Kimmeridgian sequences across the Danish Basin to the Skagerrak-Kattegat Platform. Note the deep truncation at the base of the "Middle Jurassic" (SB 19-22) outside the fault-bounded Sorgenfrei-Tornquist Zone clearly indicating that deposition continued in the Sorgenfrei-Tornquist Zone in Middle Jurassic time while erosion prevailed at other places. Modified from Nielsen (in press).

Fig. 43: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 19 to TS 22, corresponding to the Fjerritslev Formation; dip section.

Fig. 44: Well-log panel displaying sequence stratigraphy versus organic geochemistry of the succession SB 19 to TS 22, corresponding to the Fjerritslev Formation; strike section.

Fig. 45: Well-log panel from the Ringkøbing-Fyn High (Ullerslev-1) to the northeastern basin margin (Skagen-2) summarising the Upper Triassic–Upper Jurassic third-order sequences, their key-surfaces and depositional environment. Modified from Nielsen (in press).

Fig. 46: North–south trending seismic section showing local effect in the Mejrup-1 area; refer to fig. 54 for location.

Fig. 47: North–south trending seismic section showing local effect in the Inez-1 area. Note the seismic anamoly in the rim-syncline at the level of Gassum Fm or F-I Mb (left part of section). Refer to fig. 54 for location.

Fig. 48: Aproximately north–south trending seismic section showing local effect in the K-1 area.

Refer to fig. 54 for location.

Fig. 49: Map showing the distibution and depth of the F-III Member, and kerogen types. The map is constructed by adding the thickness of F-IV Member to the Base Middle Jurassic depth map.

Fig. 50: West–east trending seismic section showing local high amplitude anomaly at the F-III Member level in the Kvols area, that may indicate the presence of organic-rich mudstones. Refer to fig. 54 for location.

Fig. 51: South–north trending seismic section showing local high amplitude anomaly at the F-III Member level in the Kvols area, that may indicate the presence of organic-rich mudstones. Refer to fig. 54 for location.

Fig. 52: Map showing the distibution and depth of the F-IV Member, and kerogen types. The map corresponds to the Base Middle Jurassic map with minor depth corrections.

Fig. 53: East–west trending seismic section through Rønde-1 well showing the formation of a local basin caused by deep-seated faults and salt movements. Refer to fig. 54 for location.

Fig. 54: Map displaying the positions of the seismic sections shown in figs 46–48, 50, 51; 53.

Table 1.

Enclosure 1.

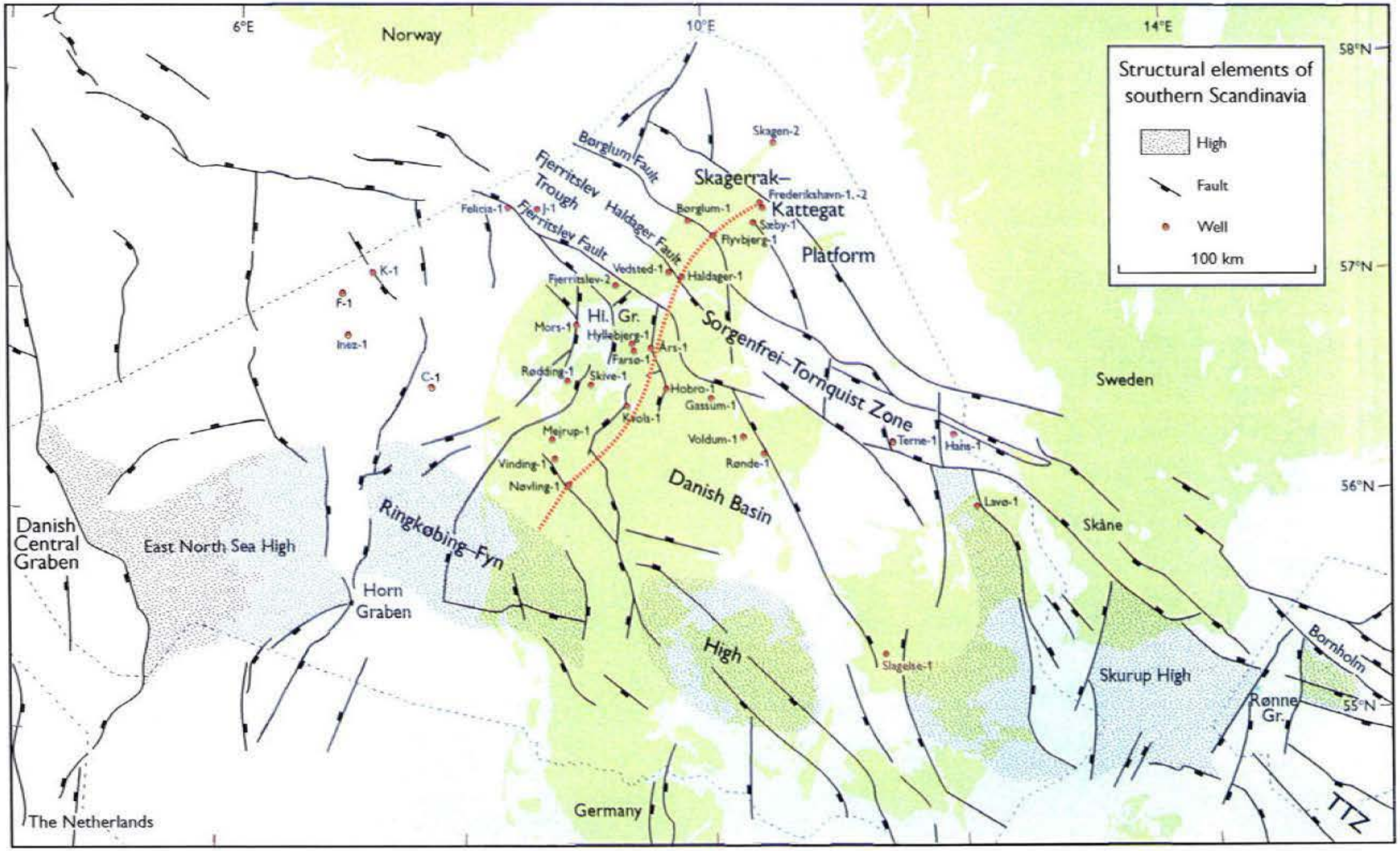

6°E
Norway
10°E
14°E
58°N
57°N
56°N
55°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Skagen-2
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Vedsted-1
Haldager-1
Fjerritslev-2
Hl. Gr.
Mors-1
Hyllebjerg-1
Års-1
Farsø-1
Rødding-1
Skive-1
Hobro-1
Gassum-1
Kvols-1
Mejrup-1
Voldum-1
Vinding-1
Rønde-1
Nøvling-1
Sorgenfrei–Tornquist Zone
Terne-1
Hans-1
Sweden
Danish Basin
Lavø-1
Skåne
Ringkøbing–Fyn High
Danish Central Graben
East North Sea High
Horn Graben
Slagelse-1
Skurup High
Bornholm
Rønne Gr.
TTZ
Germany
The Netherlands

Fig.1

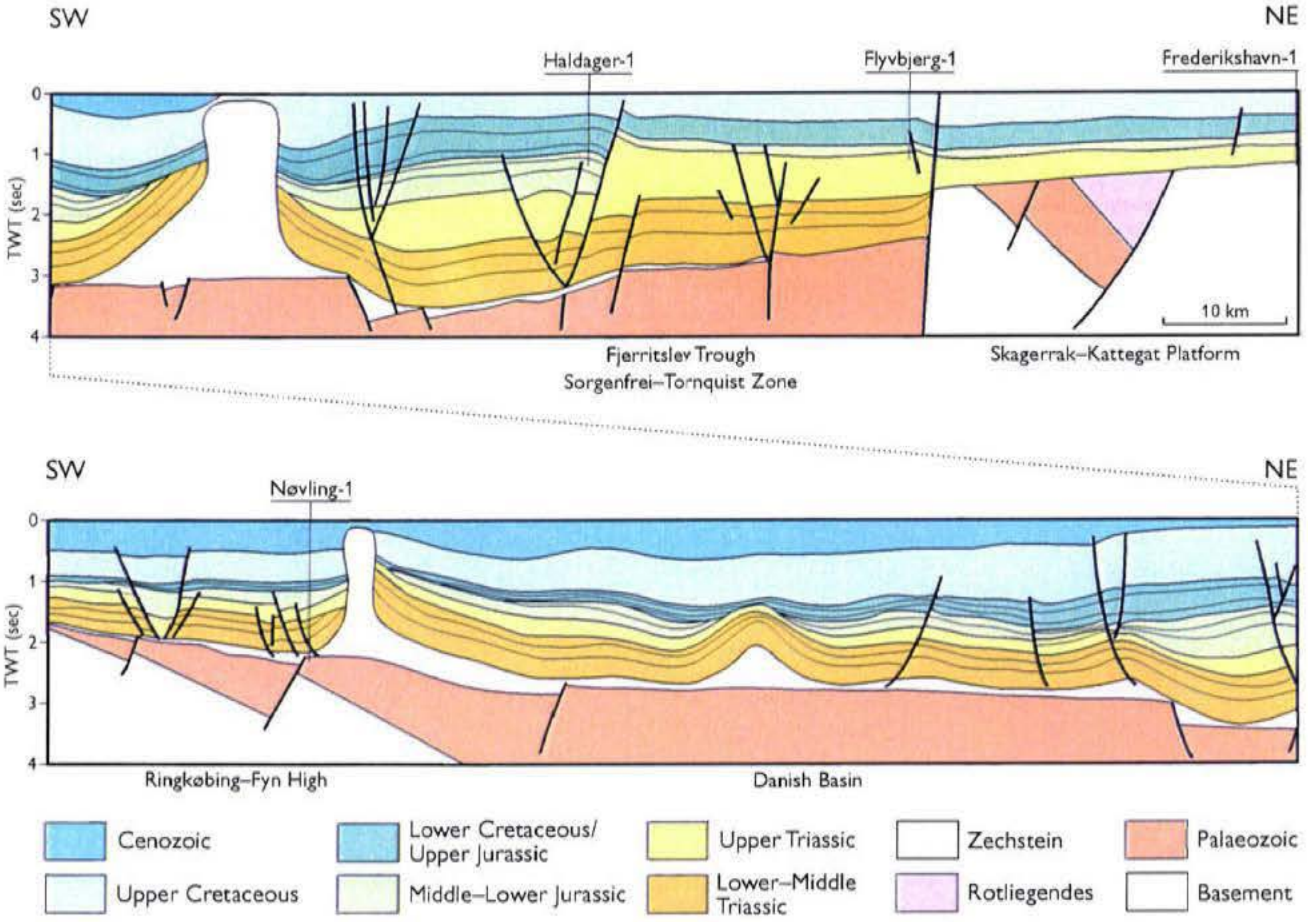

SW
NE
Haldager-1
Flyvbjerg-1
Frederikshavn-1
TWT (sec)
0
1
2
3
4
10 km
Fjerritslev Trough
Sorgenfrei–Tornquist Zone
Skagerrak–Kattegat Platform
SW
NE
Nøvling-1
TWT (sec)
0
1
2
3
4
Ringkøbing–Fyn High
Danish Basin
Cenozoic
Upper Cretaceous
Lower Cretaceous/ Upper Jurassic
Middle–Lower Jurassic
Upper Triassic
Lower–Middle Triassic
Zechstein
Rotliegendes
Palaeozoic
Basement

Fig.2

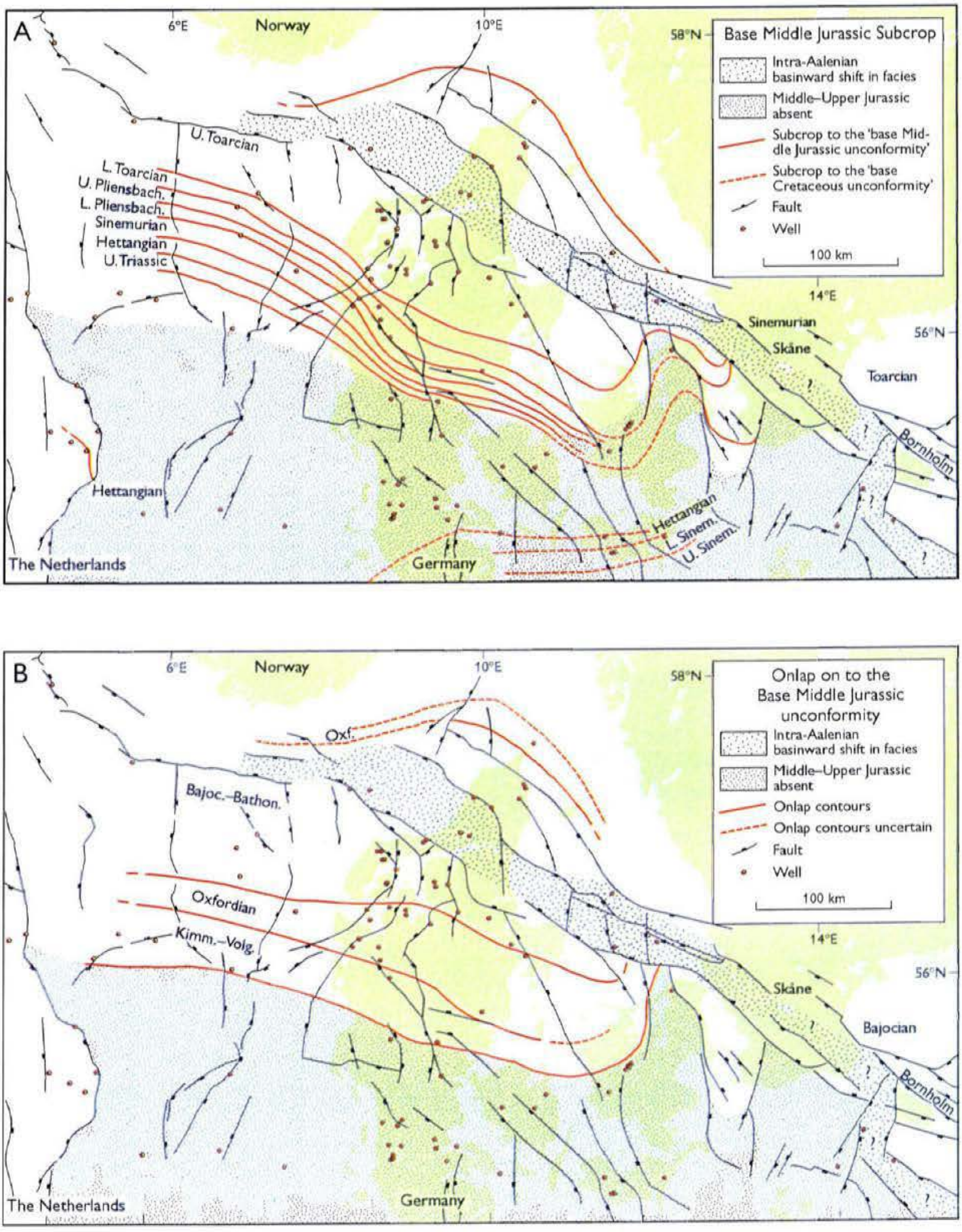

A
6°E
Norway
10°E
58°N
Base Middle Jurassic Subcrop
Intra-Aalenian basinward shift in facies
Middle–Upper Jurassic absent
Subcrop to the 'base Middle Jurassic unconformity'
Subcrop to the 'base Cretaceous unconformity'
Fault
Well
100 km
14°E
56°N
U. Toarcian
L. Toarcian
U. Pliensbach.
L. Pliensbach.
Sinemurian
Hettangian
U. Triassic
Sinemurian
Skåne
Toarcian
Bornholm
Hettangian
Hettangian
L. Sinem.
U. Sinem.
The Netherlands
Germany
B
6°E
Norway
10°E
58°N
Onlap on to the Base Middle Jurassic unconformity
Intra-Aalenian basinward shift in facies
Middle–Upper Jurassic absent
Onlap contours
Onlap contours uncertain
Fault
Well
100 km
14°E
56°N
Oxf.
Bajoc.–Bathon.
Oxfordian
Kimm.–Volg.
Skåne
Bajocian
Bornholm
The Netherlands
Germany

Fig.3

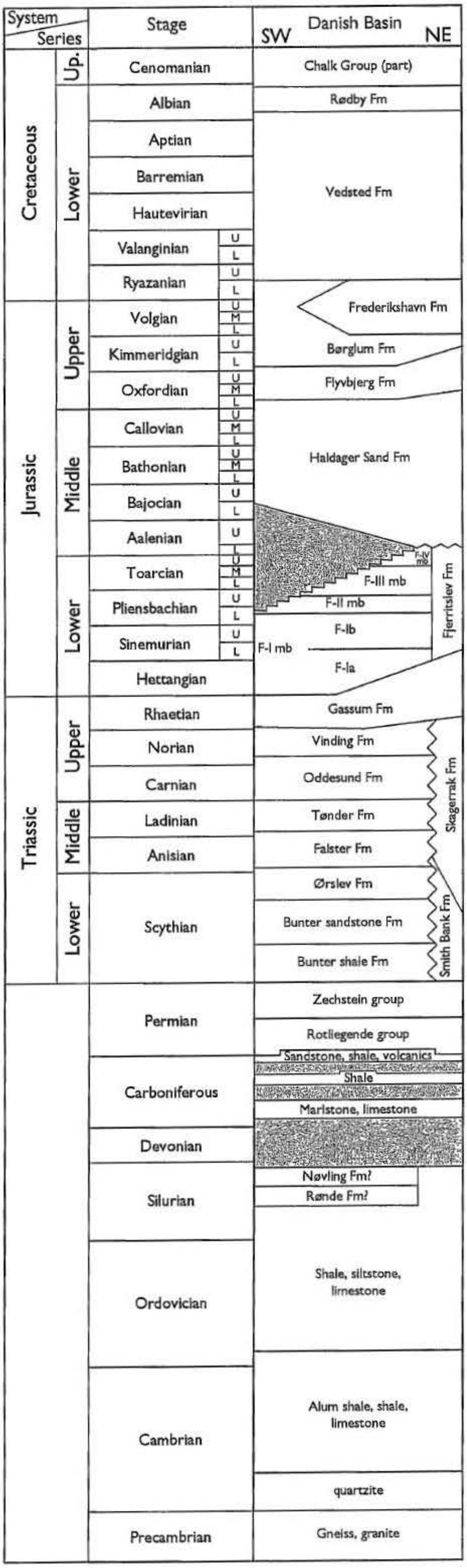
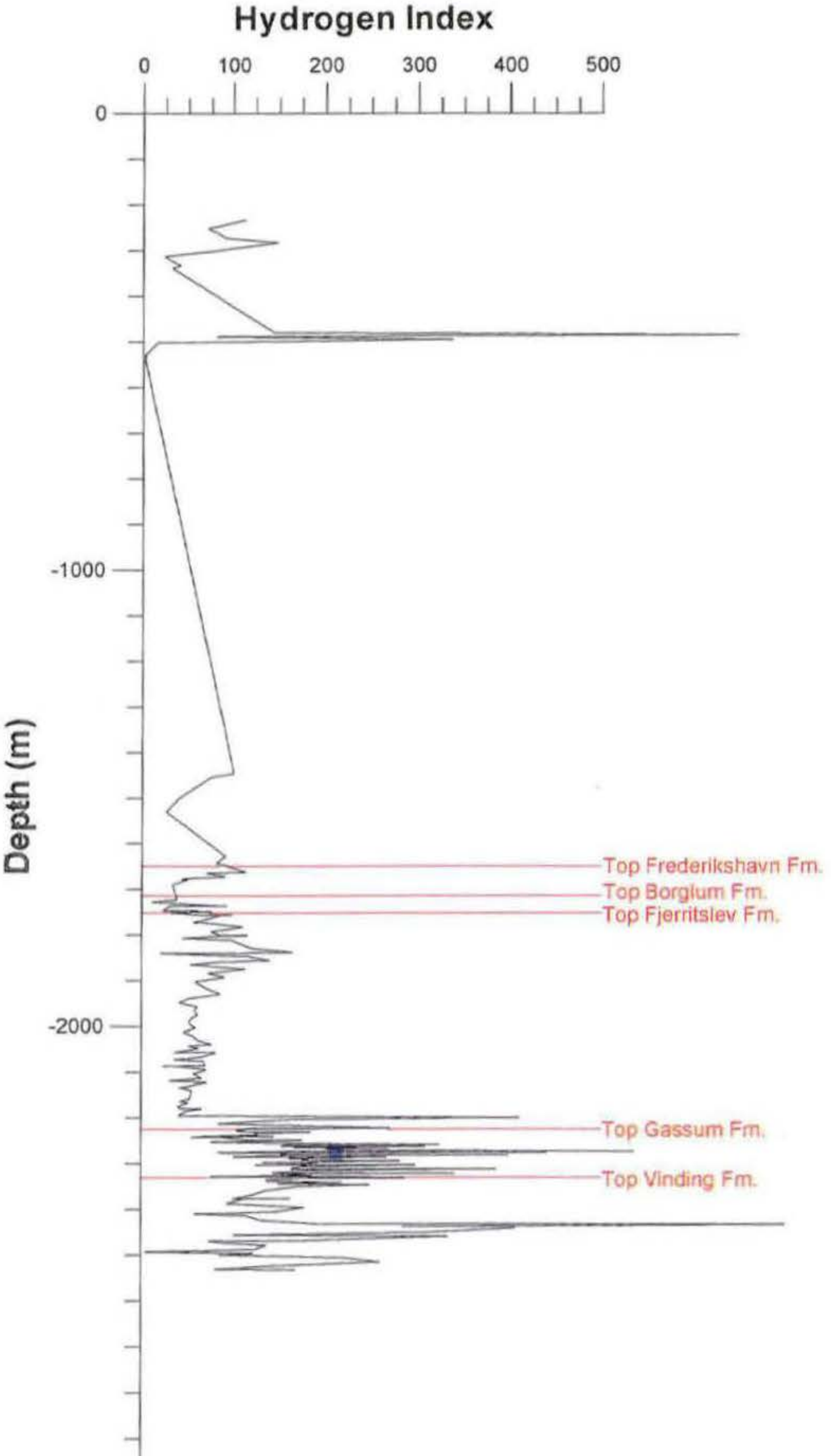

System
Series
Stage
Danish Basin
SW
NE
Cretaceous
Up.
Lower
Cenomanian
Albian
Aptian
Barremian
Hauteverian
Valanginian
Ryazanian
Chalk Group (part)
Rødby Fm
Vedsted Fm
Jurassic
Upper
Middle
Lower
Volgian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
U
M
L
Frederikshavn Fm
Børglum Fm
Flyvbjerg Fm
Haldager Sand Fm
F-IV mb
F-III mb
F-II mb
F-Ib
F-I mb
F-Ia
Fjerritslev Fm
Triassic
Upper
Middle
Lower
Rhaetian
Norian
Carnian
Ladinian
Anisian
Scythian
Gassum Fm
Vinding Fm
Oddesund Fm
Tønder Fm
Falster Fm
Ørslev Fm
Bunter sandstone Fm
Bunter shale Fm
Skagerrak Fm
Smith Bank Fm
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Zechstein group
Rotliegende group
Sandstone, shale, volcanics
Shale
Marlstone, limestone
Nøvling Fm?
Rønde Fm?
Shale, siltstone, limestone
Alum shale, shale, limestone
quartzite
Gneiss, granite

Fig.4


Hydrogen Index
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100
200
300
400
500
0
-1000
-2000
-3000
Depth (m)
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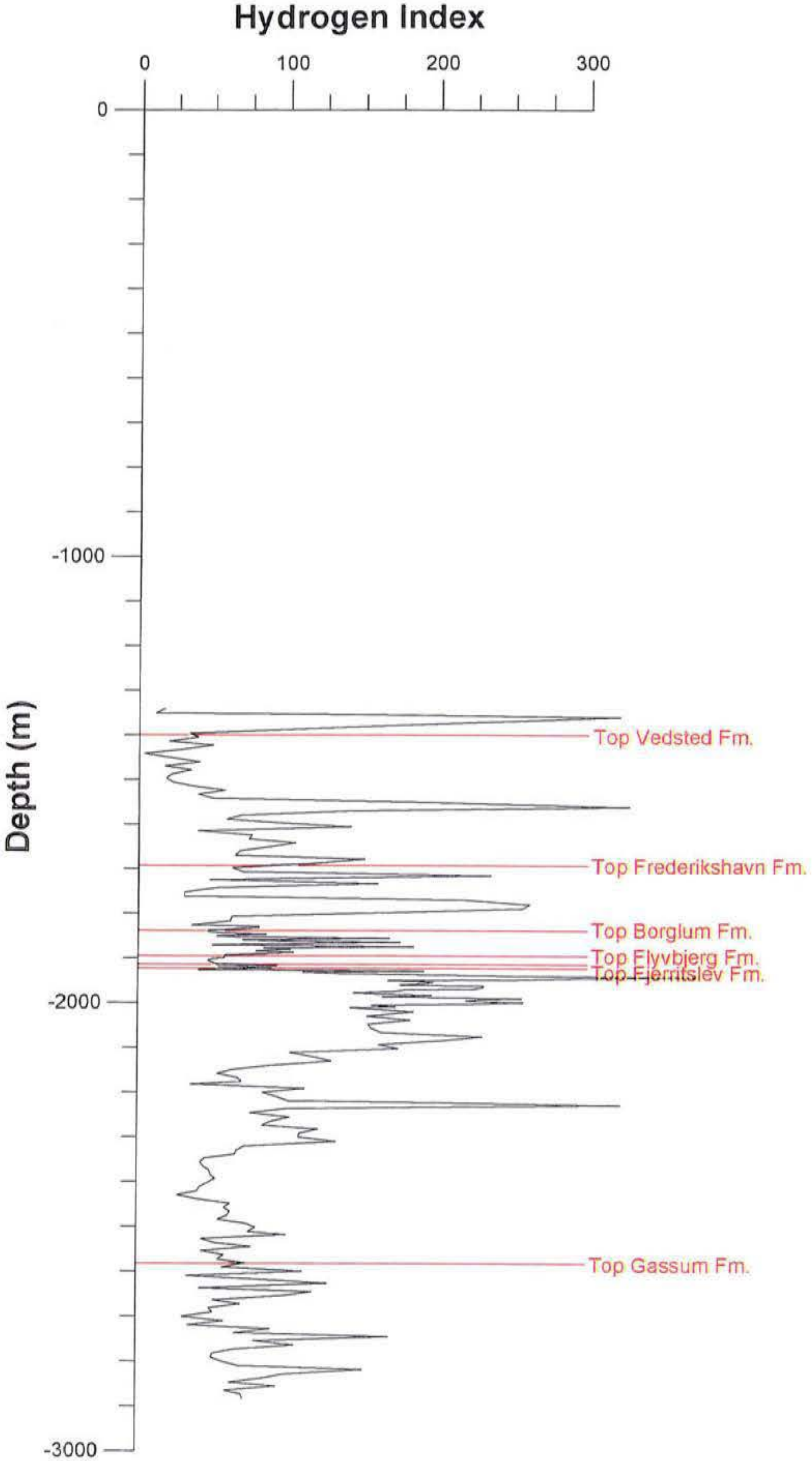
Top Borglum Fm.
Top Fjerritslev Fm.
Top Gassum Fm.
Top Vinding Fm.

Fig. 5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100
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-3000
Depth (m)
Top Vedsted Fm.
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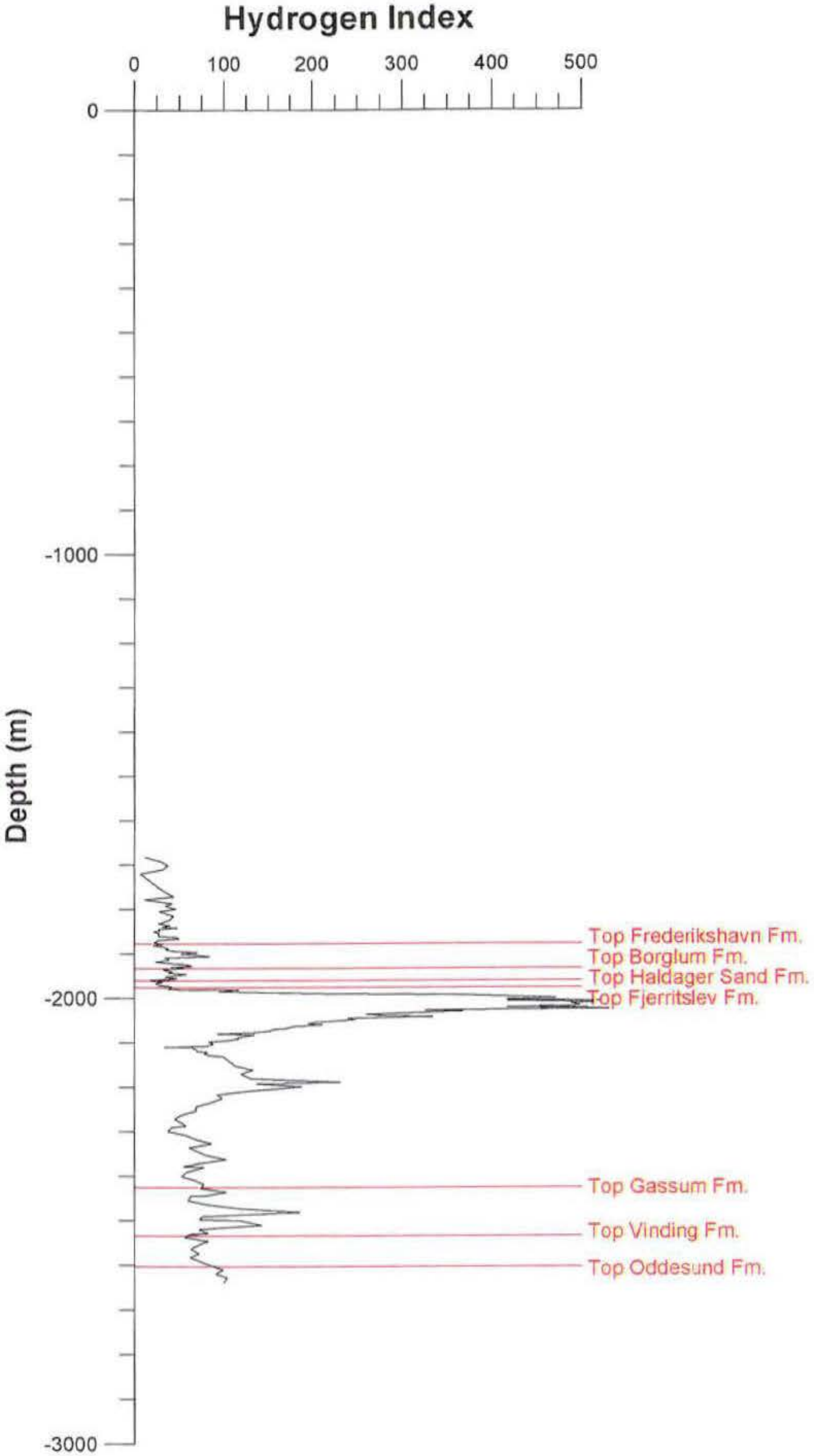
Top Borglum Fm.
Top Flyvbjerg Fm.
Top Fjerritslev Fm.
Top Gassum Fm.

Fig. 6


Hydrogen Index
0
100
200
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500
Depth (m)
0
-1000
-2000
-3000
Top Frederikshavn Fm.
Top Borglum Fm.
Top Haldager Sand Fm.
Top Fjerritslev Fm.
Top Gassum Fm.
Top Vinding Fm.
Top Oddesund Fm.

Fig. 7

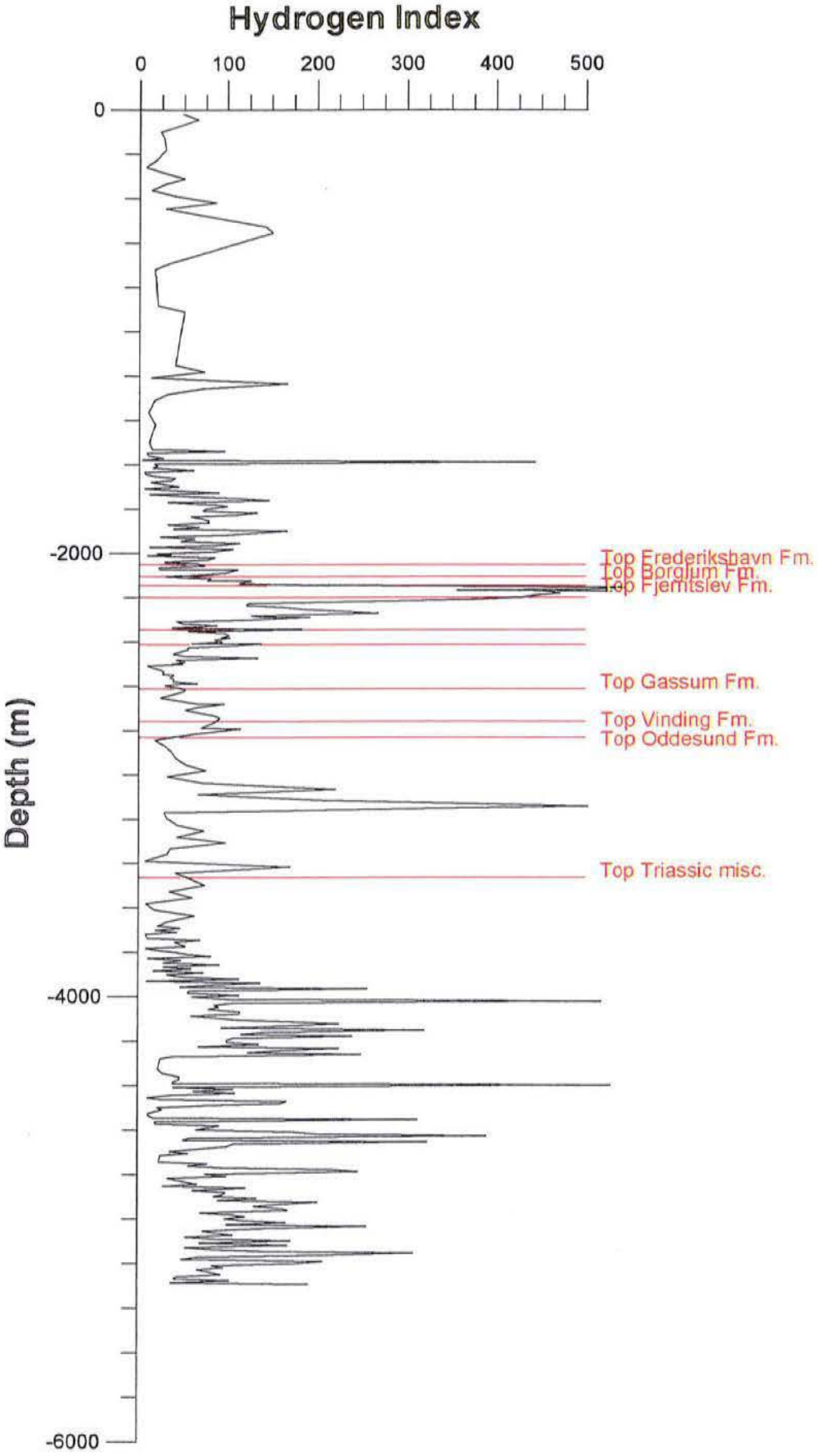

Hydrogen Index
0
100
200
300
400
500
0
-2000
-4000
-6000
Depth (m)
Top Frederikshavn Fm.
Top Borglum Fm.
Top Fjerritslev Fm.
Top Gassum Fm.
Top Vinding Fm.
Top Oddesund Fm.
Top Triassic misc.

Fig. 8

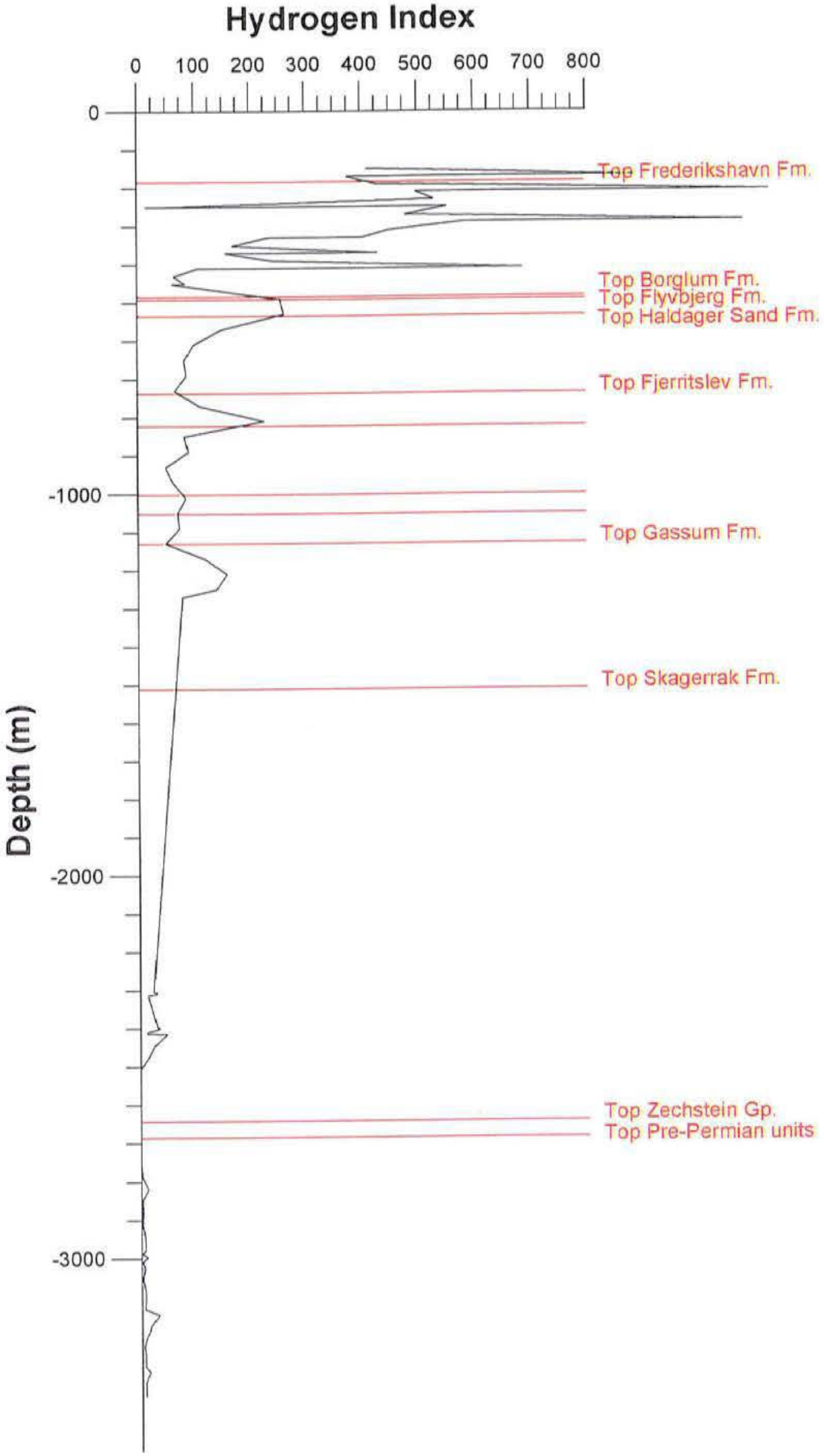

Hydrogen Index
0
100
200
300
400
500
600
700
800
0
-1000
-2000
-3000
Depth (m)
Top Frederikshavn Fm.
Top Borglum Fm.
Top Flyvbjerg Fm.
Top Haldager Sand Fm.
Top Fjerritslev Fm.
Top Gassum Fm.
Top Skagerrak Fm.
Top Zechstein Gp.
Top Pre-Permian units

Fig. 9

Fjerritslev Formation, F-1 Member, n=575

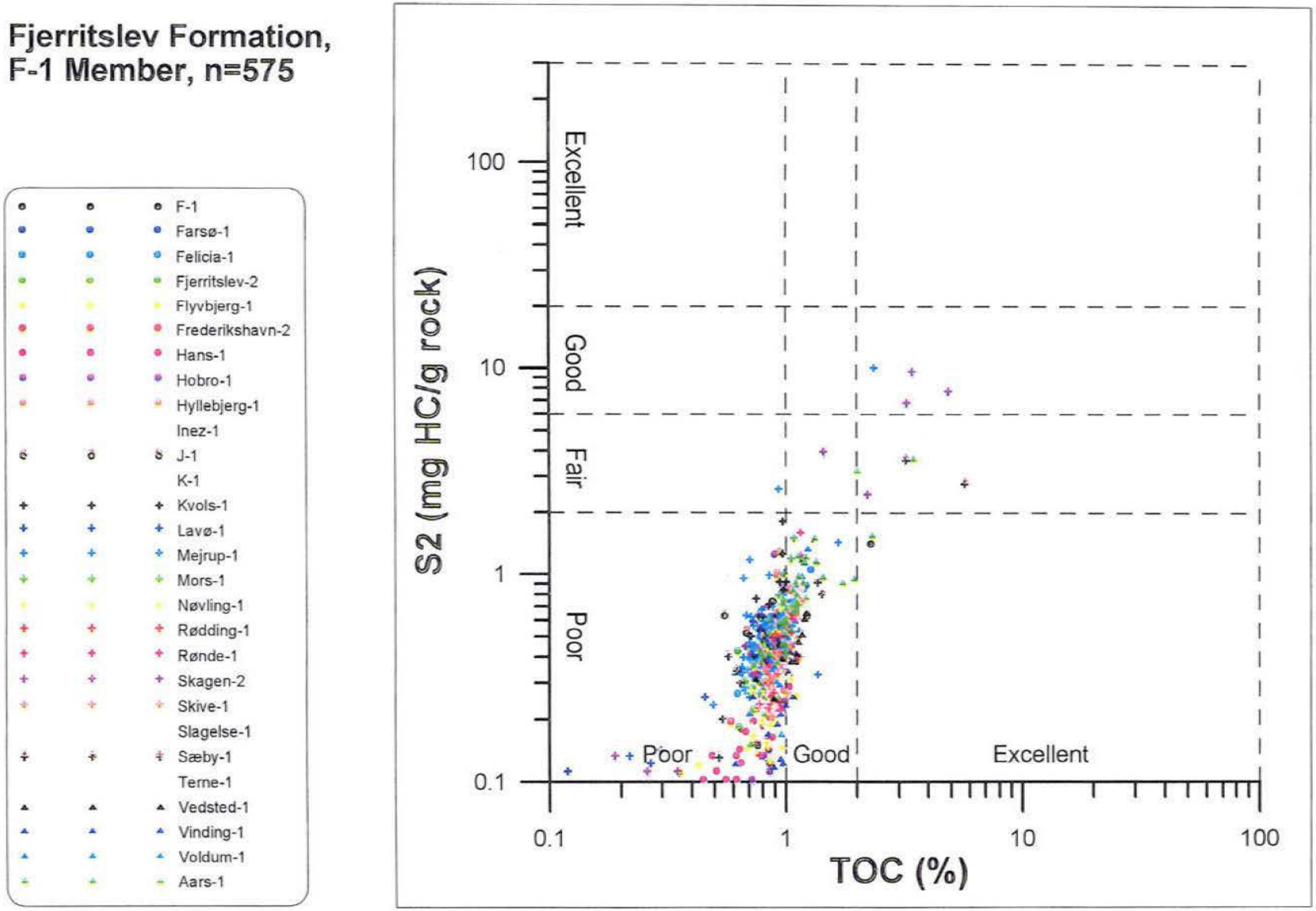
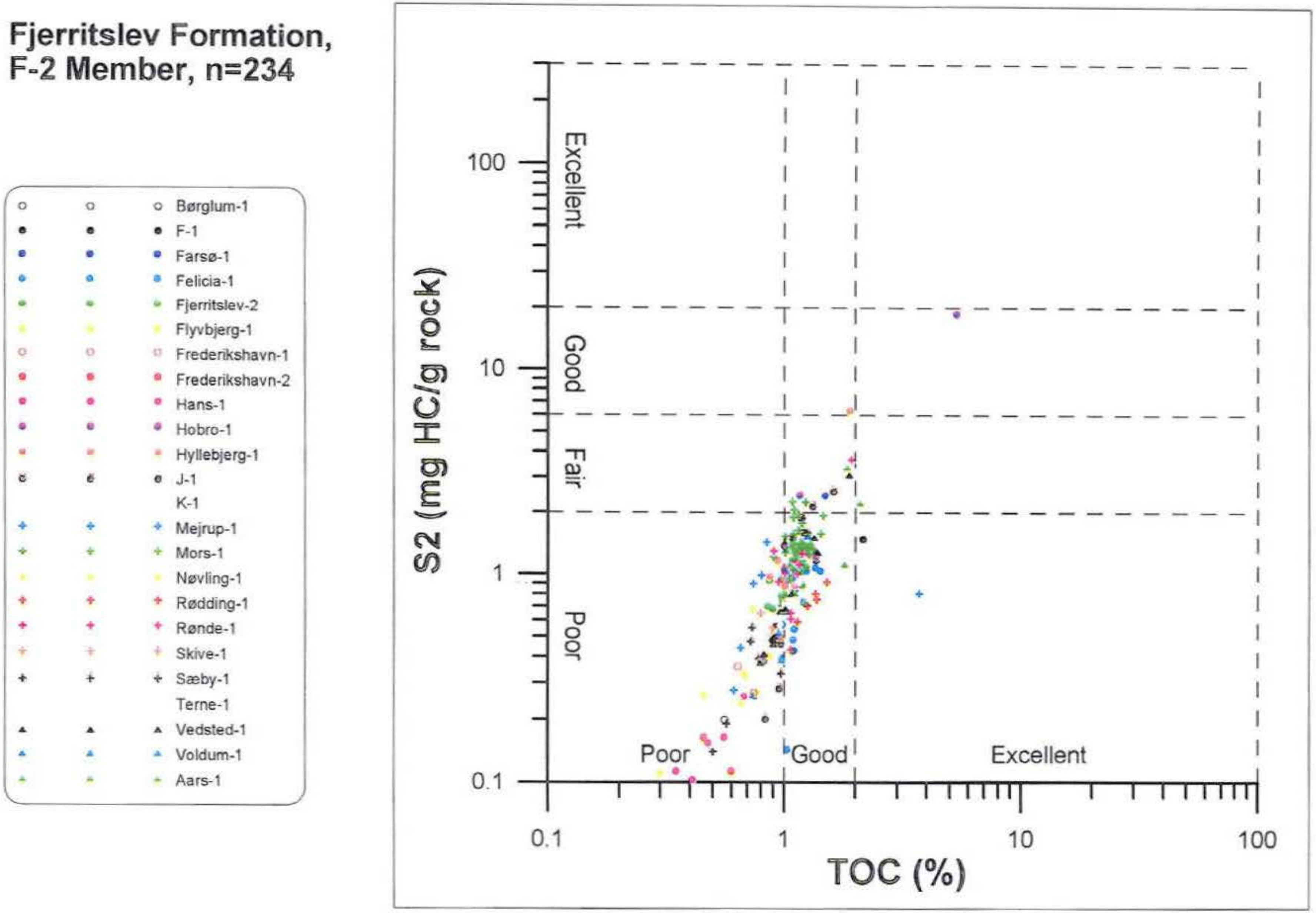


Fig. 10



Fjerritslev Formation, F-2 Member, n=234

Fig. 11

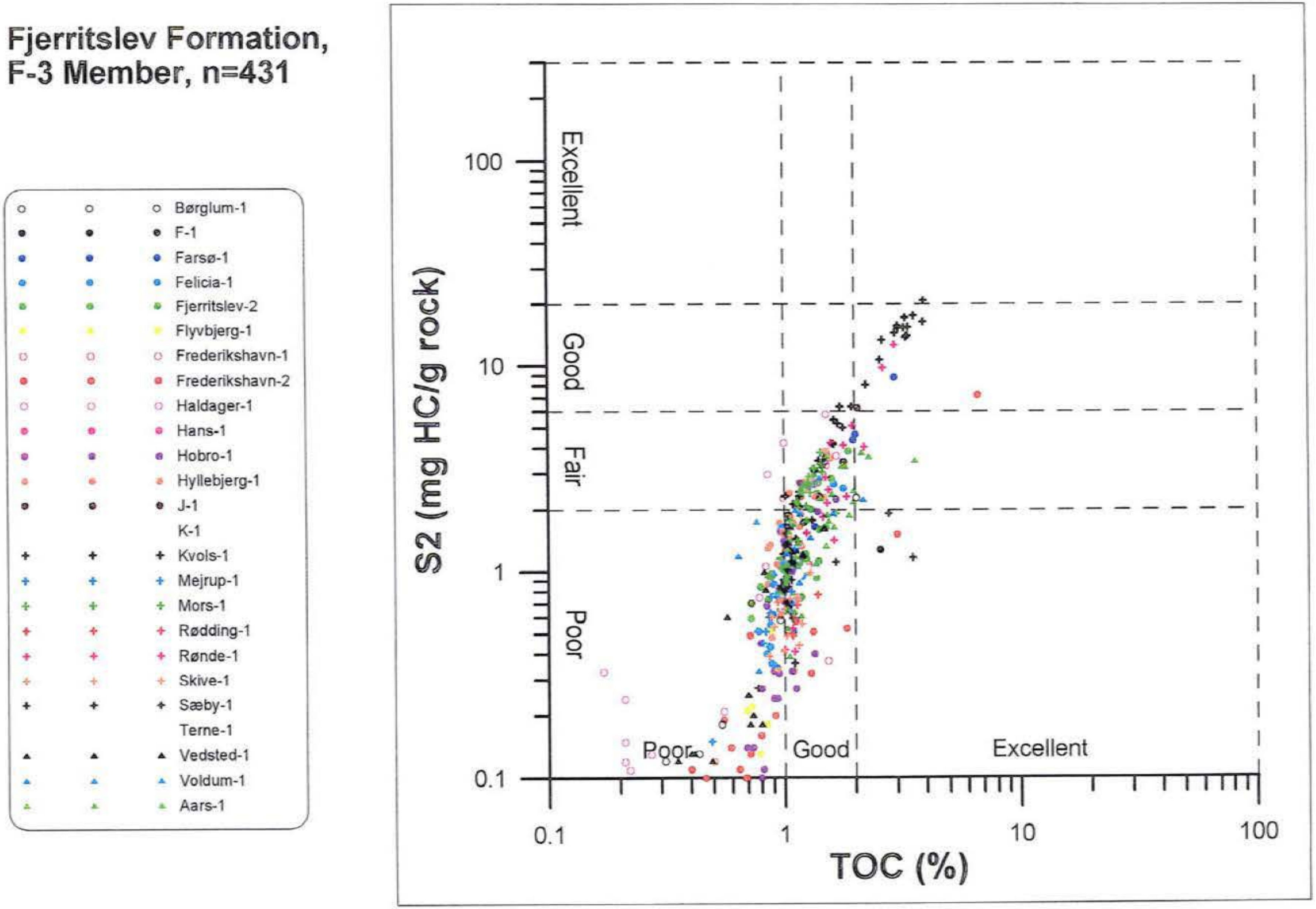

Fjerritslev Formation, F-3 Member, n=431
Børglum-1
F-1
Farsø-1
Felicia-1
Fjerritslev-2
Flyvbjerg-1
Frederikshavn-1
Frederikshavn-2
Haldager-1
Hans-1
Hobro-1
Hyllebjerg-1
J-1
K-1
Kvols-1
Mejrup-1
Mors-1
Rødding-1
Rønde-1
Skive-1
Sæby-1
Terne-1
Vedsted-1
Voldum-1
Aars-1
S2 (mg HC/g rock)
100
10
1
0.1
Excellent
Good
Fair
Poor
Poor
Good
Excellent
0.1
1
10
100
TOC (%)

Fig. 12

**Fjerritslev Formation,
F-4 Member, n=318**

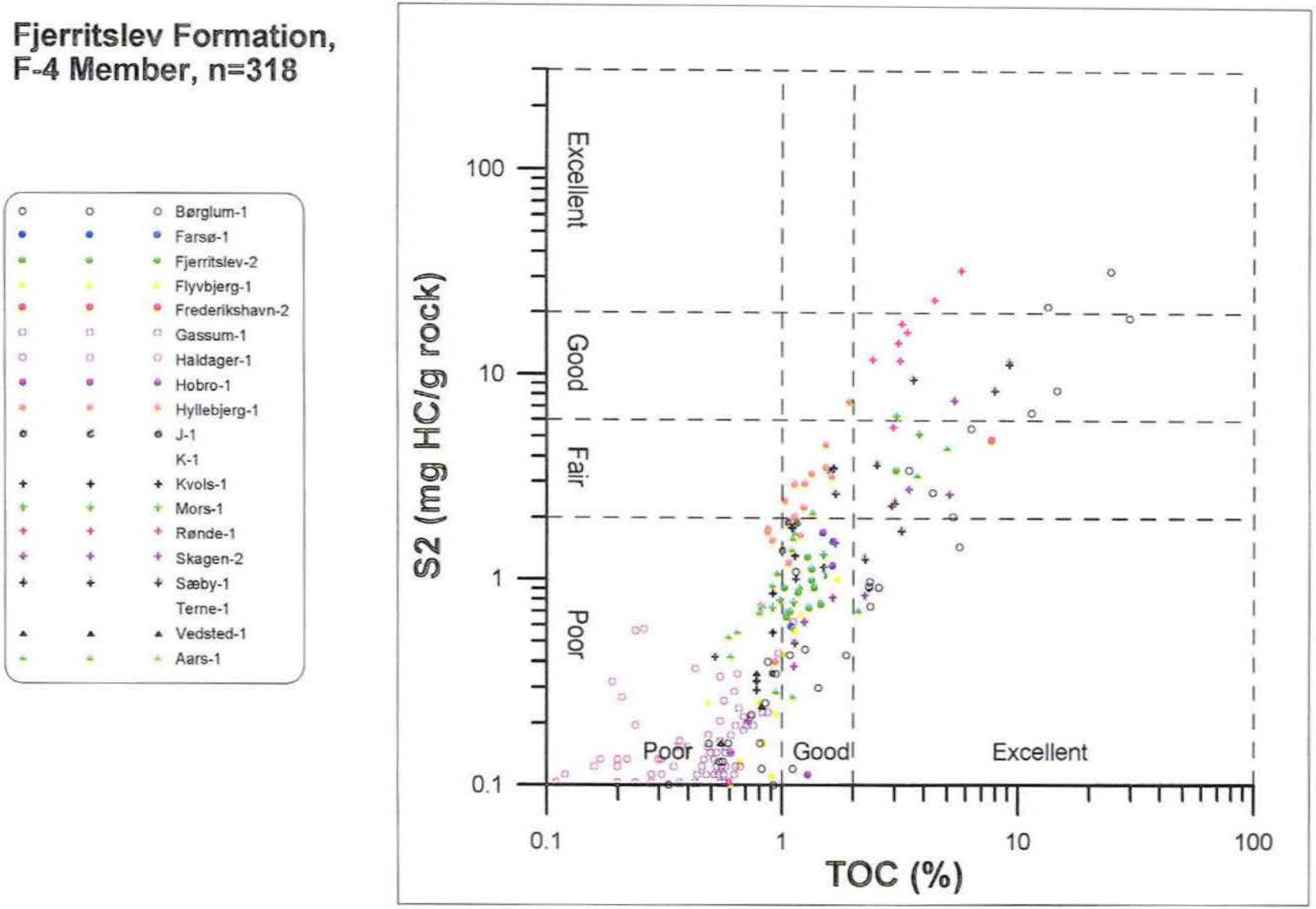


Fig. 13

Fjerritslev Formation, F-1 Member, n=575

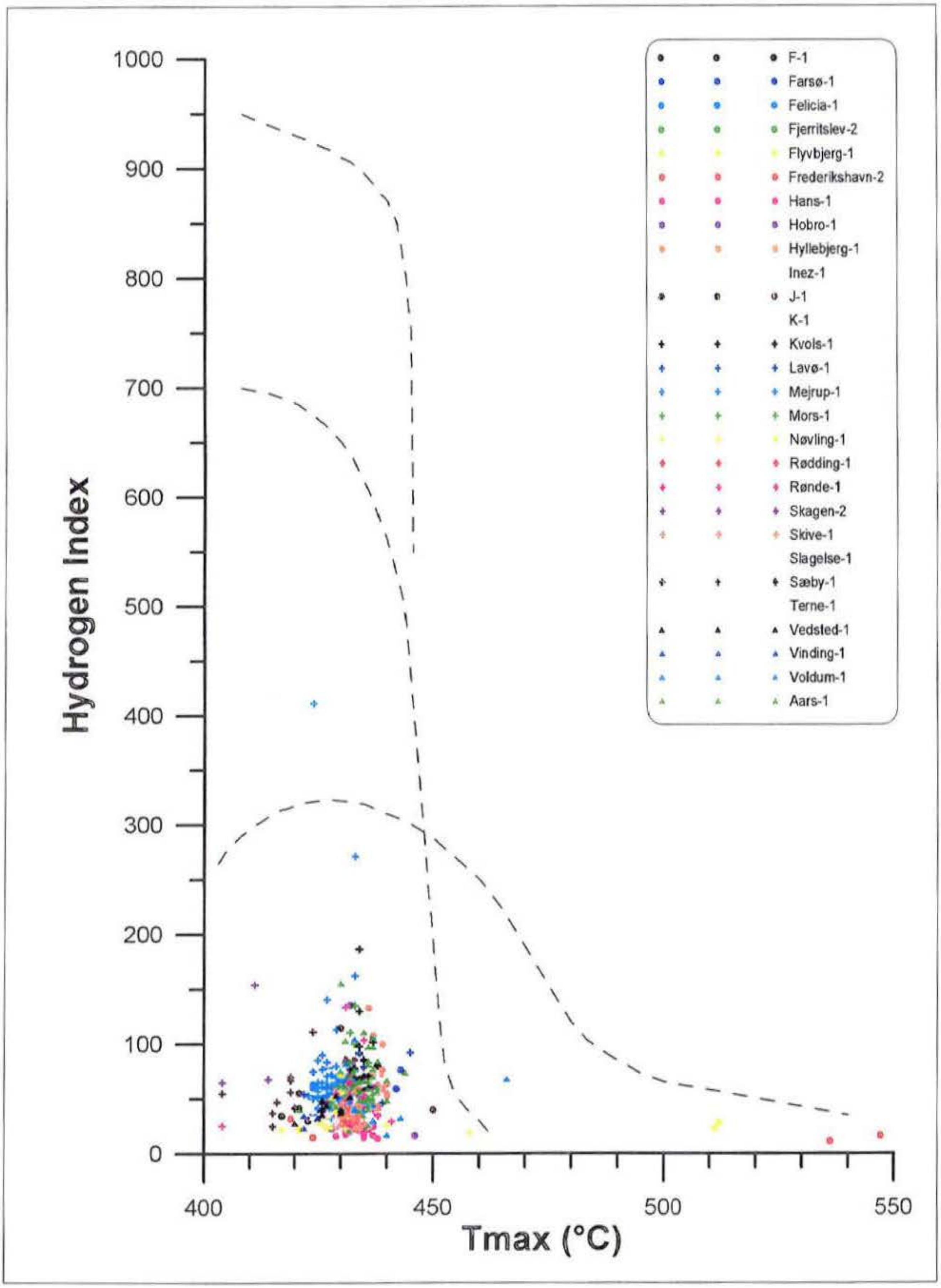


Fig. 14

Fjerritslev Formation, F-2 Member, n=234

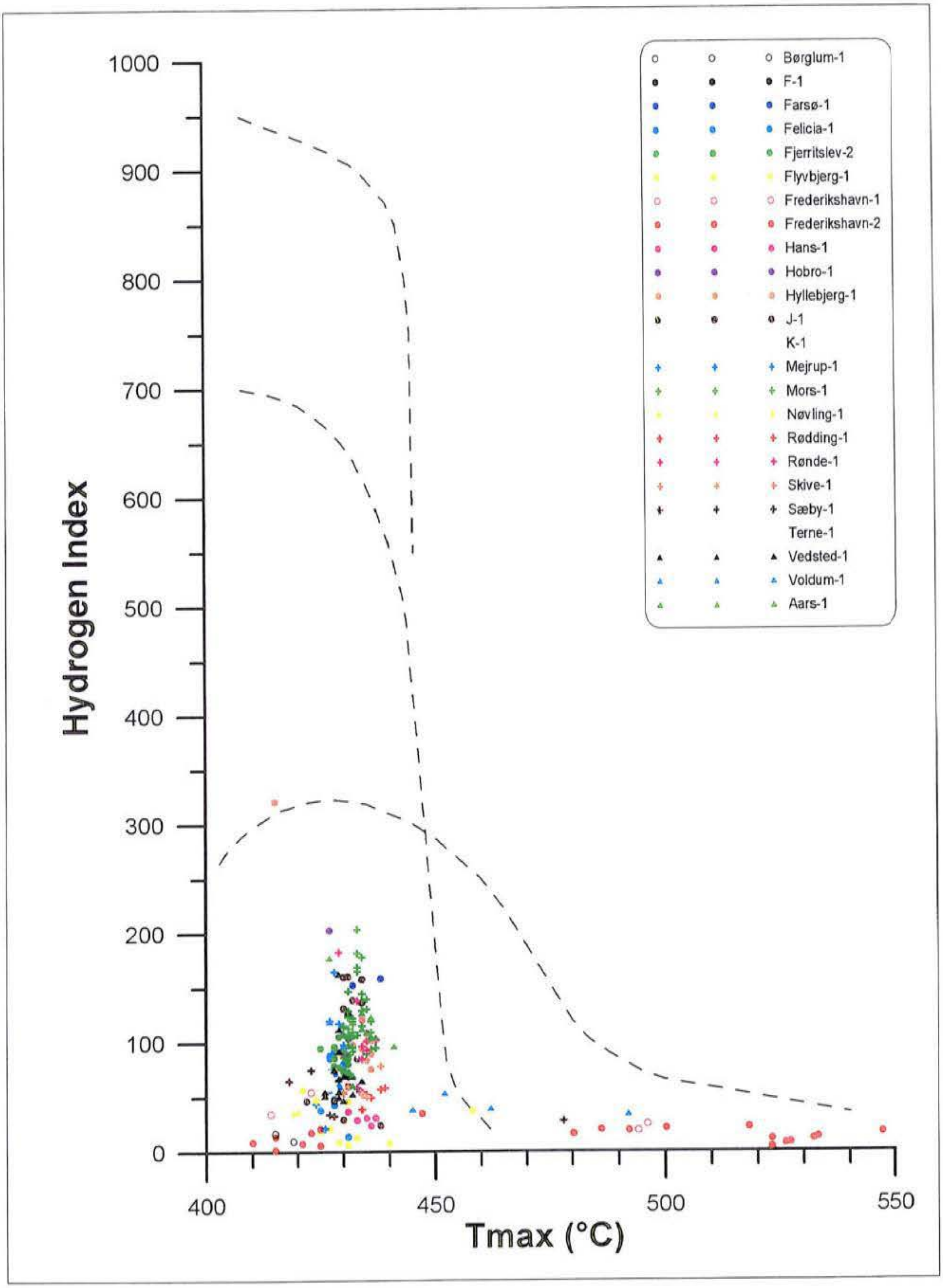


Fig. 15

Fjerritslev Formation, F-3 Member, n=431

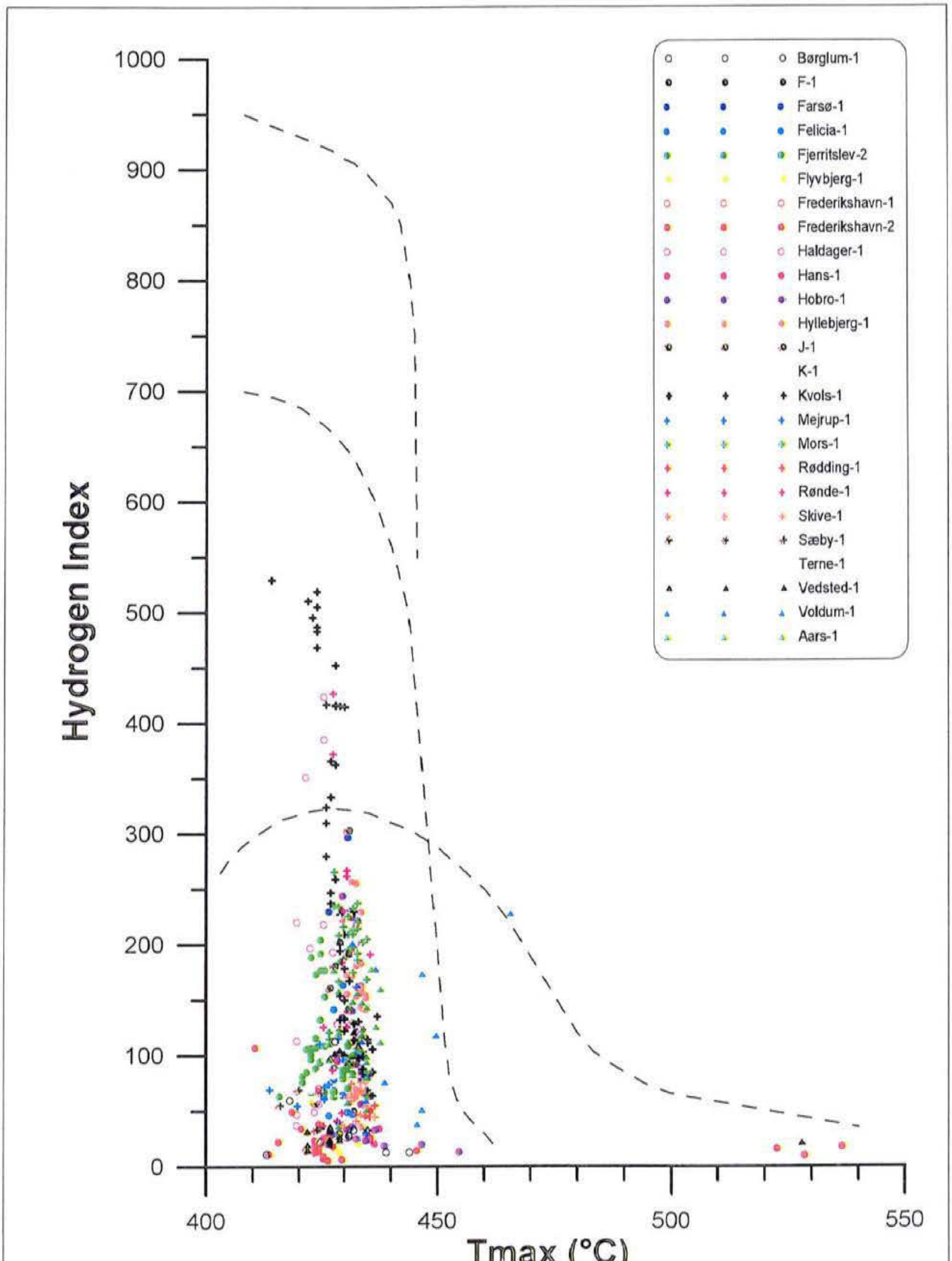


Fig. 16

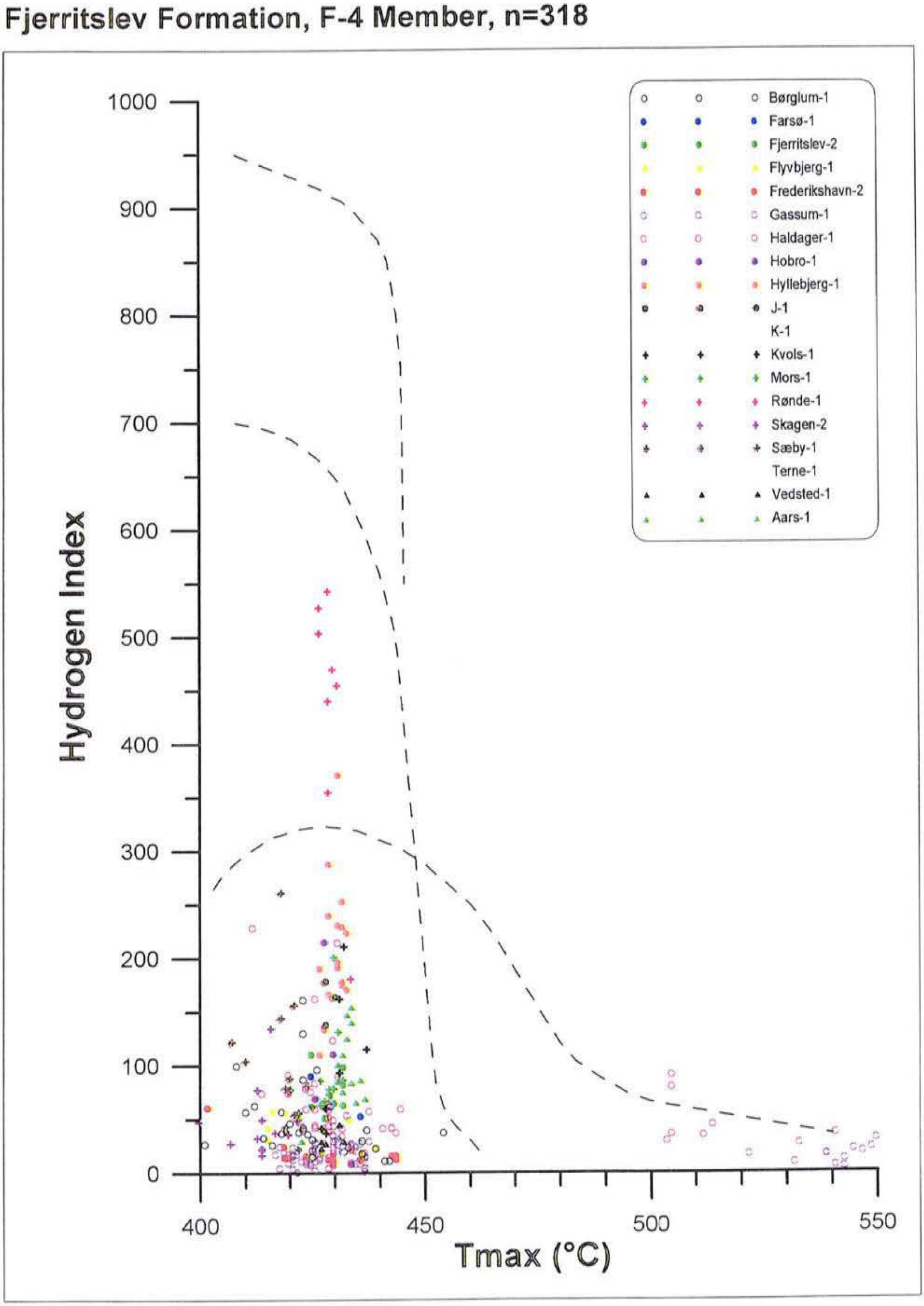

Fjerritslev Formation, F-4 Member, n=318
Hydrogen Index
0
100
200
300
400
500
600
700
800
900
1000
Tmax (°C)
400
450
500
550
Børglum-1
Farsø-1
Fjerritslev-2
Flyvbjerg-1
Frederikshavn-2
Gassum-1
Haldager-1
Hobro-1
Hyllebjerg-1
J-1
K-1
Kvols-1
Mors-1
Rønde-1
Skagen-2
Sæby-1
Terne-1
Vedsted-1
Aars-1

Fig. 17

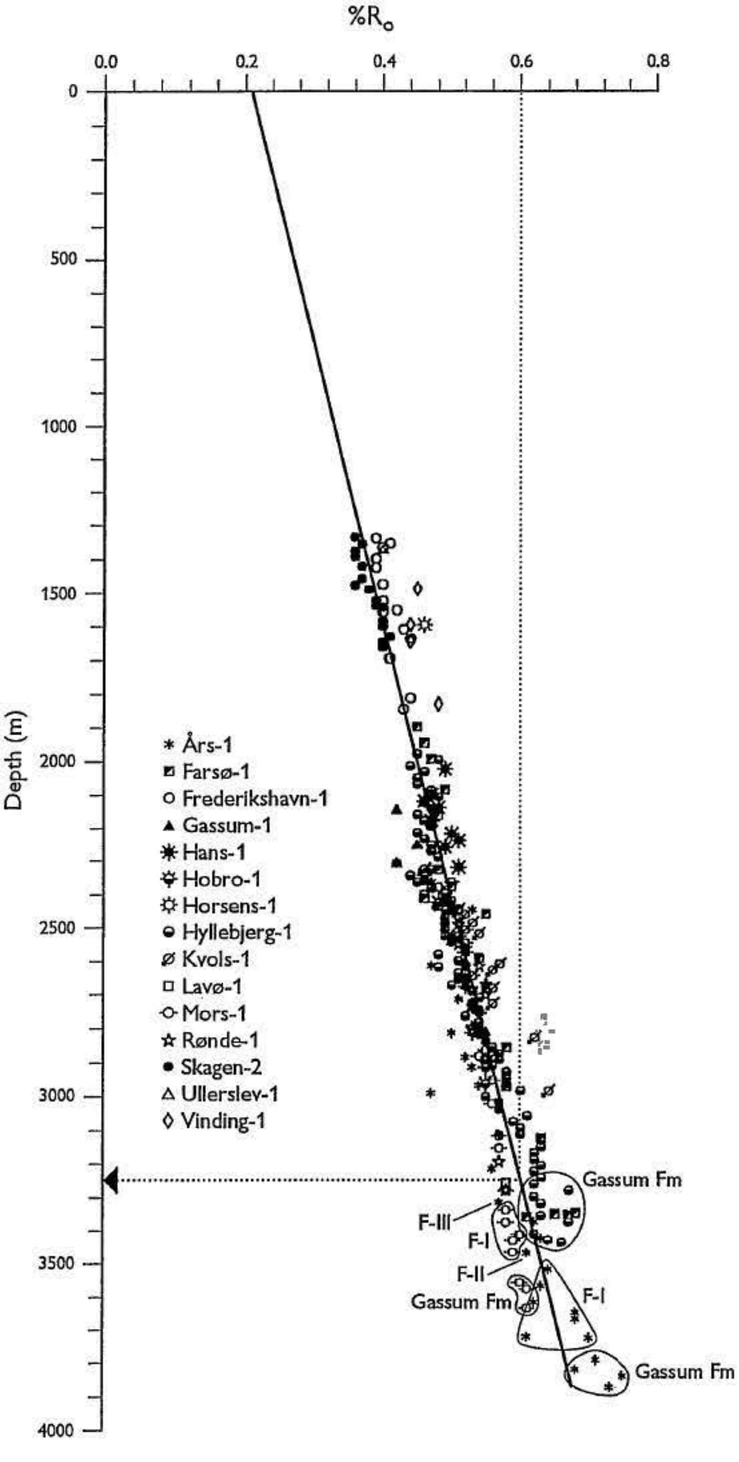

%R_o
0.0
0.2
0.4
0.6
0.8
0
500
1000
1500
2000
2500
3000
3500
4000
Depth (m)
* Års-1
▨ Farsø-1
○ Frederikshavn-1
▲ Gassum-1
✳ Hans-1
Hobro-1
Horsens-1
◒ Hyllebjerg-1
ø Kvols-1
□ Lavø-1
-○- Mors-1
☆ Rønde-1
● Skagen-2
△ Ullerslev-1
◊ Vinding-1
Gassum Fm
F-III
F-I
F-II
Gassum Fm
F-I
Gassum Fm

Fig. 18

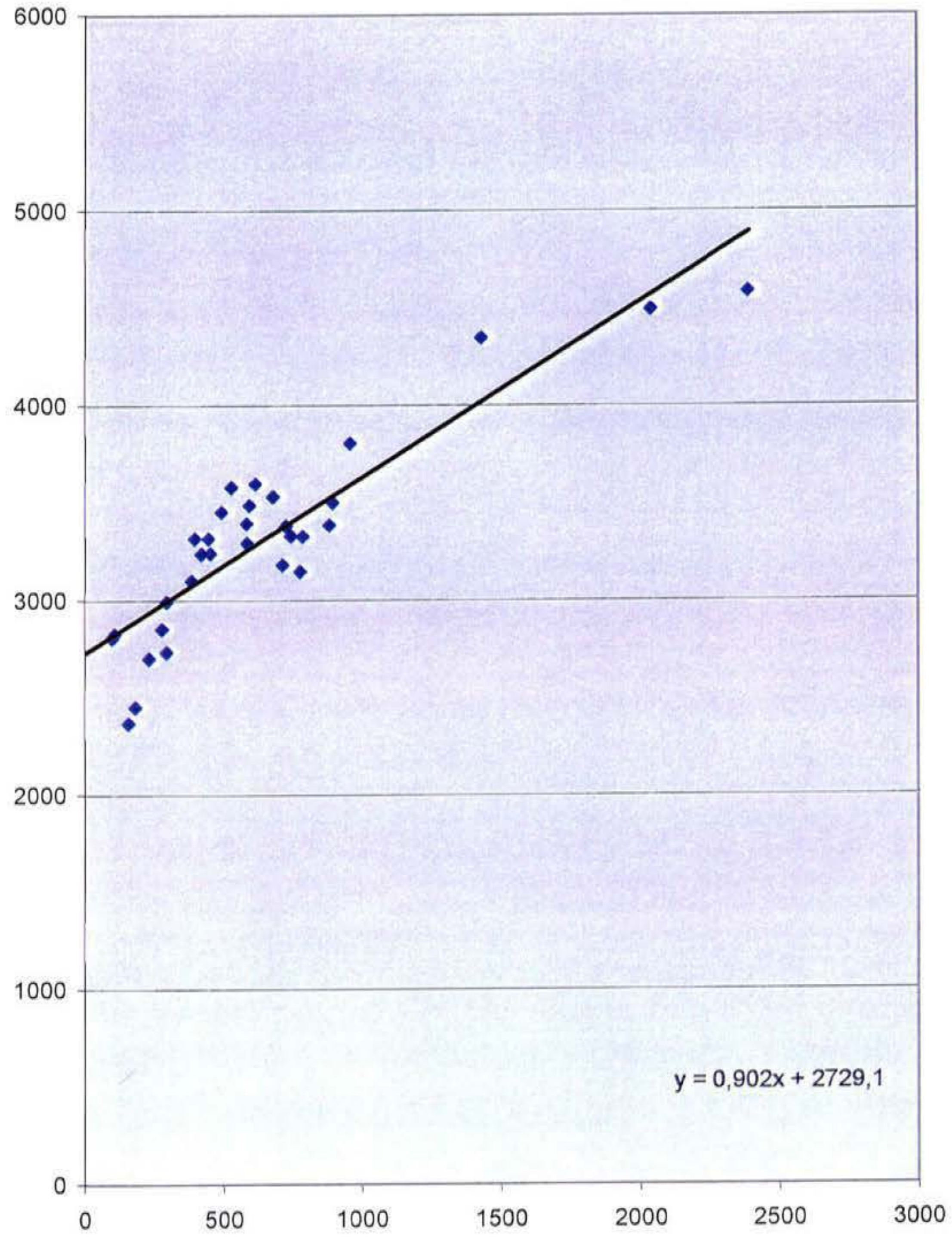


Figure 19 Upper Cretaceous
TWT. depth to center of formation and interval velocity

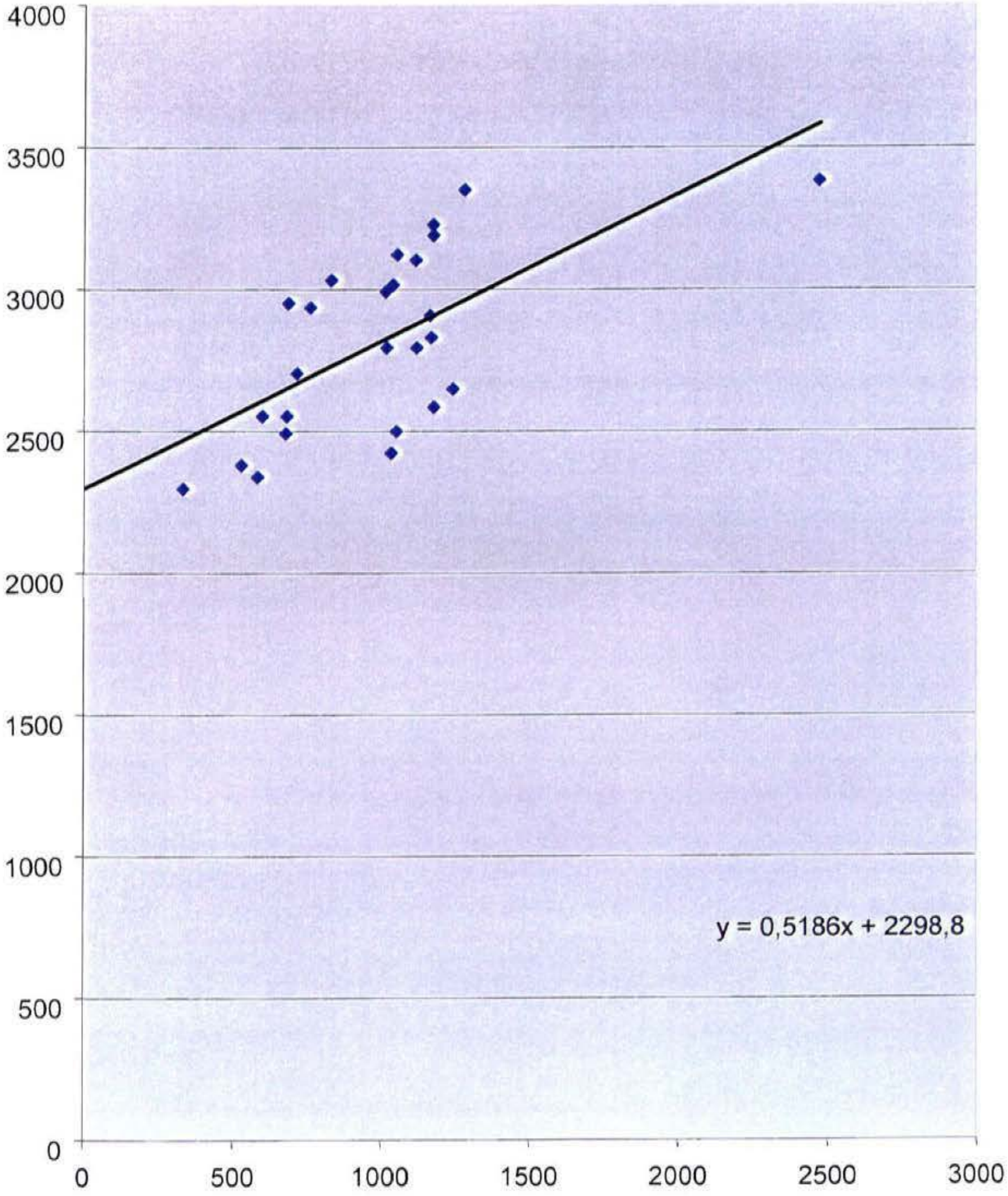


Figure 20 Base Upper Cretaceous to Middle Jurassic Unconformity
TWT. depth to center of formation and interval velocity

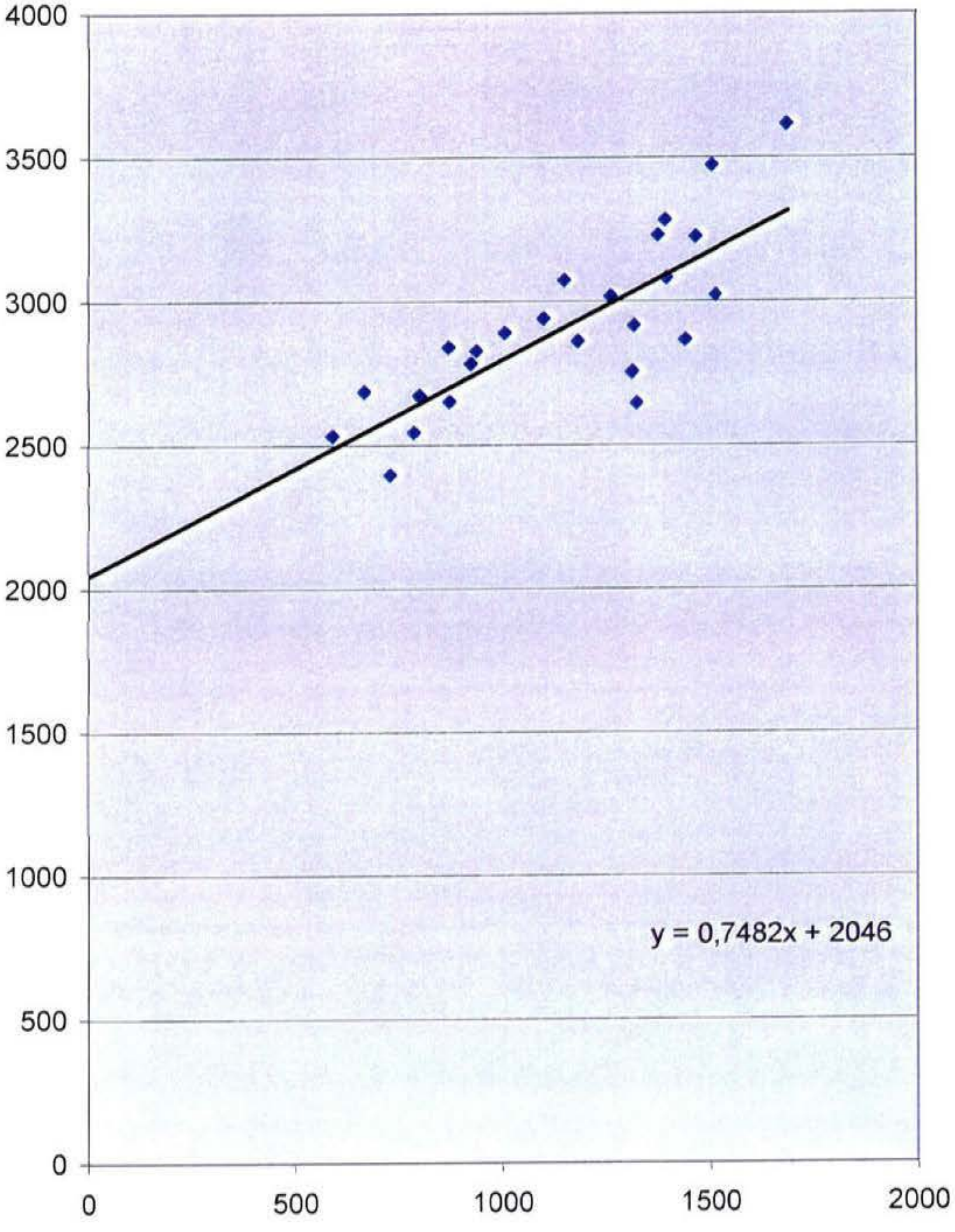
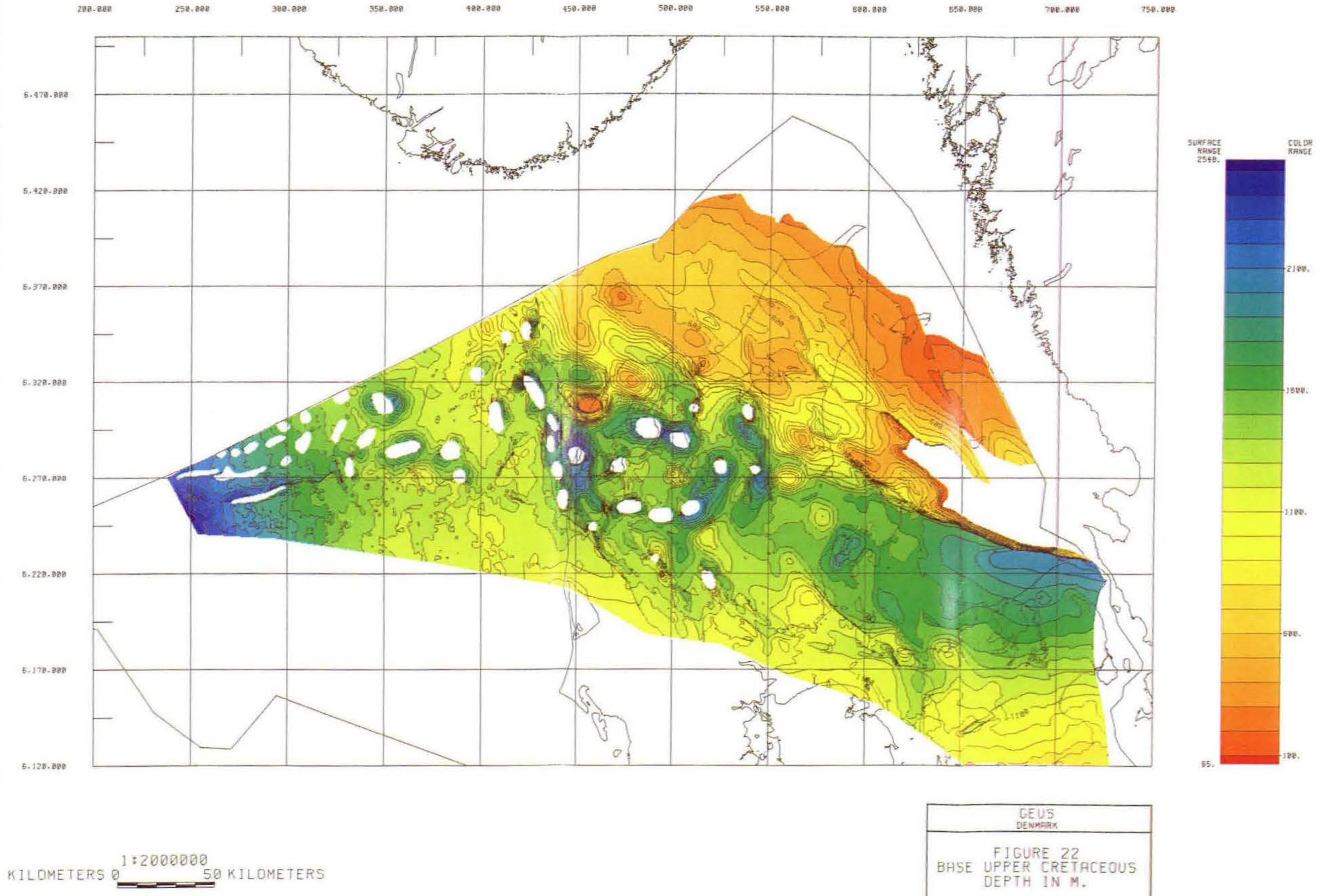
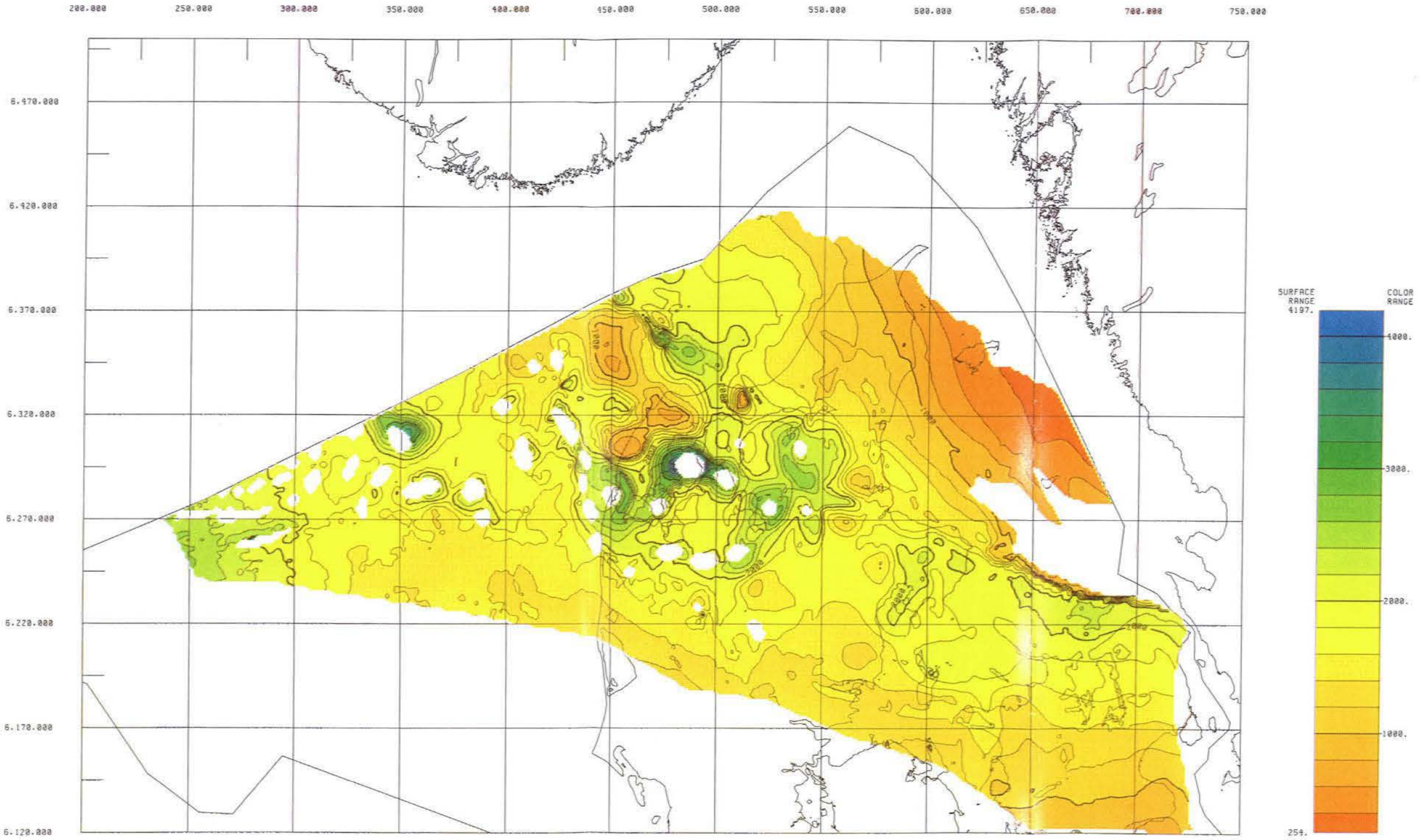


Figure 21 Fjeritslev Formation
TWT. depth to center of formation and interval velocity



GEUS
DENMARK

FIGURE 22
BASE UPPER CRETACEOUS
DEPTH IN M.



1:2000000
KILOMETERS 0 50 KILOMETERS

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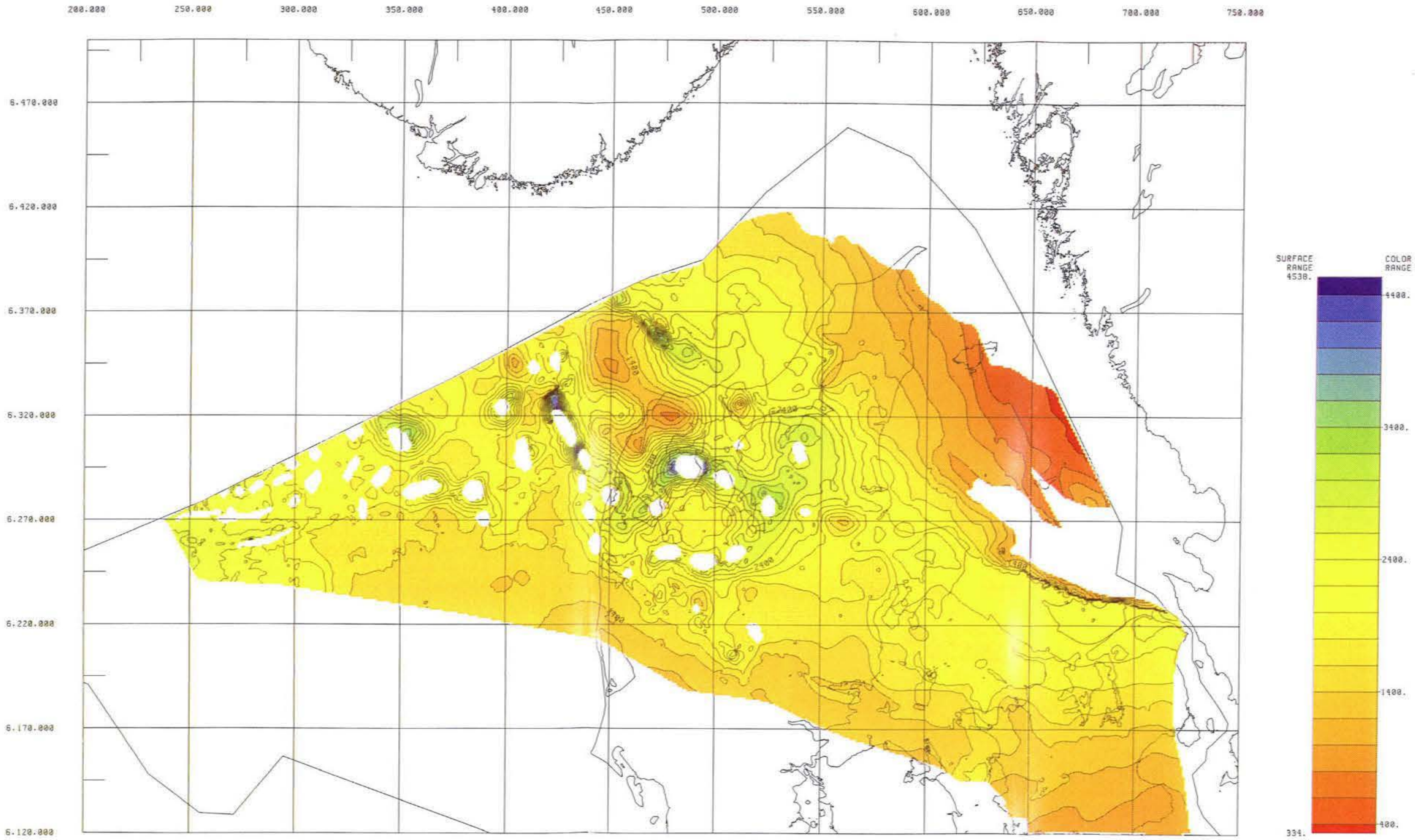
DENMARK

FIGURE 23
MIDDLE JURASSIC UNCONFORMITY
DEPTH IN M.

1:2000000 TB 12-DEC-2002



1:2000000
KILOMETERS 0 50 KILOMETERS

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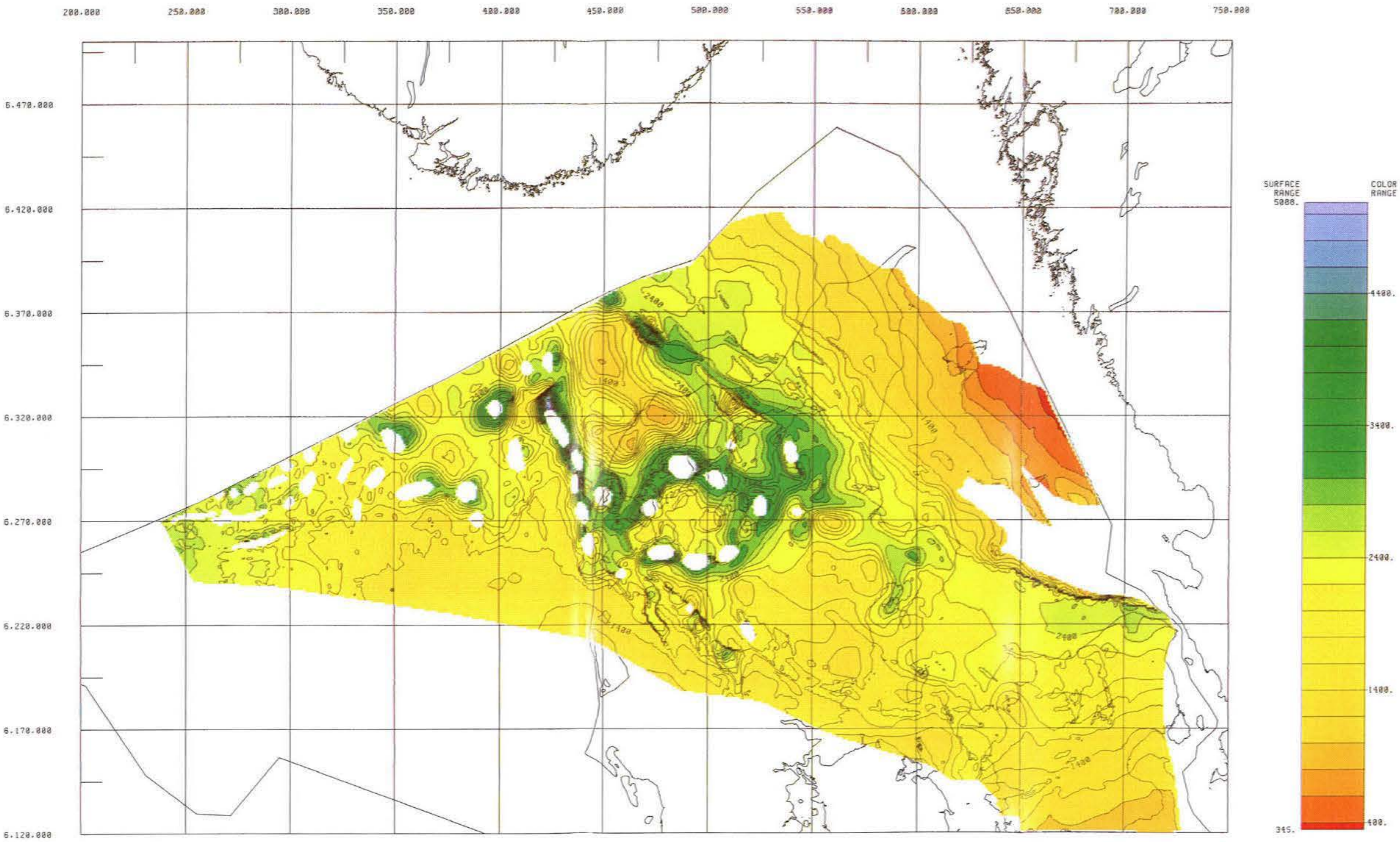
DENMARK

FIGURE 24
TOP FJERITSLEV FORMATION F-I MEMBER
DEPTH IN M.

1:2000000 | TB | 12-DEC-2002



1:2000000
KILOMETERS 0 50 KILOMETERS

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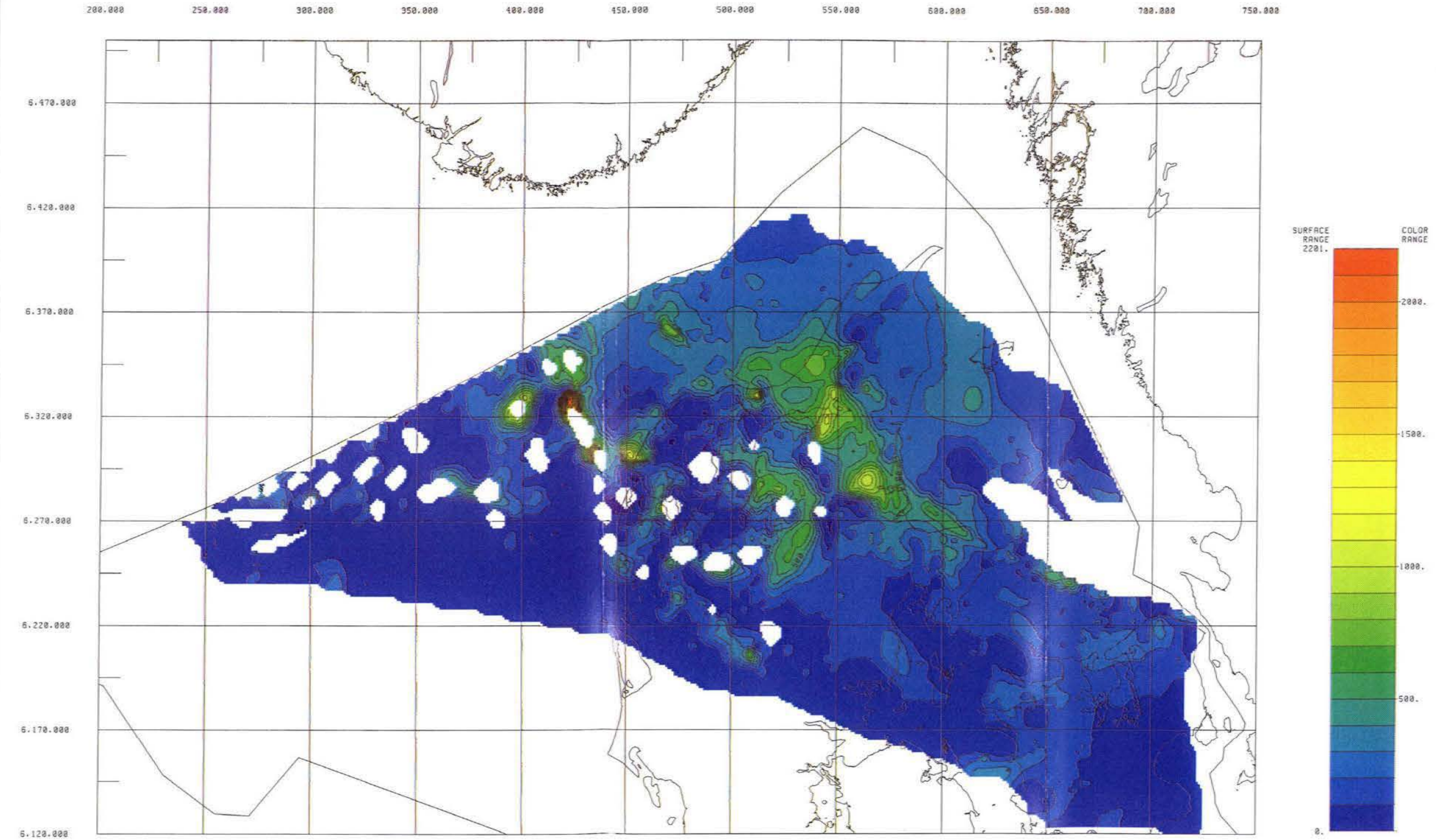
FIGURE 25
TOP GASSUM FORMATION
DEPTH IN M.

1:2000000 TB 12-DEC-2002



1:2000000
KILOMETERS 0 50 KILOMETERS

GEUS
DENMARK

FIGURE 26
FJERITSLEV FORMATION FII - FIV MEMBERS
ISOCORE IN M.

1:2000000 TB 12-DEC-2002

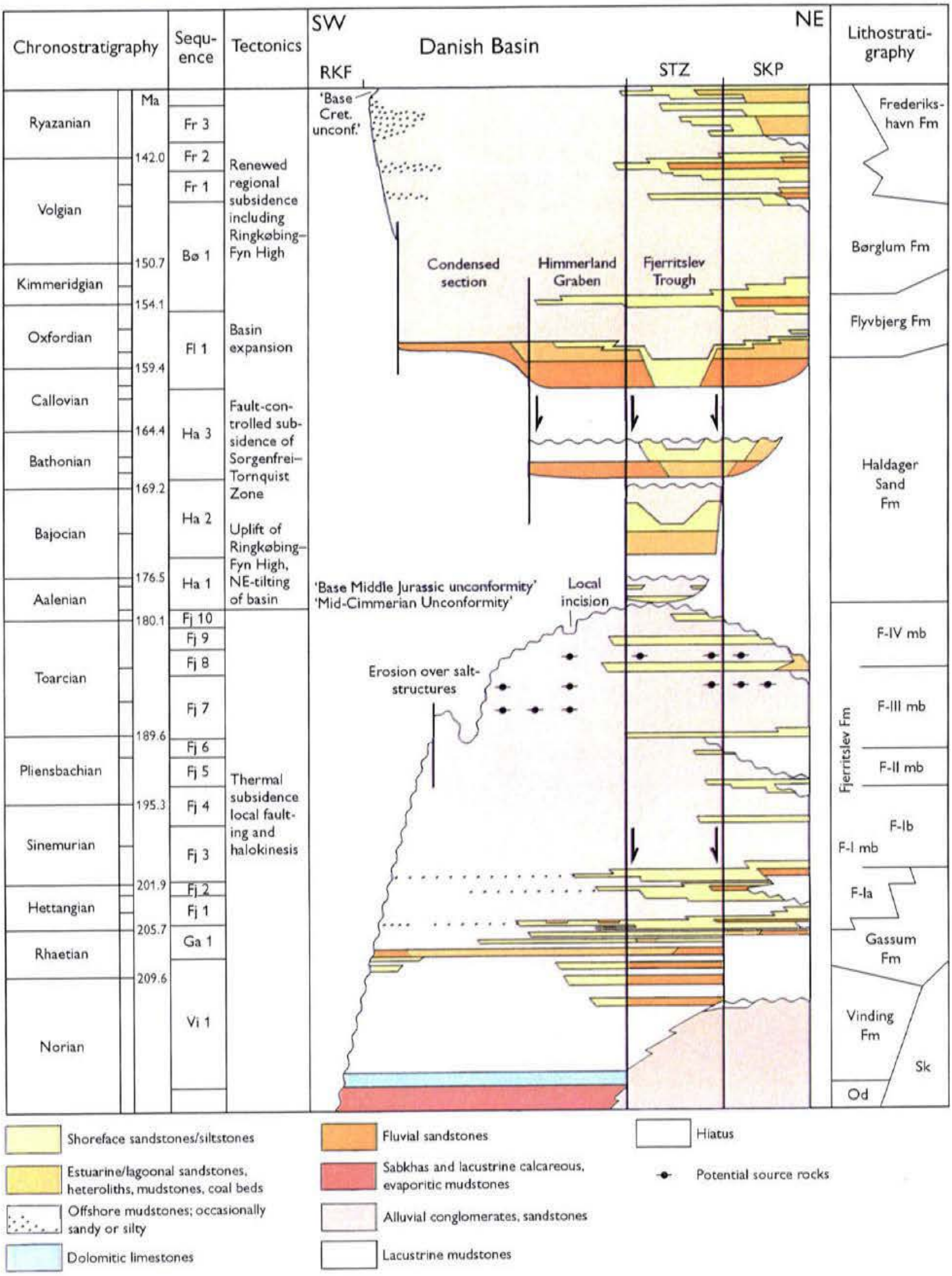

Chronostratigraphy
Ma
Ryazanian
Volgian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
142.0
150.7
154.1
159.4
164.4
169.2
176.5
180.1
189.6
195.3
201.9
205.7
209.6
Sequ-ence
Fr 3
Fr 2
Fr 1
Bø 1
Fl 1
Ha 3
Ha 2
Ha 1
Fj 10
Fj 9
Fj 8
Fj 7
Fj 6
Fj 5
Fj 4
Fj 3
Fj 2
Fj 1
Ga 1
Vi 1
Tectonics
Renewed regional subsidence including Ringkøbing–Fyn High
Basin expansion
Fault-controlled subsidence of Sorgenfrei–Tornquist Zone
Uplift of Ringkøbing–Fyn High, NE-tilting of basin
Thermal subsidence local faulting and halokinesis
SW
Danish Basin
NE
RKF
STZ
SKP
'Base Cret. unconf.'
Condensed section
Himmerland Graben
Fjerritslev Trough
'Base Middle Jurassic unconformity'
'Mid-Cimmerian Unconformity'
Local incision
Erosion over salt-structures
Lithostratigraphy
Frederikshavn Fm
Børglum Fm
Flyvbjerg Fm
Haldager Sand Fm
Fjerritslev Fm
F-IV mb
F-III mb
F-II mb
F-Ib
F-I mb
F-Ia
Gassum Fm
Vinding Fm
Sk
Od
Shoreface sandstones/siltstones
Estuarine/lagoonal sandstones, heteroliths, mudstones, coal beds
Offshore mudstones; occasionally sandy or silty
Dolomitic limestones
Fluvial sandstones
Sabkhas and lacustrine calcareous, evaporitic mudstones
Alluvial conglomerates, sandstones
Lacustrine mudstones
Hiatus
Potential source rocks

Fig.27

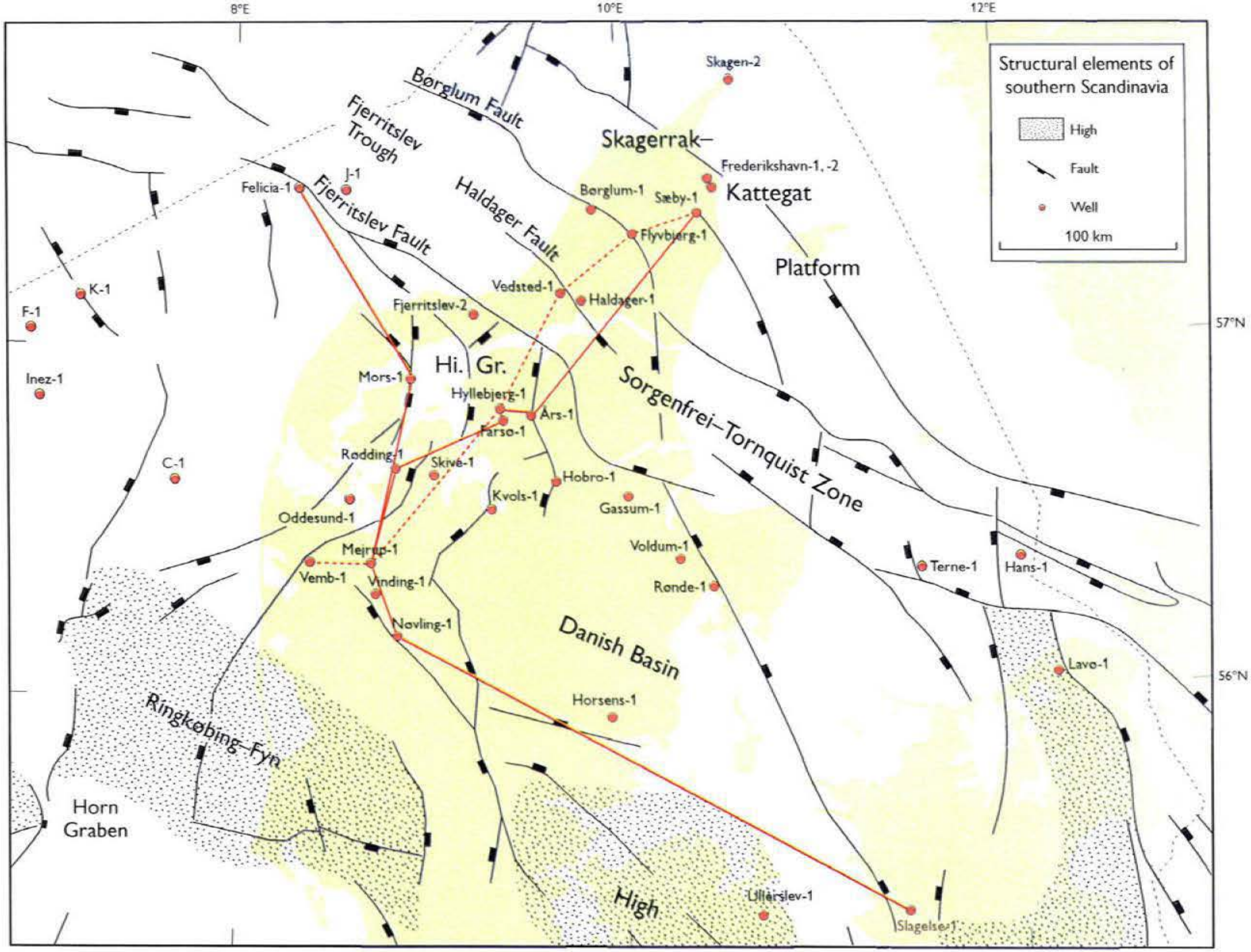

8°E
10°E
12°E
57°N
56°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Hi. Gr.
Danish Basin
Ringkøbing–Fyn High
Horn Graben
Skagen-2
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Vedsted-1
Haldager-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Fjerritslev-2
Mors-1
Hyllebjerg-1
Års-1
Farsø-1
Rødding-1
Skive-1
Hobro-1
Kvols-1
Gassum-1
Oddesund-1
Mejrup-1
Vemb-1
Vinding-1
Voldum-1
Rønde-1
Nøvling-1
Terne-1
Hans-1
Lavø-1
Horsens-1
Ullerslev-1
Slagelse-1

Fig.28

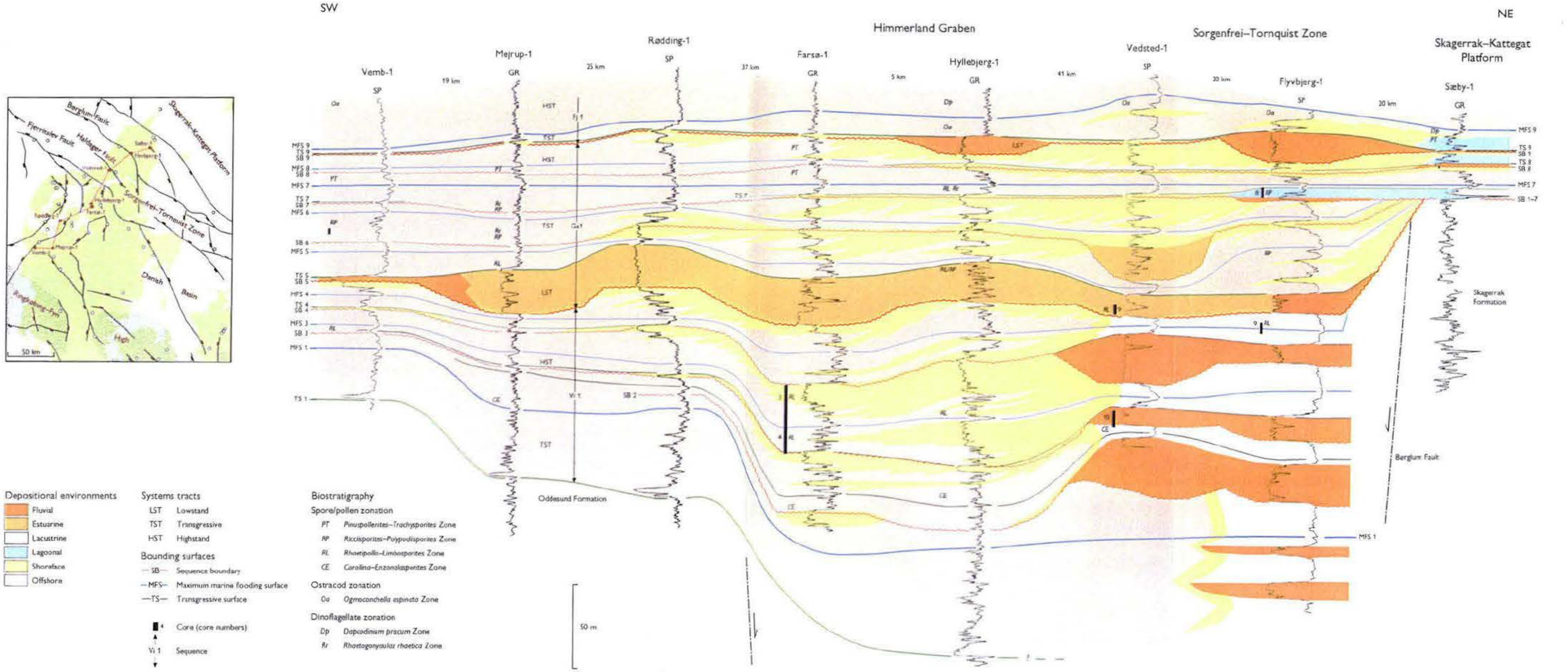
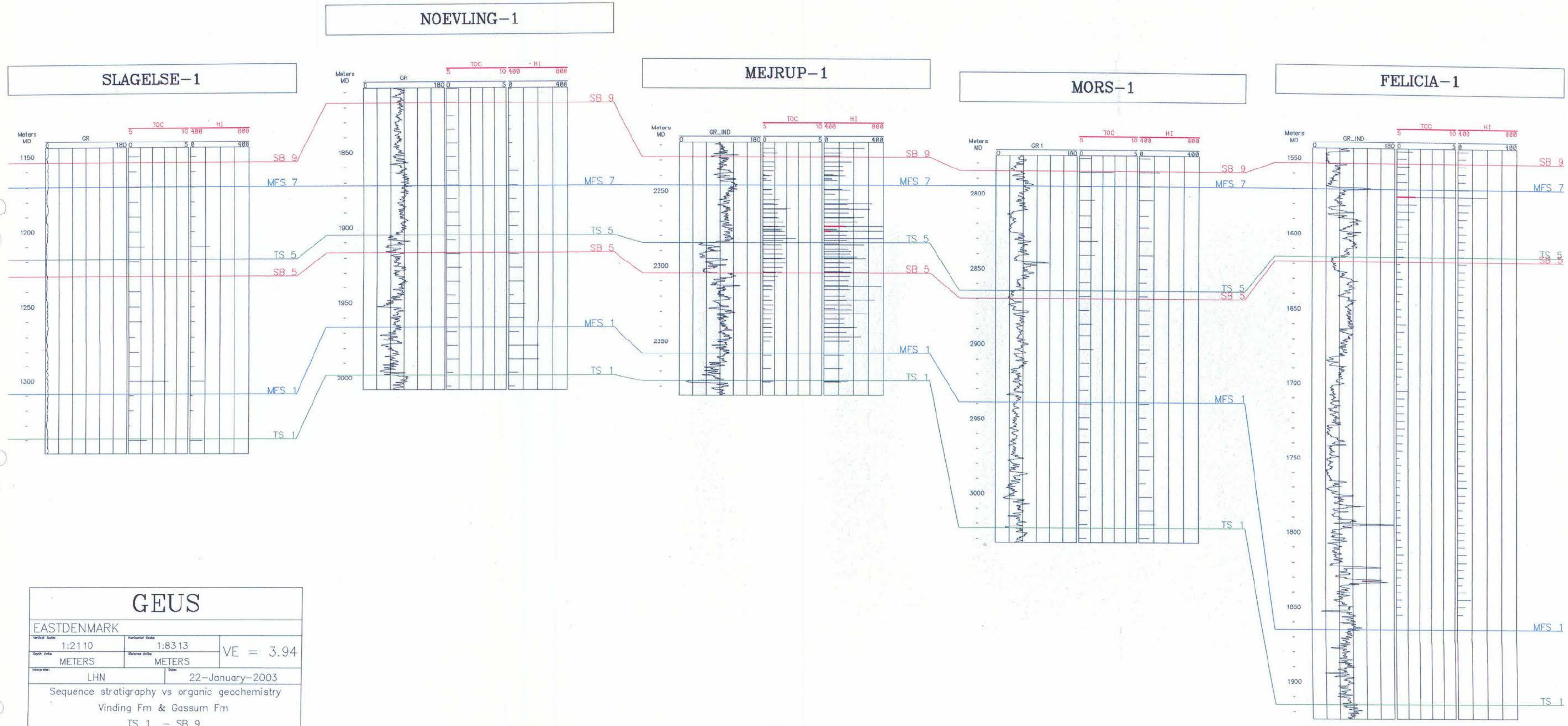

SW
NE
Himmerland Graben
Sorgenfrei–Tornquist Zone
Skagerrak–Kattegat Platform
Vemb-1
Mejrup-1
Rødding-1
Farsø-1
Hyllebjerg-1
Vedsted-1
Flyvbjerg-1
Sæby-1
SP
GR
19 km
25 km
37 km
5 km
41 km
30 km
20 km
MFS 9
TS 9
SB 9
MFS 8
SB 8
TS 8
MFS 7
TS 7
SB 7
MFS 6
SB 6
MFS 5
TS 5
SB 5
MFS 4
TS 4
SB 4
MFS 3
SB 3
MFS 1
TS 1
SB 1–7
SB 2
HST
TST
LST
Fj 1
Ga 1
Vi 1
Oa
Dp
PT
RP
RL
Rr
CE
RL/RP
Oddesund Formation
Skagerrak Formation
Børglum Fault
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Danish Basin
Ringkøbing–Fyn High
50 km
50 m
Depositional environments
Fluvial
Estuarine
Lacustrine
Lagoonal
Shoreface
Offshore
Systems tracts
LST Lowstand
TST Transgressive
HST Highstand
Bounding surfaces
—SB— Sequence boundary
—MFS— Maximum marine flooding surface
—TS— Transgressive surface
Core (core numbers)
Vi 1 Sequence
Biostratigraphy
Spore/pollen zonation
PT Pinuspollenites–Trachysporites Zone
RP Ricciisporites–Polypodiisporites Zone
RL Rhaetipollis–Limbosporites Zone
CE Corollina–Enzonalasporites Zone
Ostracod zonation
Oa Ogmoconchella aspinata Zone
Dinoflagellate zonation
Dp Dapcodinium priscum Zone
Rr Rhaetogonyaulax rhaetica Zone

Fig.29

GEUS
EASTDENMARK
Sequence stratigraphy vs organic geochemistry
Vinding Fm & Gassum Fm
TS1 – SB9
Figure 30



GEUS

EASTDENMARK

Vertical Scale:	Horizontal Scale:	
1:2110	1:8313	VE = 3.94
Depth Units: METERS	Distance Units: METERS	
Interpreter: LHN	Date: 22-January-2003	

Sequence stratigraphy vs organic geochemistry

Vinding Fm & Gassum Fm

TS 1 – SB 9

Figure 31

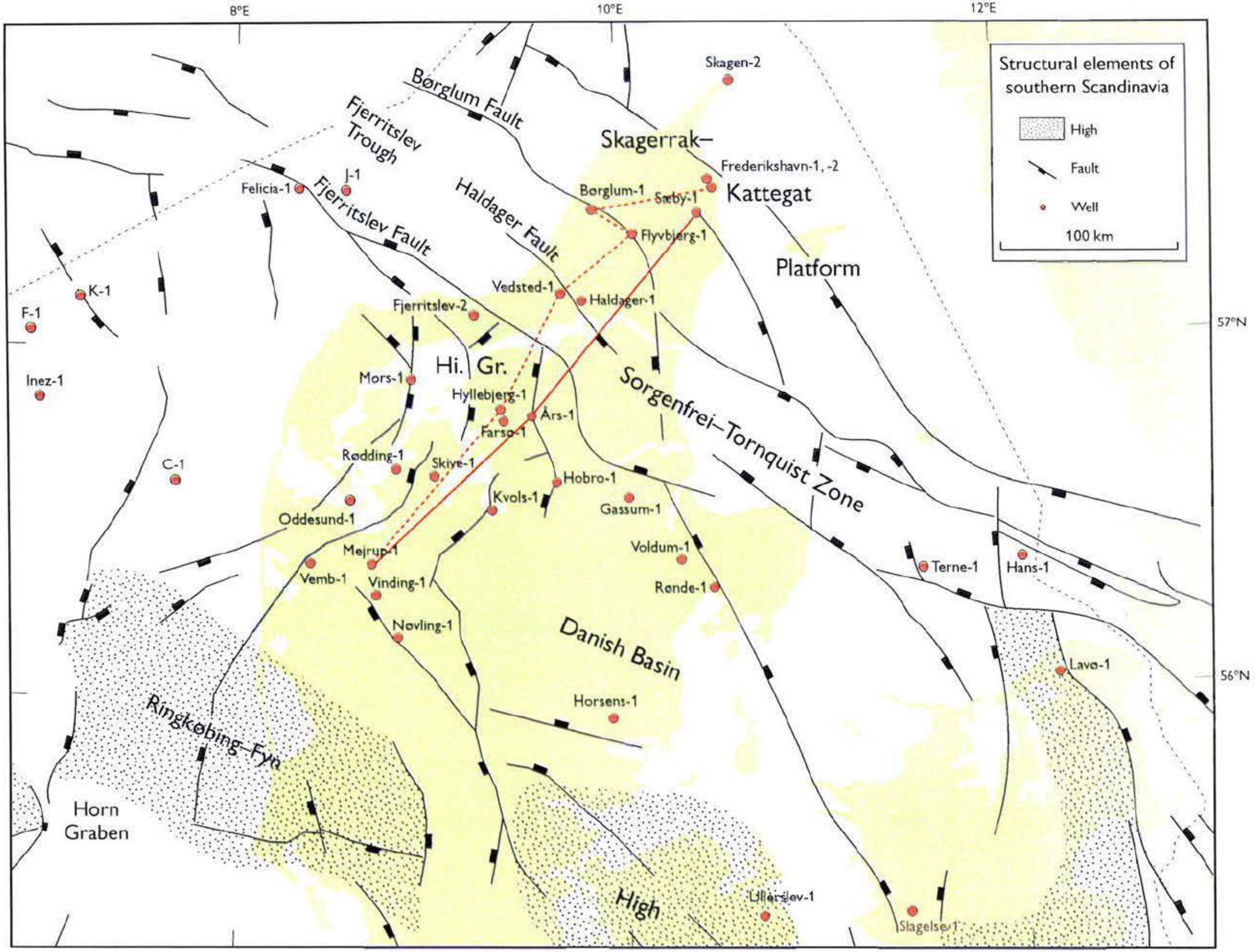

8°E
10°E
12°E
57°N
56°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Danish Basin
Ringkøbing–Fyn High
Horn Graben
Hi. Gr.
Skagen-2
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Vedsted-1
Haldager-1
Fjerritslev-2
Mors-1
Hyllebjerg-1
Farsø-1
Års-1
Rødding-1
Skive-1
Hobro-1
Gassum-1
Kvols-1
Oddesund-1
Mejrup-1
Vemb-1
Vinding-1
Voldum-1
Rønde-1
Nøvling-1
Terne-1
Hans-1
Lavø-1
Horsens-1
Ullerslev-1
Slagelse-1

Fig.32

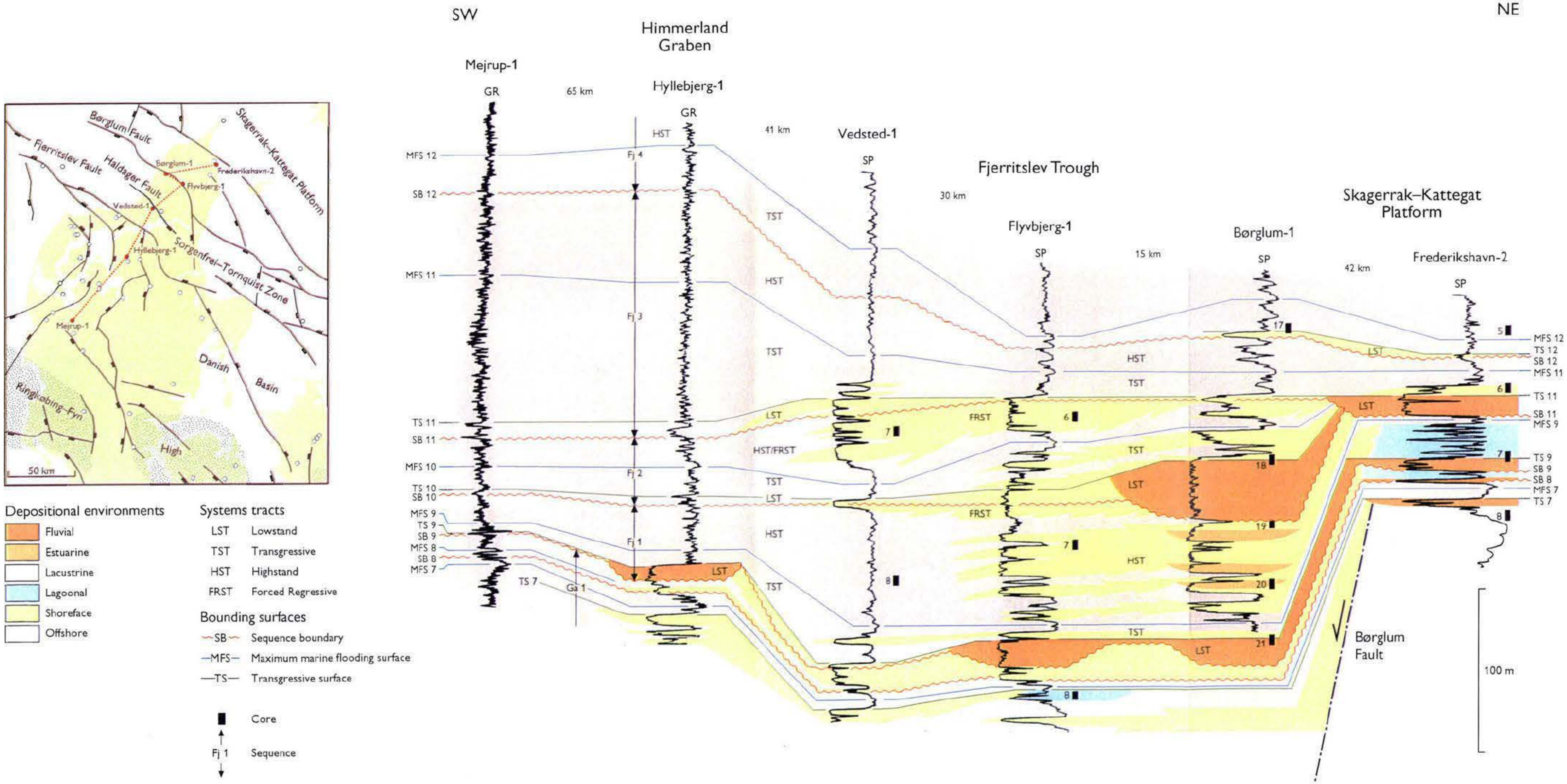
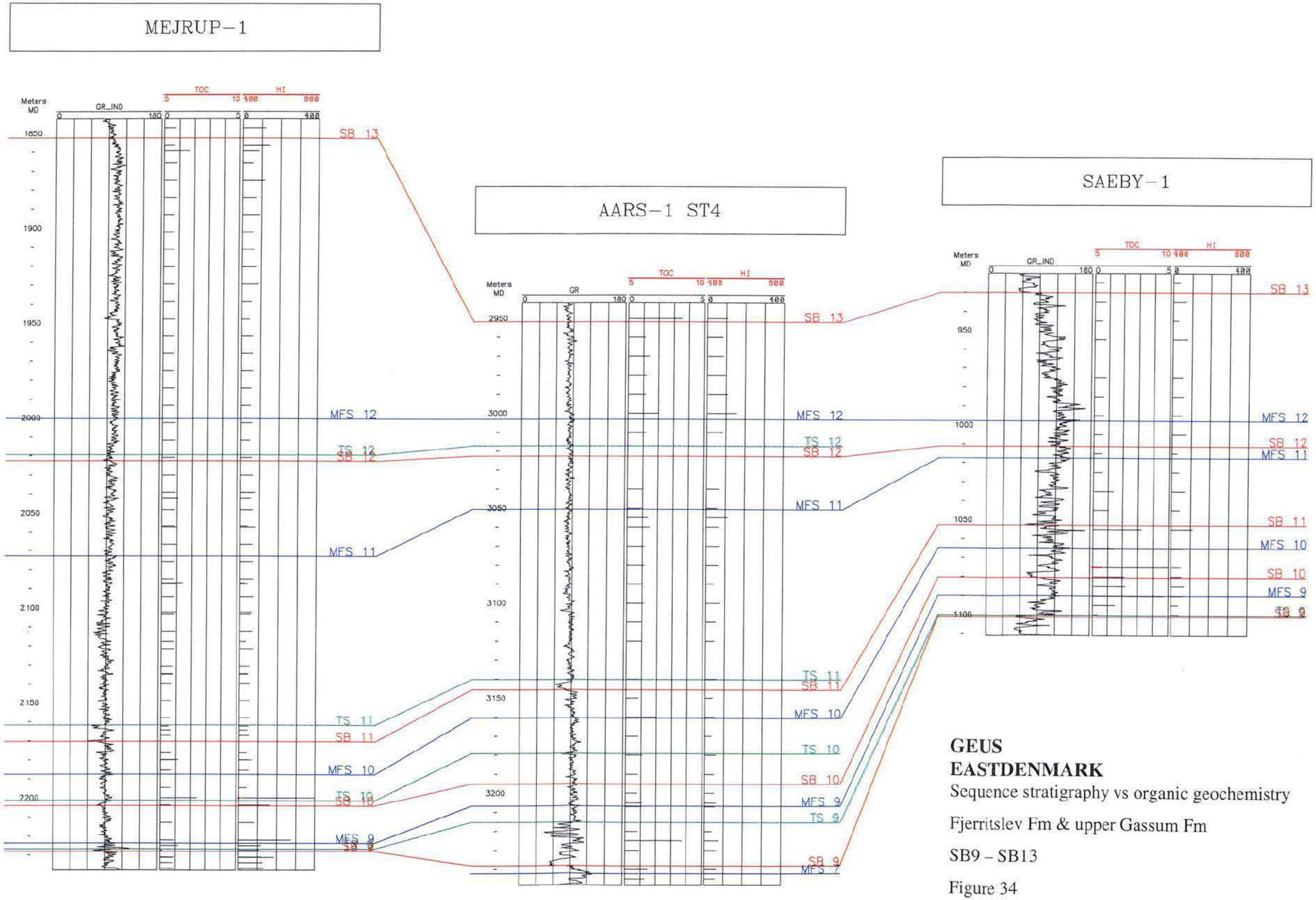

SW
NE
Himmerland Graben
Fjerritslev Trough
Skagerrak–Kattegat Platform
Mejrup-1
Hyllebjerg-1
Vedsted-1
Flyvbjerg-1
Børglum-1
Frederikshavn-2
GR
SP
65 km
41 km
30 km
15 km
42 km
MFS 12
SB 12
MFS 11
TS 11
SB 11
MFS 10
TS 10
SB 10
MFS 9
TS 9
SB 9
MFS 8
SB 8
MFS 7
TS 7
TS 12
MFS 11
TS 9
Fj 4
Fj 3
Fj 2
Fj 1
Ga 1
HST
TST
LST
HST/FRST
FRST
Børglum Fault
100 m
Børglum Fault
Skagerrak–Kattegat Platform
Fjerritslev Fault
Haldager Fault
Sorgenfrei–Tornquist Zone
Danish Basin
Ringkøbing–Fyn High
50 km
Depositional environments
Fluvial
Estuarine
Lacustrine
Lagoonal
Shoreface
Offshore
Systems tracts
LST Lowstand
TST Transgressive
HST Highstand
FRST Forced Regressive
Bounding surfaces
SB Sequence boundary
MFS Maximum marine flooding surface
TS Transgressive surface
Core
Fj 1 Sequence

Fig.33



GEUS

EASTDENMARK

Sequence stratigraphy vs organic geochemistry

Fjerritslev Fm & upper Gassum Fm

SB9 – SB13

Figure 34

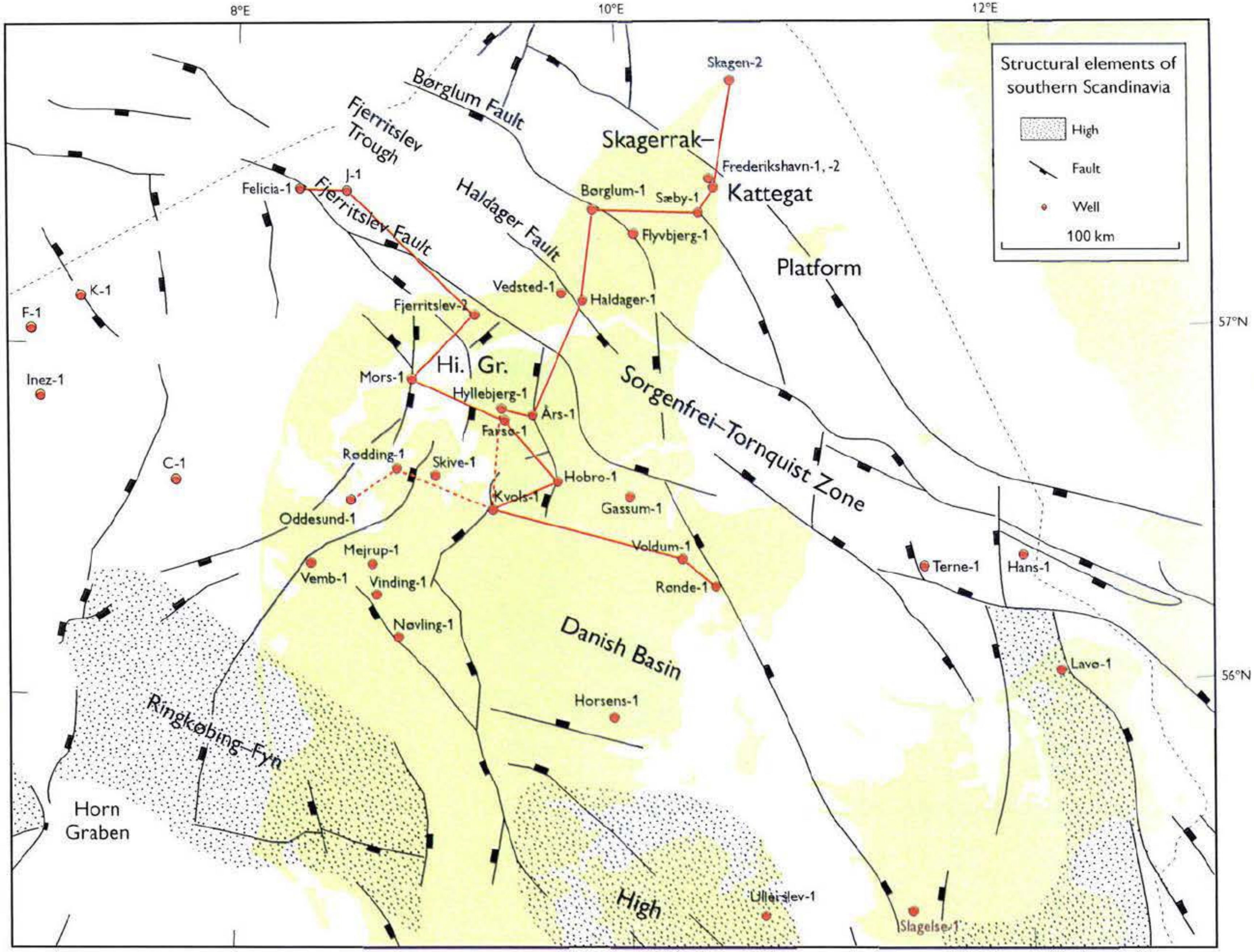

8°E
10°E
12°E
57°N
56°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Hi. Gr.
Danish Basin
Ringkøbing–Fyn High
Horn Graben
Skagen-2
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Fjerritslev-2
Vedsted-1
Haldager-1
Mors-1
Hyllebjerg-1
Års-1
Farsø-1
Rødding-1
Skive-1
Hobro-1
Kvols-1
Gassum-1
Oddesund-1
Mejrup-1
Vemb-1
Vinding-1
Voldum-1
Rønde-1
Nøvling-1
Terne-1
Hans-1
Lavø-1
Horsens-1
Ullerslev-1
Slagelse-1

Fig.35

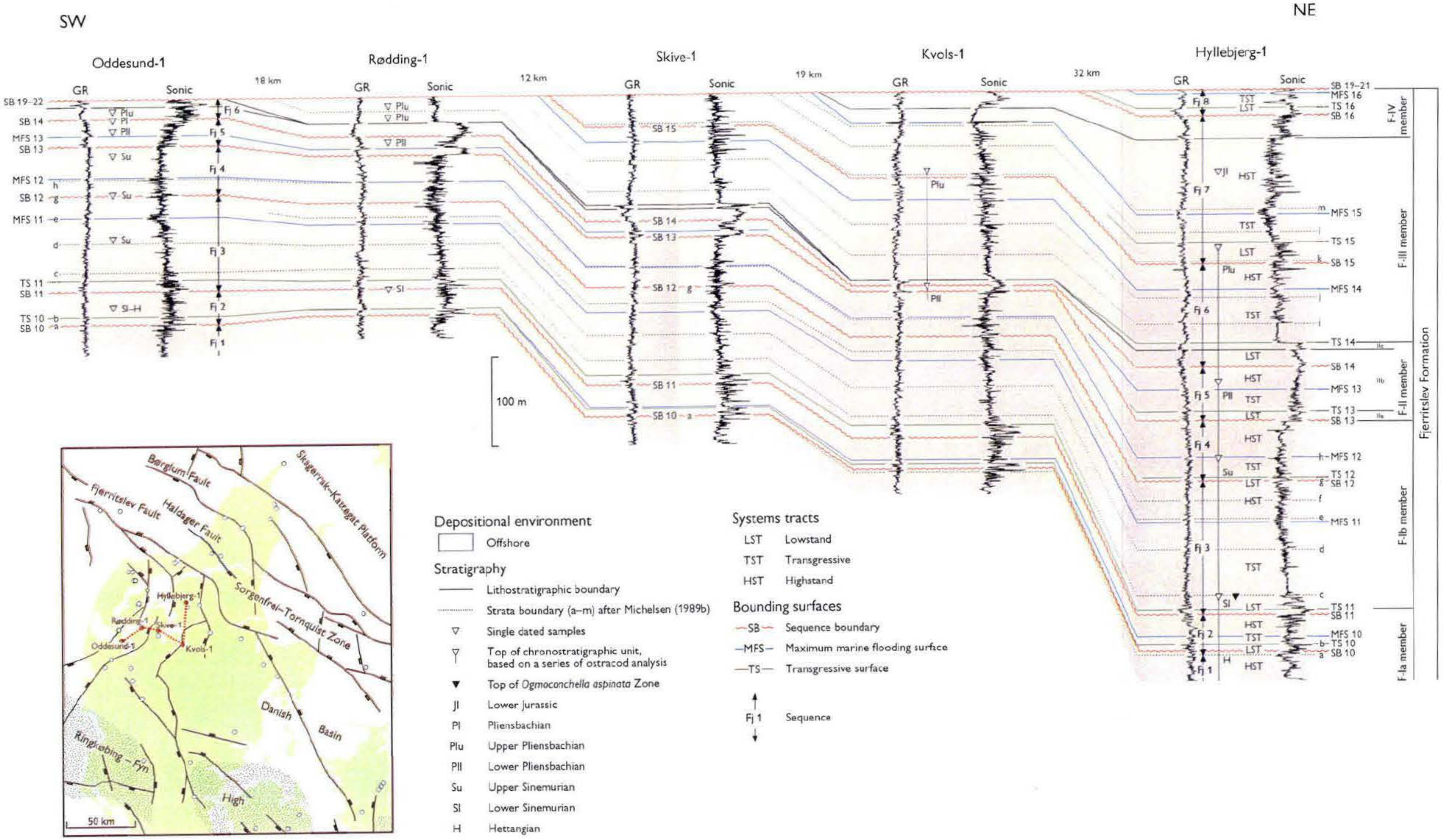

SW
NE
Oddesund-1
Rødding-1
Skive-1
Kvols-1
Hyllebjerg-1
GR
Sonic
18 km
12 km
19 km
32 km
SB 19–22
SB 14
MFS 13
SB 13
MFS 12
SB 12
MFS 11
TS 11
SB 11
TS 10
SB 10
SB 15
SB 14
SB 13
SB 12
SB 11
SB 10
Plu
Pl
Pll
Su
Sl
Sl–H
Jl
H
Fj 1
Fj 2
Fj 3
Fj 4
Fj 5
Fj 6
Fj 7
Fj 8
LST
TST
HST
SB 19–21
MFS 16
TS 16
SB 16
MFS 15
TS 15
SB 15
MFS 14
TS 14
SB 14
MFS 13
TS 13
SB 13
MFS 12
TS 12
SB 12
MFS 11
TS 11
SB 11
MFS 10
TS 10
SB 10
a
b
c
d
e
f
g
h
i
j
k
l
m
IIa
IIb
IIc
F-IV member
F-III member
F-II member
F-Ib member
F-Ia member
Fjerritslev Formation
100 m
Børglum Fault
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Danish Basin
Ringkøbing – Fyn High
Hyllebjerg-1
Rødding-1
Skive-1
Oddesund-1
Kvols-1
50 km
Depositional environment
Offshore
Stratigraphy
Lithostratigraphic boundary
Strata boundary (a–m) after Michelsen (1989b)
▽ Single dated samples
Top of chronostratigraphic unit, based on a series of ostracod analysis
▼ Top of Ogmoconchella aspinata Zone
Jl Lower Jurassic
Pl Pliensbachian
Plu Upper Pliensbachian
Pll Lower Pliensbachian
Su Upper Sinemurian
Sl Lower Sinemurian
H Hettangian
Systems tracts
LST Lowstand
TST Transgressive
HST Highstand
Bounding surfaces
–SB– Sequence boundary
–MFS– Maximum marine flooding surface
–TS– Transgressive surface
Fj 1 Sequence

Fig.36

GEUS

EASTDENMARK

Vertical Scale:	Horizontal Scale:	
1:2566	1:10 102	VE = 3.937008
Depth Units: METERS	Distance Units: METERS	
Interpreter: LHN	Date: 16-December-2002	

Sequence stratigraphy vs organic geochemistry

Fjerritslev Fm

SB 13 – SB 19

Figure 37

GEUS

EASTDENMARK

Vertical Scale: 1:2375	Horizontal Scale: 1:9351	VE = 3.937008
Depth Units: METERS	Distance Units: METERS	

Interpreter: LHN

Date: 13-December-2002

Sequence stratigraphy vs organic geochemistry

Fjerritslev Fm

SB 13 - SB 19

Figure 38

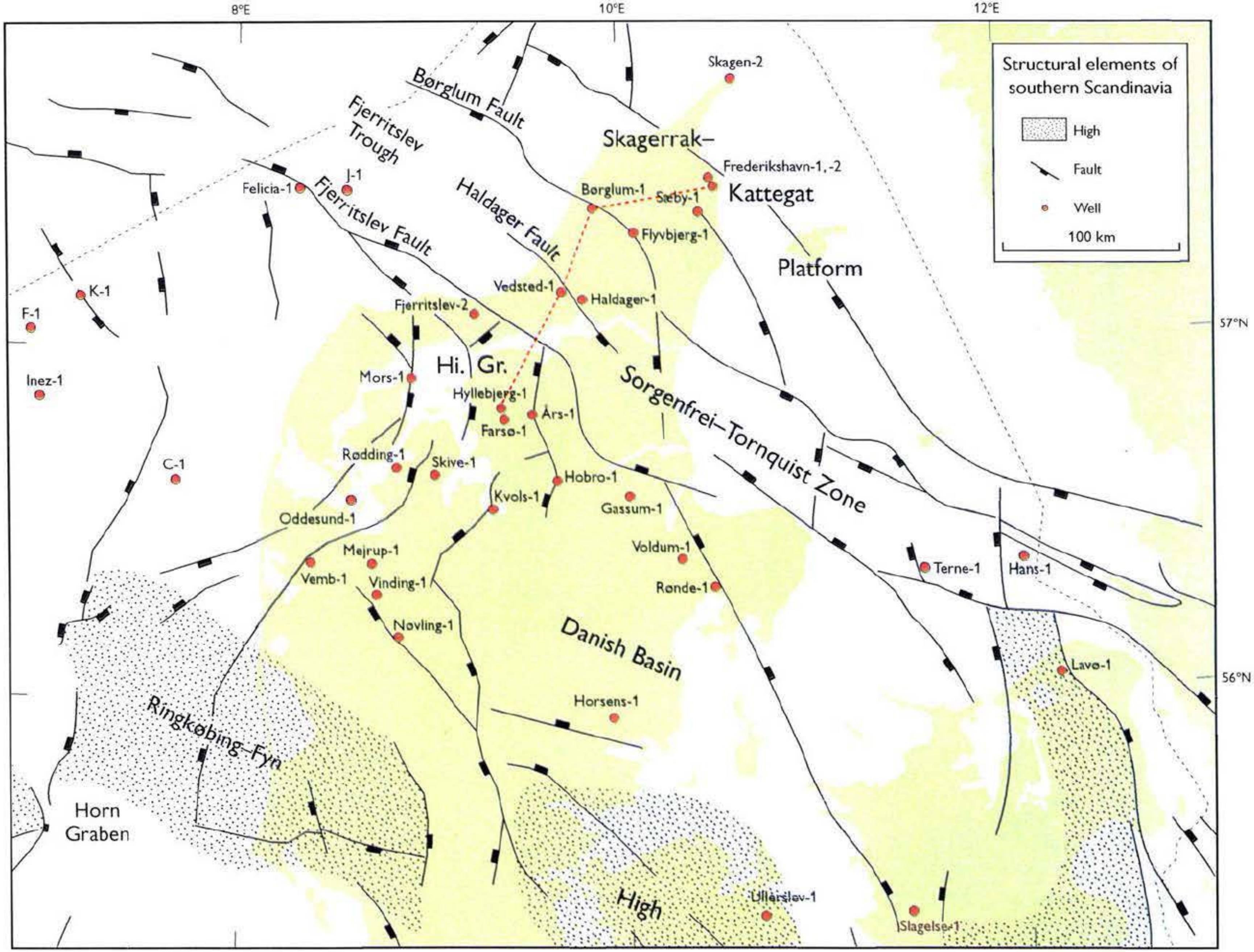

8°E
10°E
12°E
57°N
56°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Hi. Gr.
Danish Basin
Ringkøbing–Fyn High
Horn Graben
Skagen-2
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Vedsted-1
Haldager-1
Fjerritslev-2
Mors-1
Hyllebjerg-1
Farsø-1
Års-1
Rødding-1
Skive-1
Hobro-1
Kvols-1
Gassum-1
Oddesund-1
Mejrup-1
Vemb-1
Vinding-1
Novling-1
Voldum-1
Rønde-1
Terne-1
Hans-1
Lavø-1
Horsens-1
Ullerslev-1
Slagelse-1

Fig.39

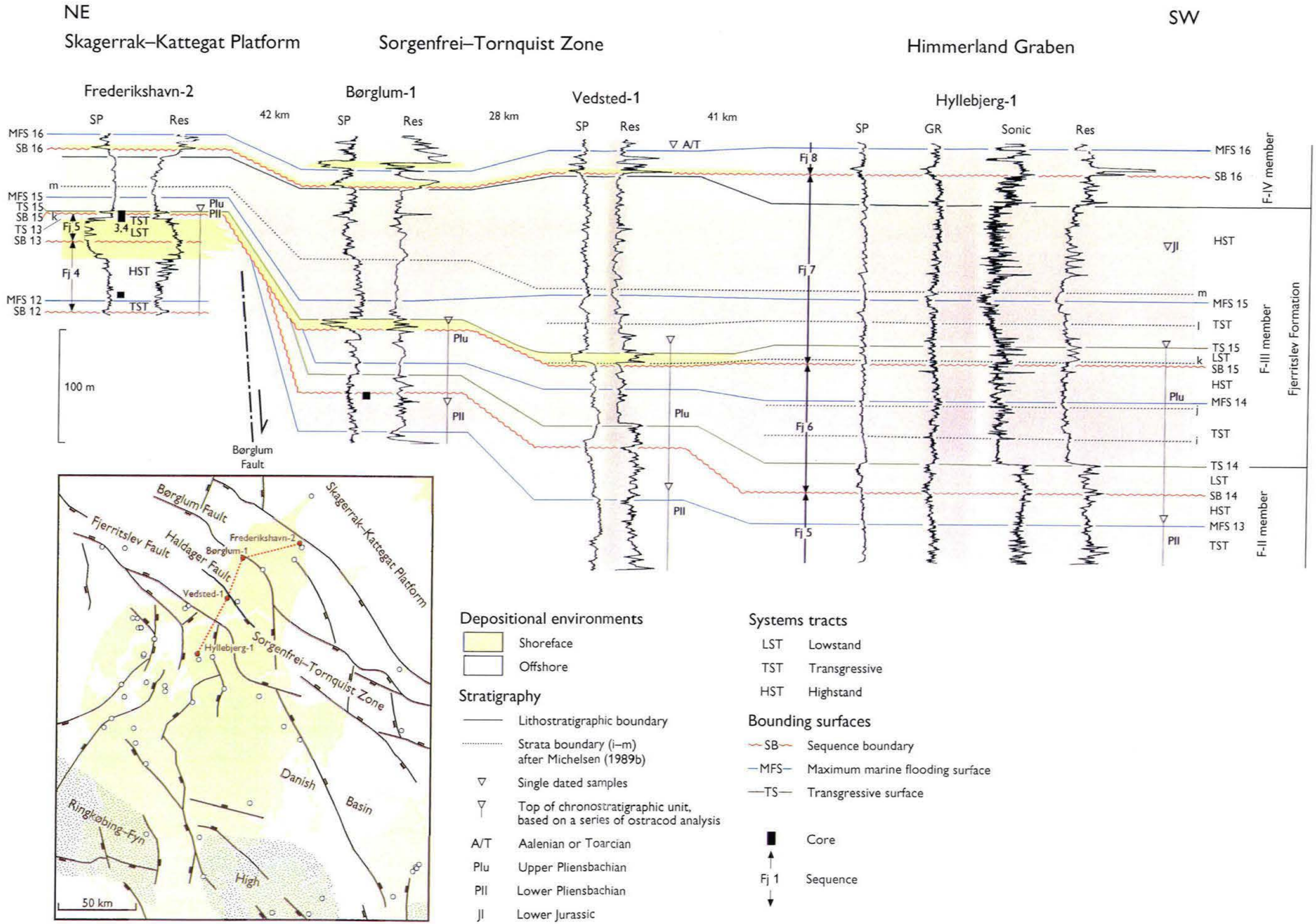

NE
SW
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Himmerland Graben
Frederikshavn-2
Børglum-1
Vedsted-1
Hyllebjerg-1
42 km
28 km
41 km
SP
Res
GR
Sonic
MFS 16
SB 16
m
MFS 15
TS 15
SB 15
k
TS 13
SB 13
MFS 12
SB 12
Fj 4
Fj 5
Fj 6
Fj 7
Fj 8
3,4
TST
LST
HST
Plu
Pll
A/T
Jl
l
j
i
MFS 14
TS 14
SB 14
MFS 13
100 m
Børglum Fault
F-IV member
F-III member
F-II member
Fjerritslev Formation
Børglum Fault
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Danish
Basin
Ringkøbing–Fyn
High
Frederikshavn-2
Børglum-1
Vedsted-1
Hyllebjerg-1
50 km
Depositional environments
Shoreface
Offshore
Stratigraphy
Lithostratigraphic boundary
Strata boundary (i–m) after Michelsen (1989b)
Single dated samples
Top of chronostratigraphic unit, based on a series of ostracod analysis
A/T Aalenian or Toarcian
Plu Upper Pliensbachian
Pll Lower Pliensbachian
Jl Lower Jurassic
Systems tracts
LST Lowstand
TST Transgressive
HST Highstand
Bounding surfaces
SB Sequence boundary
MFS Maximum marine flooding surface
TS Transgressive surface
Core
Fj 1 Sequence

Fig.40

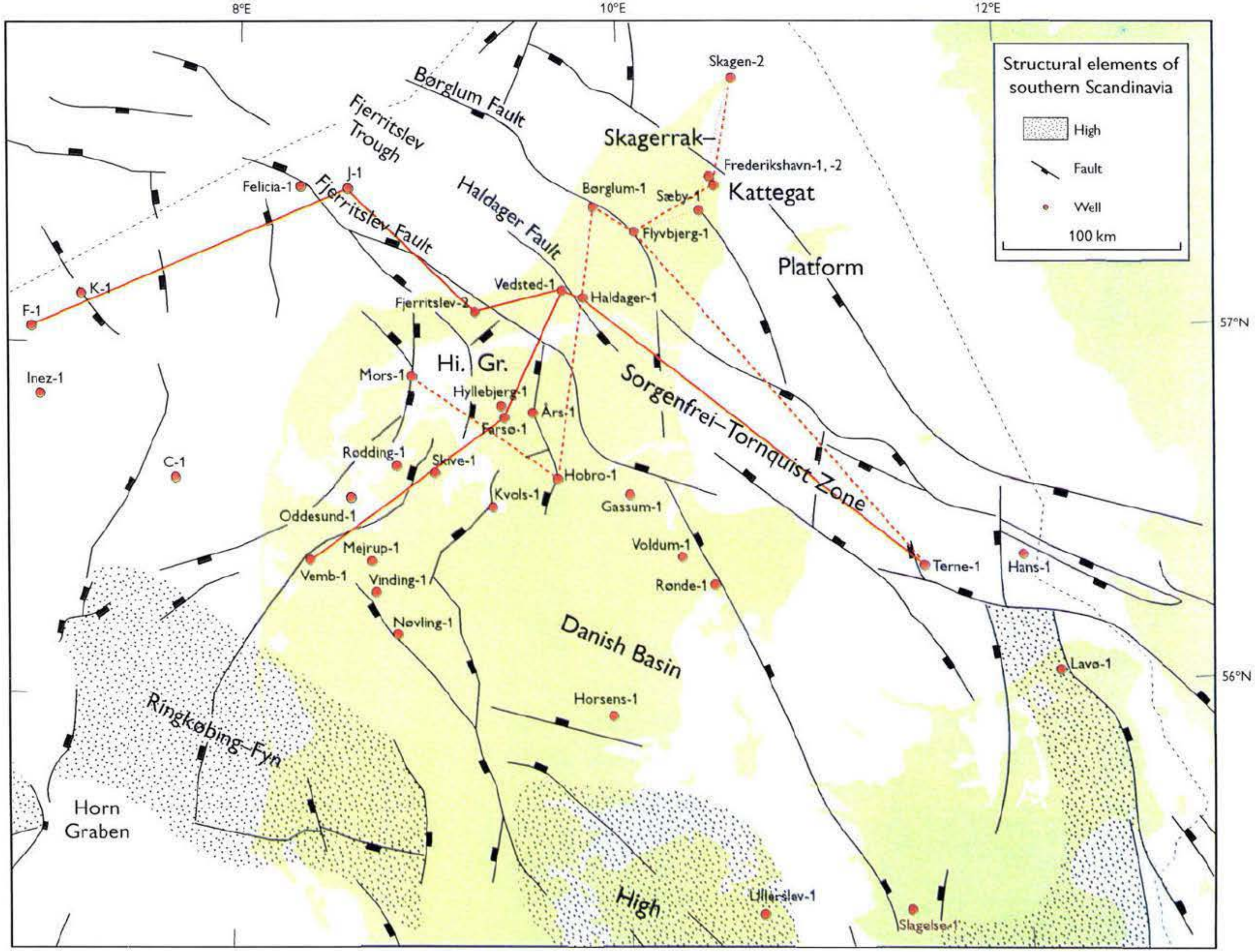

8°E
10°E
12°E
57°N
56°N
Structural elements of southern Scandinavia
High
Fault
Well
100 km
Børglum Fault
Fjerritslev Trough
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Hi. Gr.
Danish Basin
Ringkøbing-Fyn High
Horn Graben
Skagen-2
Frederikshavn-1, -2
Børglum-1
Sæby-1
Flyvbjerg-1
Felicia-1
J-1
K-1
F-1
Inez-1
C-1
Vedsted-1
Haldager-1
Fjerritslev-2
Mors-1
Hyllebjerg-1
Års-1
Farsø-1
Rødding-1
Skive-1
Hobro-1
Kvols-1
Gassum-1
Oddesund-1
Mejrup-1
Vemb-1
Vinding-1
Nøvling-1
Voldum-1
Rønde-1
Terne-1
Hans-1
Lavø-1
Horsens-1
Lillerslev-1
Slagelse-1

Fig.41

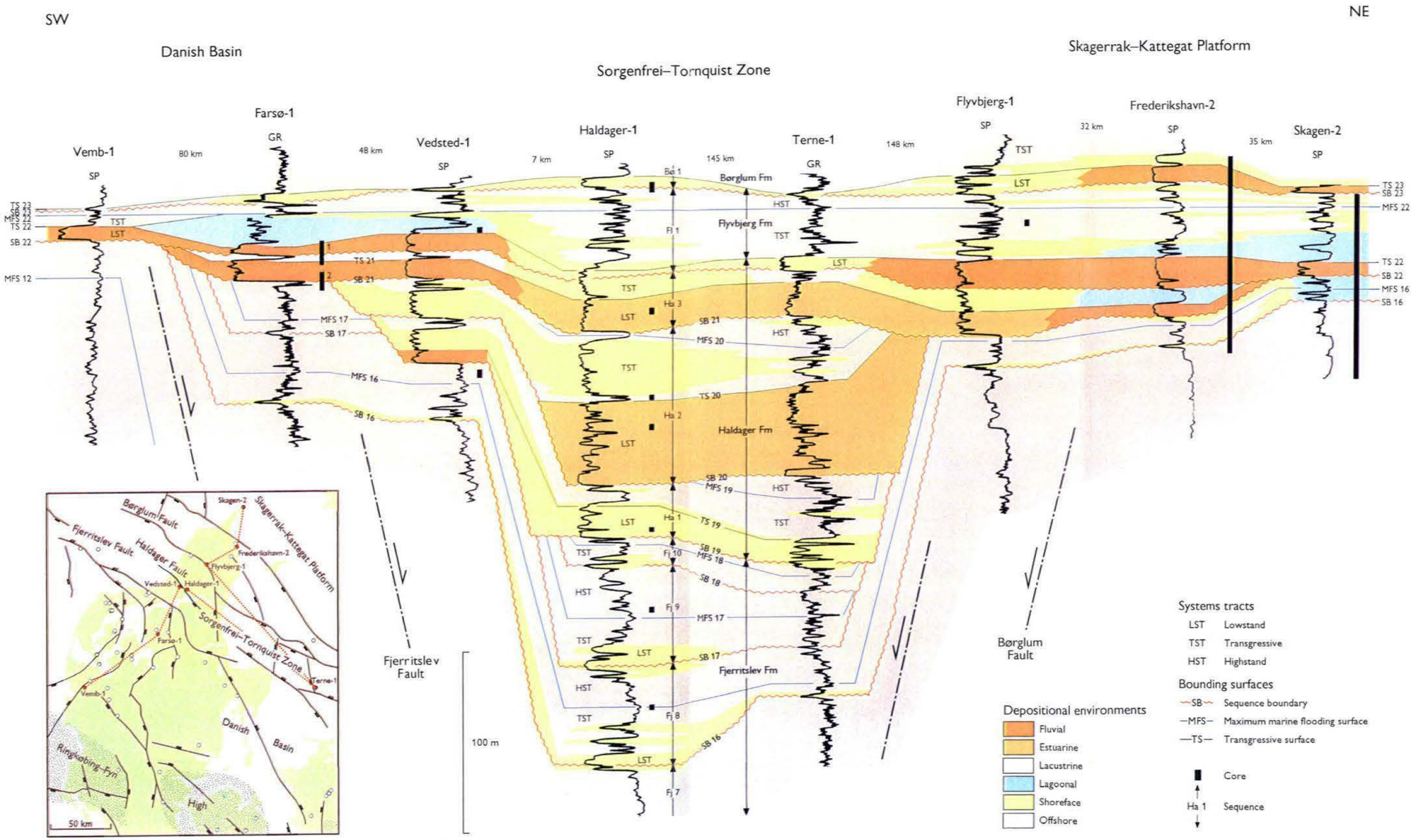

SW
NE
Danish Basin
Sorgenfrei–Tornquist Zone
Skagerrak–Kattegat Platform
Vemb-1
Farsø-1
Vedsted-1
Haldager-1
Terne-1
Flyvbjerg-1
Frederikshavn-2
Skagen-2
SP
GR
80 km
48 km
7 km
145 km
148 km
32 km
35 km
Børglum Fm
Flyvbjerg Fm
Haldager Fm
Fjerritslev Fm
Bø 1
Fl 1
Ha 3
Ha 2
Ha 1
Fj 10
Fj 9
Fj 8
Fj 7
TS 23
SB 23
MFS 22
TS 22
SB 22
MFS 12
TS 21
SB 21
MFS 17
SB 17
MFS 16
SB 16
MFS 20
TS 20
SB 20
MFS 19
TS 19
SB 19
MFS 18
SB 18
LST
TST
HST
Fjerritslev Fault
Børglum Fault
100 m
Børglum Fault
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Sorgenfrei–Tornquist Zone
Danish Basin
Ringkøbing–Fyn High
50 km
Depositional environments
Fluvial
Estuarine
Lacustrine
Lagoonal
Shoreface
Offshore
Systems tracts
LST Lowstand
TST Transgressive
HST Highstand
Bounding surfaces
SB Sequence boundary
MFS Maximum marine flooding surface
TS Transgressive surface
Core
Ha 1 Sequence

Fig.42

GEUS

EASTDENMARK

Vertical Scale: 1:1474
Horizontal Scale: 1:5810
VE = 3.939999
Depth Units: METERS
Distance Units: METERS
Interpreter: LHN
Date: 23-January-2003

Sequence stratigraphy vs organic geochemistry

Haldager Sand Fm

SB 19 – TS 22

Figure 43

GEUS

EASTDENMARK

Vertical Scale: 1:899
Horizontal Scale: 1:7091
VE = 7.88
Depth Units: METERS
Distance Units: METERS
Interpreter: LHN
Date: 23-January-2003

Sequence stratigraphy vs organic geochemistry

Haldager Sand Fm

SB 19 – TS 22

Figure 44

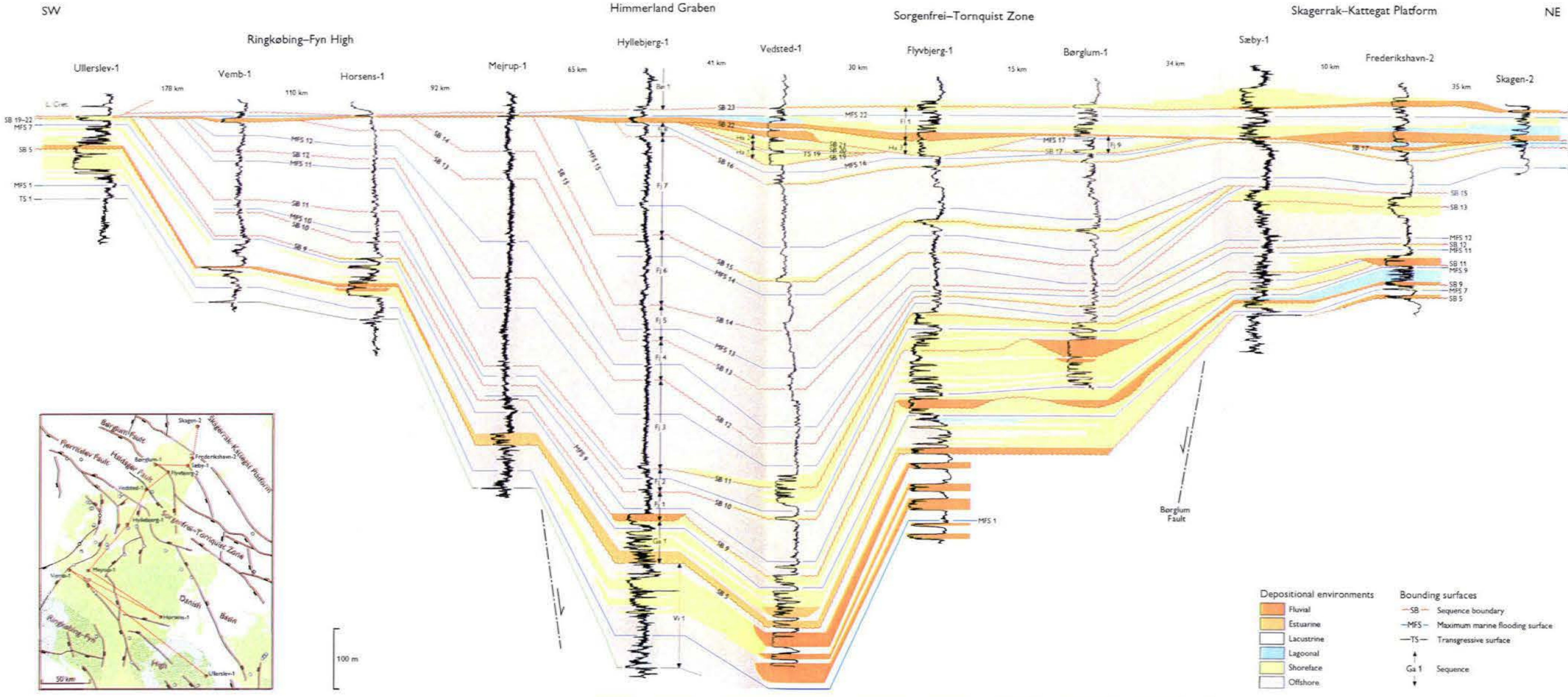
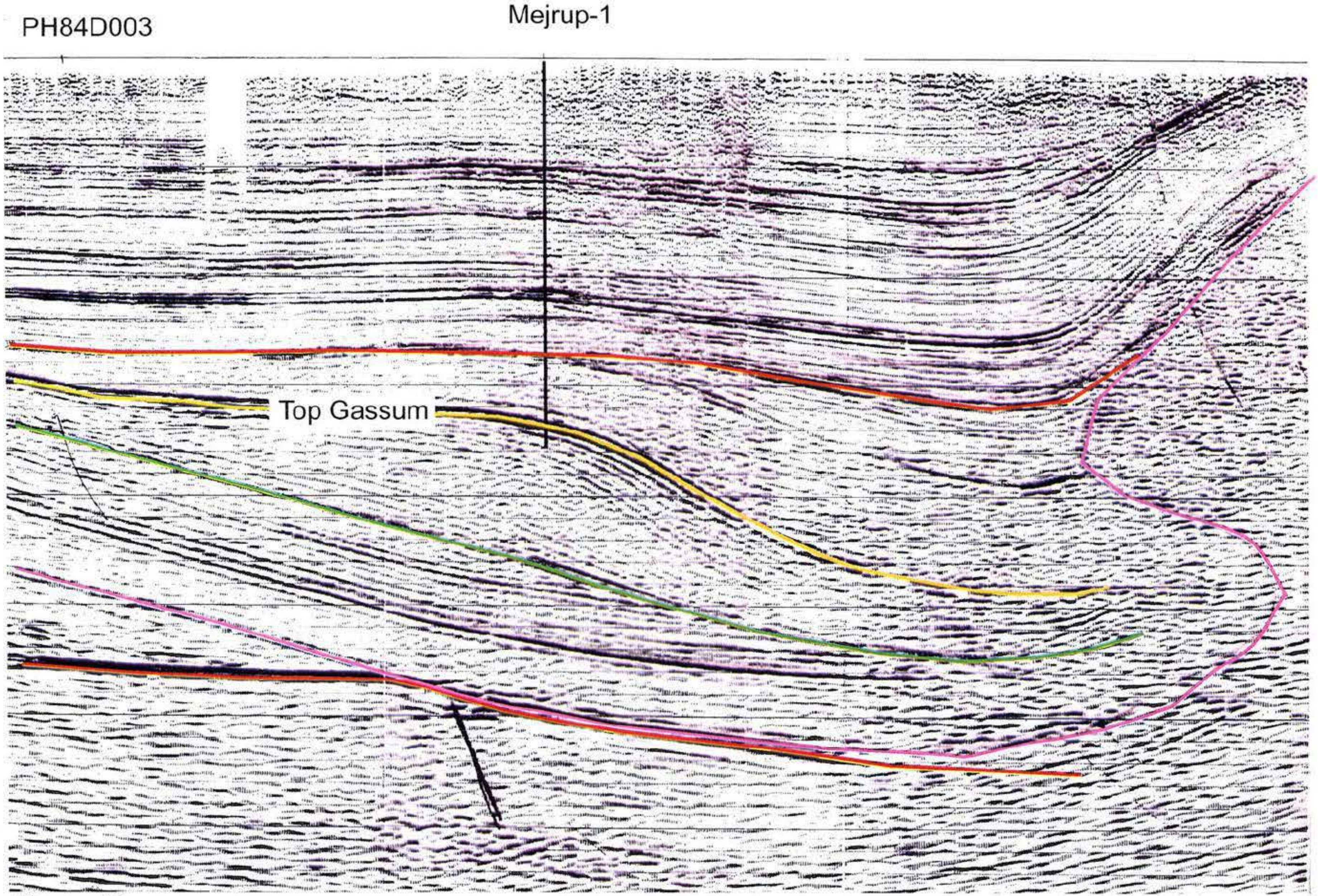

SW
Himmerland Graben
Sorgenfrei–Tornquist Zone
Skagerrak–Kattegat Platform
NE
Ringkøbing–Fyn High
Ullerslev-1
Vemb-1
Horsens-1
Mejrup-1
Hyllebjerg-1
Vedsted-1
Flyvbjerg-1
Børglum-1
Sæby-1
Frederikshavn-2
Skagen-2
178 km
110 km
92 km
65 km
41 km
30 km
15 km
34 km
10 km
35 km
L. Cret.
SB 19–22
MFS 7
SB 5
MFS 1
TS 1
MFS 12
SB 12
MFS 11
SB 11
MFS 10
SB 10
SB 9
SB 14
SB 13
SB 15
MFS 15
MFS 9
Be 1
SB 23
SB 22
MFS 22
Ha 1
Ha 2
Ha 3
TS 19
SB 21
SB 20
SB 19
MFS 16
SB 16
MFS 17
SB 17
Fj 1
Fj 2
Fj 3
Fj 4
Fj 5
Fj 6
Fj 7
Fj 9
MFS 14
MFS 13
Ga 1
Vi 1
SB 23
MFS 22
SB 19–22
MFS 16
SB 16
MFS 15
SB 15
SB 13
MFS 12
SB 12
MFS 11
SB 11
MFS 9
SB 9
MFS 7
SB 5
Børglum Fault
100 m
Skagen-2
Børglum Fault
Fjerritslev Fault
Haldager Fault
Skagerrak–Kattegat Platform
Frederikshavn-2
Børglum-1
Sæby-1
Flyvbjerg-1
Vedsted-1
Hyllebjerg-1
Sorgenfrei–Tornquist Zone
Vemb-1
Mejrup-1
Danish Basin
Horsens-1
Ringkøbing–Fyn High
Ullerslev-1
50 km
Depositional environments
Fluvial
Estuarine
Lacustrine
Lagoonal
Shoreface
Offshore
Bounding surfaces
SB Sequence boundary
MFS Maximum marine flooding surface
TS Transgressive surface
Ga 1 Sequence

Fig.45



Figere 46.

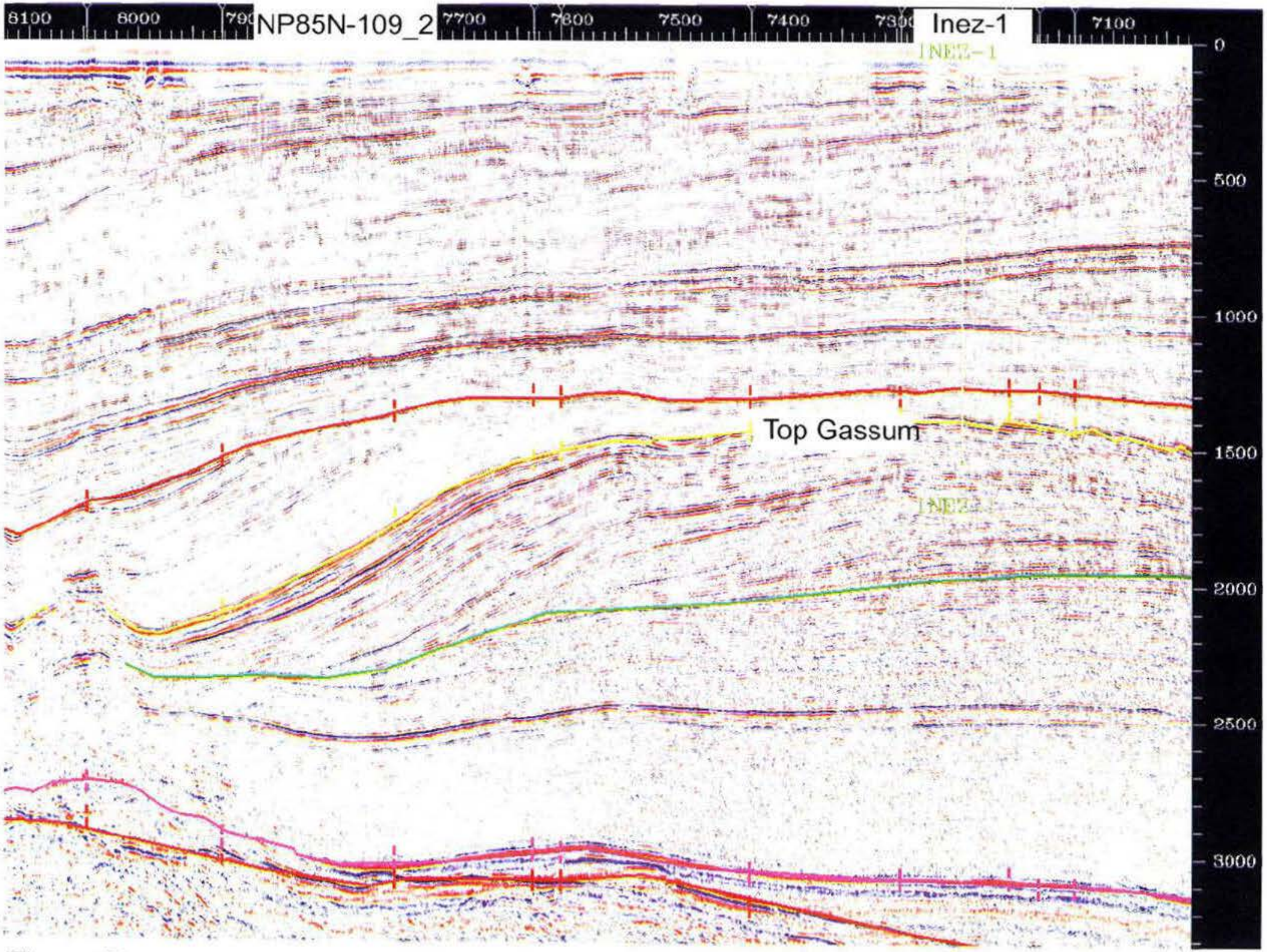

8100
8000
79
NP85N-109_2
7700
7600
7500
7400
730
Inez-1
7100
INEZ-1
Top Gassum
INEZ-1
0
500
1000
1500
2000
2500
3000

Figure 47.

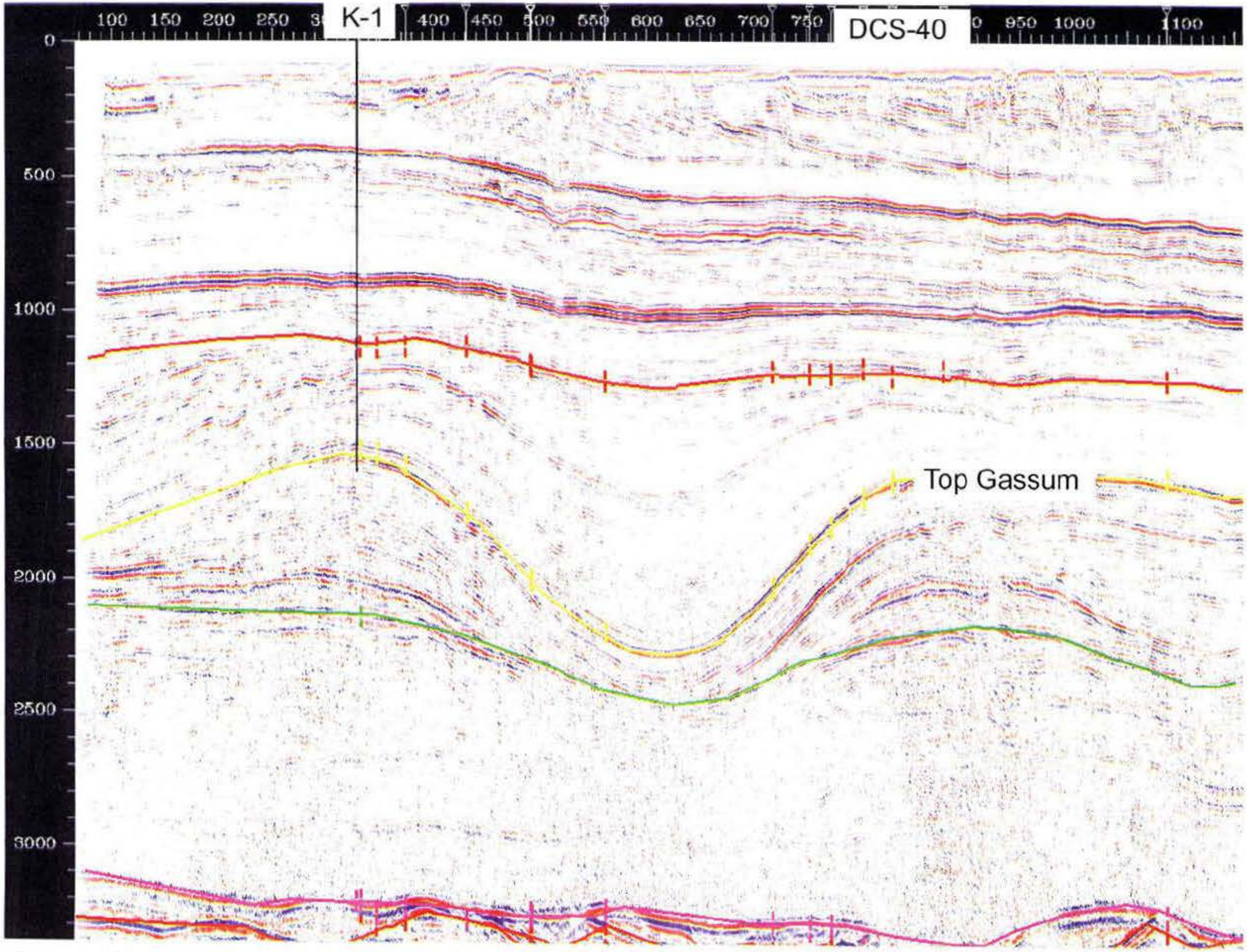

K-1
DCS-40
Top Gassum
100
150
200
250
400
450
500
550
600
650
700
750
950
1000
1100
0
500
1000
1500
2000
2500
3000

Figure 48.

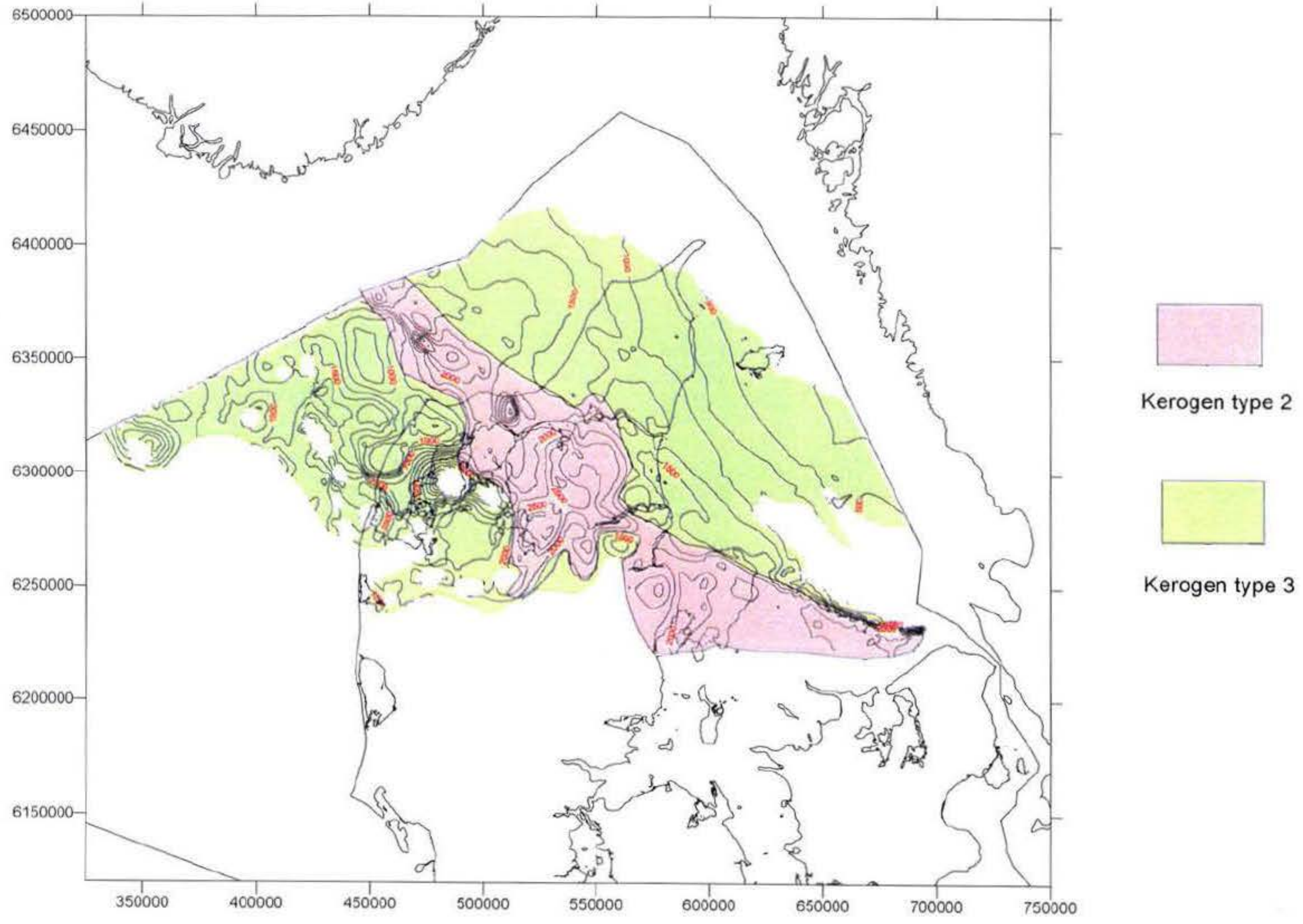


Figure 49. Depth to top of F-III Member and kerogen types

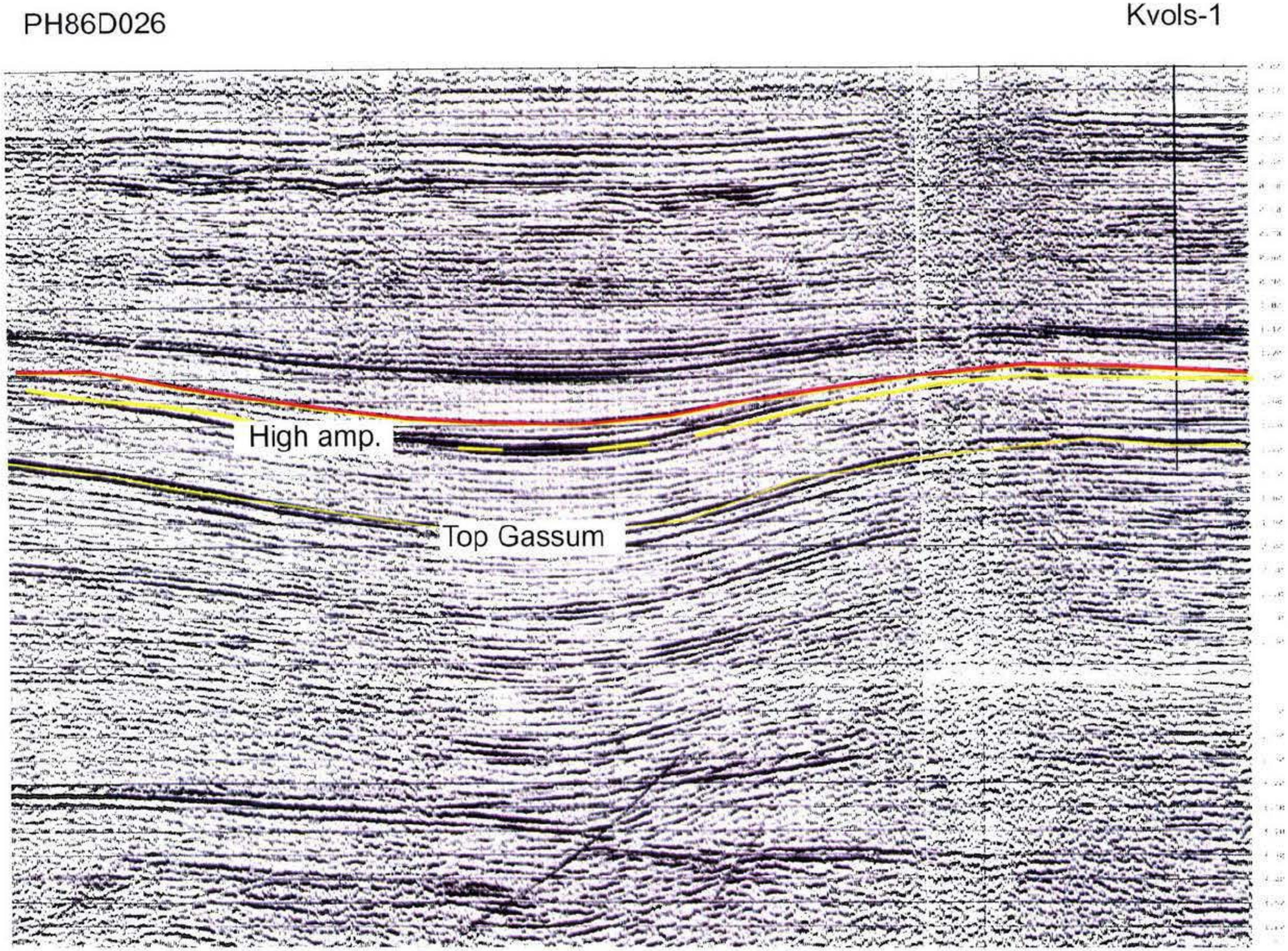


Figure 50.

PH85D008

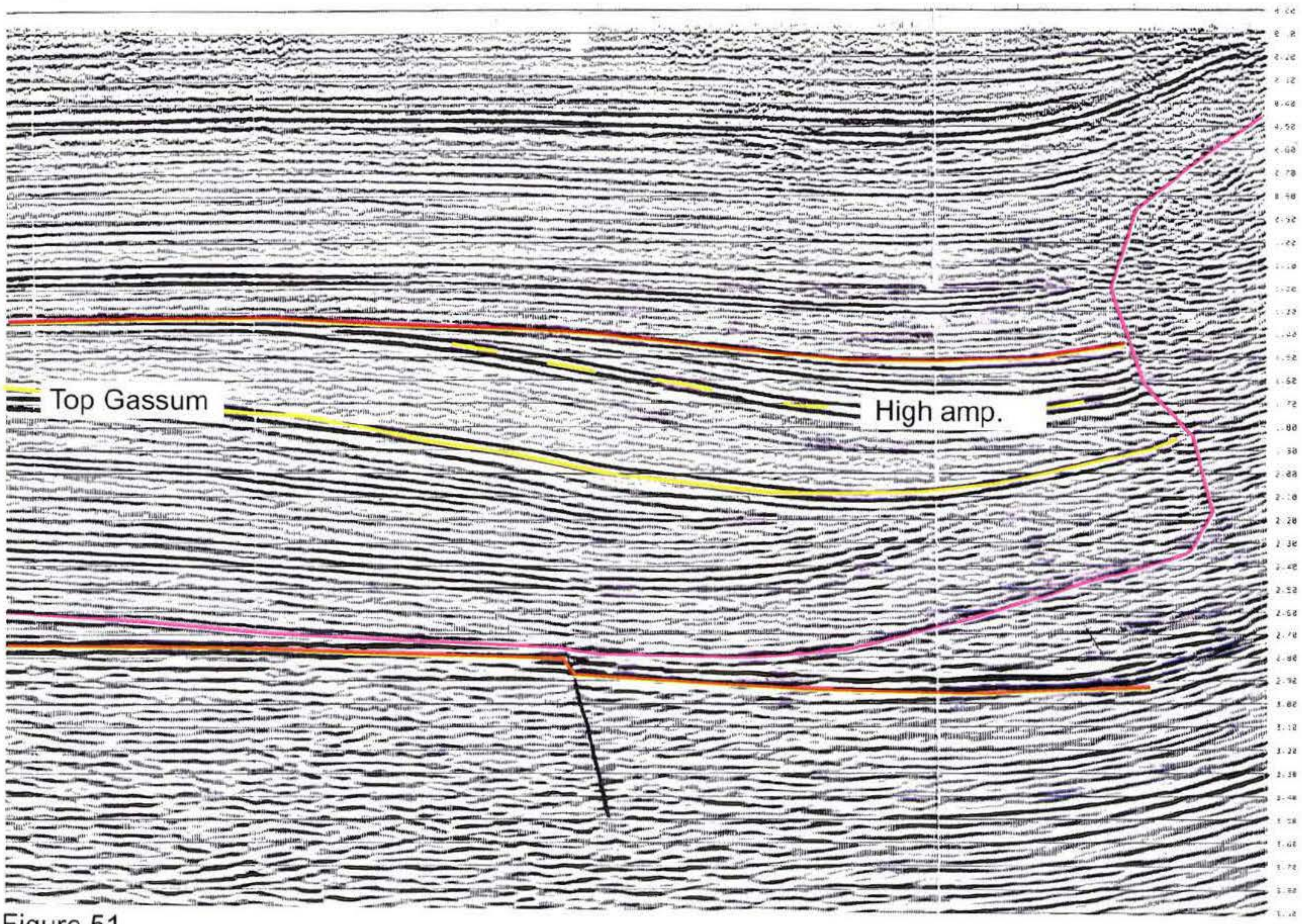


Figure 51.

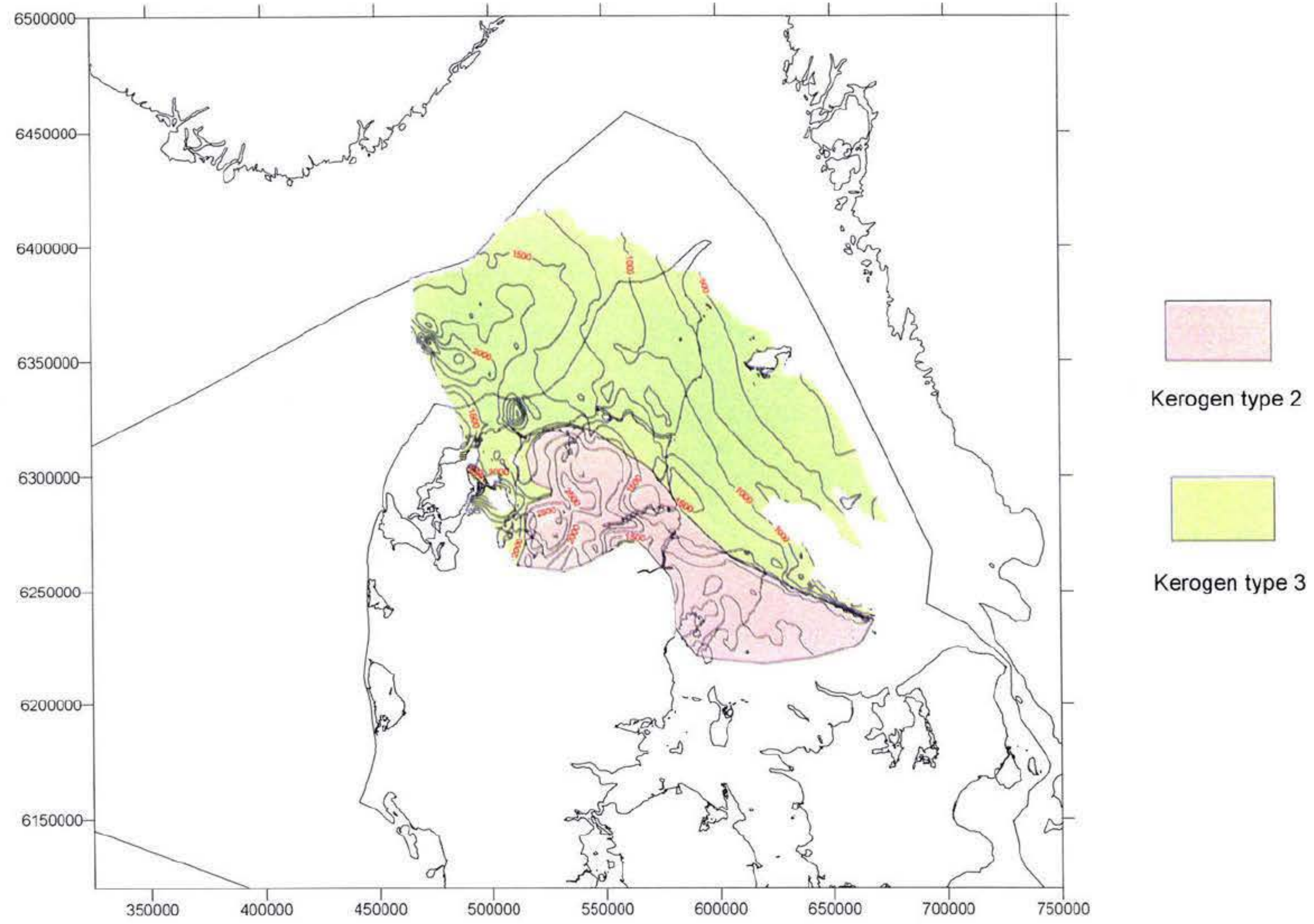
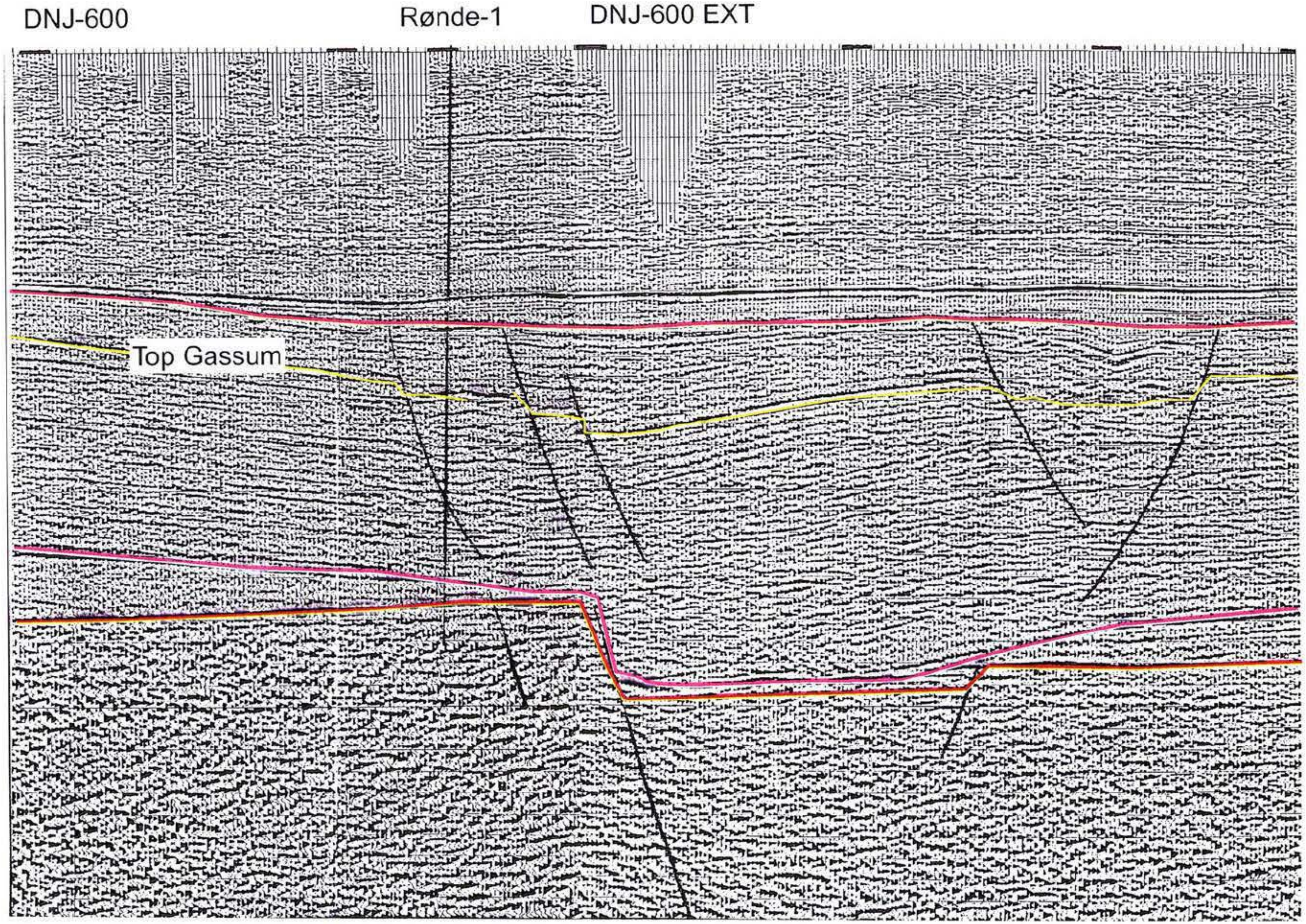


Figure 52. Depth to top of F-IV Member and kerogen types



Fugure 53.

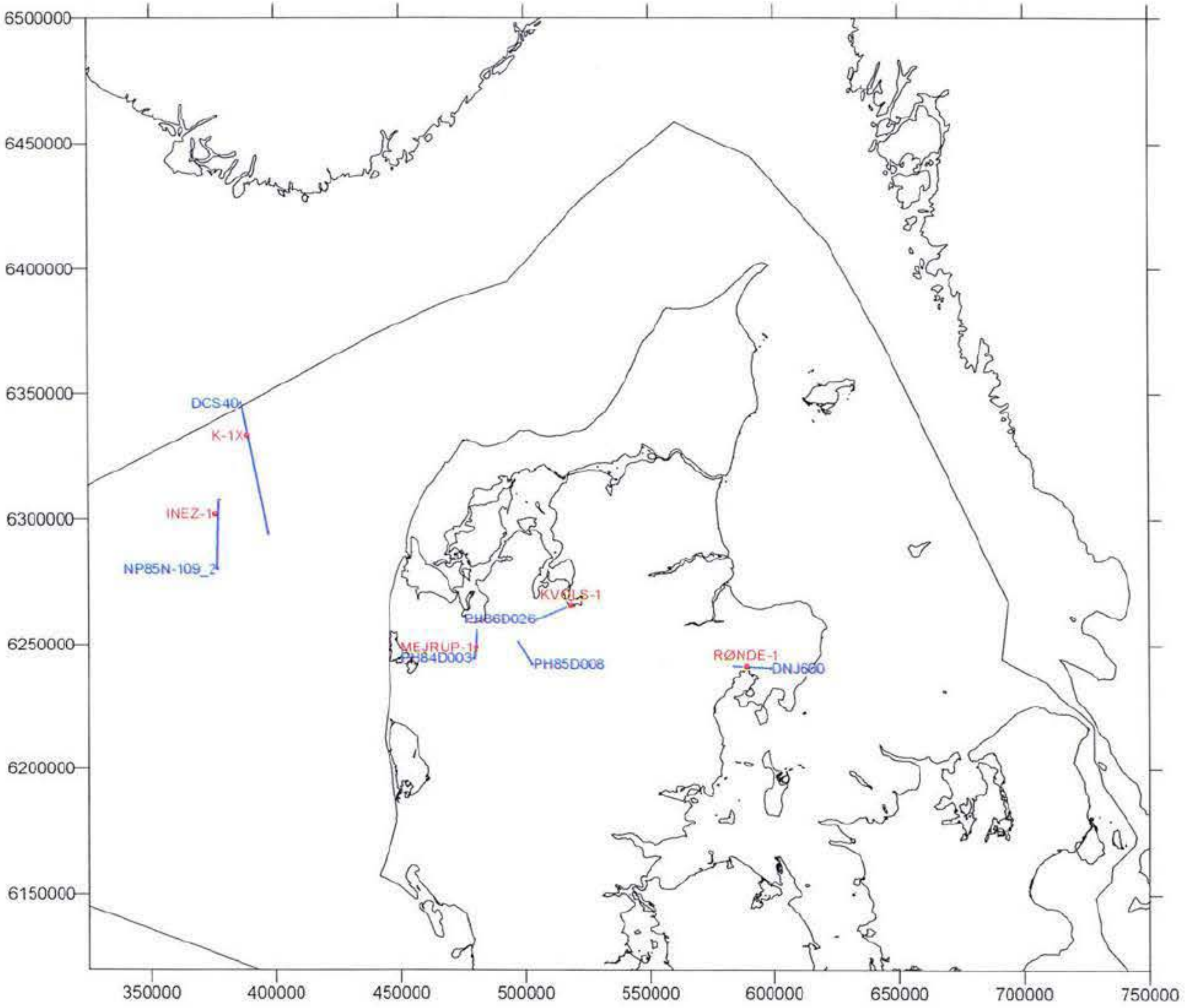

6500000
6450000
6400000
6350000
6300000
6250000
6200000
6150000
350000
400000
450000
500000
550000
600000
650000
700000
750000
DCS40
K-1X
INEZ-1
NP85N-109_2
KVOLS-1
PH86D026
MEJRUP-1
PH84D003
PH85D008
RØNDE-1
DNJ660

Figure 54.

Table 1

		Chalk			M.Jurassic ur		ormity to Base U. Chretaceous			Fjeritslev Formation			
	TWT. ms	TWT. ms	TWT. ms	Vel. m/sec	TWT. ms	T'	ms	TWT. ms	Vel. m/sec	TWT. ms	TWT. ms	TWT. ms	Vel. m/sec
Well name	Top	Base	Center	Int. vel.	Top			Center	lint vel	Top	Base	Center	Int vel
Børglum	102	364	233	2704	364			600	2555	836	1045	940,5	2829
C 1	605	957	781	3150	957			1054	2500			0	
Elna	2332	2456	2394	4587	2456			2476	3383			0	
F 1	731	1064	897,5	3504	1064			1244	2650	1424	1610	1517	3022
Farsø	24	884	454	3244	884			1057,5	3124	1231	1706	1468,5	3225
Felicia			0					0		732	1122	927	2785
Fjeritslev 1	-1	202	100,5	2808	202			333	2298	464	722	593	2535
Fjeritslev 2	7	210	108,5	2828				0				0	
Fredrikshavn	235	324	279,5	2856				0		661	802	731,5	2399
Gassum	-28	621	296,5	2996	621			688	2952	755	996	875,5	2653
Haldager	22	346	184	2455	346			683	2554	1020	1186	1103	2941
Hans								0					
Hobro	48	940	494	3457				0				0	
Hyllebjerg	-2	844	421	3243	844			1019	2994	1194	1596	1395	3284
Inez	851	1070	960,5	3808	1070			1179	2587	1288	1364	1326	2647
Ibenholt	1389	1478	1433,5	4349				0				0	
J-1	103	216	159,5	2372	216			583,5	2340	951	1356	1153,5	3075
K - 1	490	947	718,5	3184	947			1036,5	2424	1126	1513	1319,5	2916
Kvols	264	1106	685	3534	1106	1		1179	3191	1252	1544	1398	3082
L - 1	1974	2108	2041	4495				0				0	
Mejrup	525	1057	791	3332	1057	1		1167	2909	1277	1608	1442,5	2867
Mors	152	909	530,5	3584	909	1		1120	3104	1331	1684	1507,5	3473
Nøvling	498	962	730	3384				0				0	
Oddesund	462	1035	748,5	3333	1035	1		1123	2795	1211	1418	1314,5	2754
Rødding	224	952	588	3297	952	1		1022	2795	1092	1280	1186	2862
Rønde	105	1135	620	3600	1135	1		1178	3229	1231	1525	1378	3231
Skive 1	220	953	586,5	3396	953	1		1043,5	3017	1134	1393	1263,5	3019
Skive 2	120	674	397	3321	674			718	2705	762	852	807	2667
Stenlilli 1	143	750	446,5	3321	750			766	2937	782	965	873,5	2842
Sæby					369			529	2381	689	890	789,5	2547
Terne								0		544	794	669	2688
Thisted 2	3	590	296,5	2736	590			679	2494	768	836	802	2676
Vemb	671	1100	885,5	3389	1100	1		1171	2831	1242	1390	1316	2757
Voldum	-8	778	385	3104	778			836	3034	894	1125	1009,5	2892
Års	120	1074	597	3491	1074	1		1285	3351	1496	1886	1691	3615

ENCLOSURE 1: Summary of source rock potential

	Børglum-1	C-1	F-1	Farsø-1	Felicia-1	Fjerritslev-2	Flyvbjerg-1	Frederikshavn-1	Frederikshavn-2
Upper Jurassic undifferentiated	▨	no source potential	▨	▨	▨	▨	▨	▨	▨
Frederikshavn Formation	no source potential		no source potential	🟩	🟩	no source potential	no source potential	no source potential	no source potential
Børglum Formation	no source potential		no source potential	no source potential	no source potential	marginal source potential in parts of succession	no source potential	🟩	no source potential
Flyvbjerg Formation	no source potential		🟩	🟩	no source potential	no source potential	no source potential	🟩	no source potential
Haldager Sand Formation	marginal source potential in parts of succession		marginal source potential in parts of succession	🟩	no source potential	marginal to good source potential	marginal source potential in parts of succession	🟩	no source potential
Fjerritslev Formation F-IV	good to excellent source potential			no source potential		marginal source potential in parts of succession	no source potential	🟩	marginal source potential in parts of succession
Fjerritslev Formation F-III	marginal source potential in parts of succession		no source potential	marginal to good source potential	marginal source potential in parts of succession	marginal source potential in parts of succession	no source potential	no source potential	good source potential in parts of succession
Fjerritslev Formation F-II	no source potential		no source potential	marginal source potential	no source potential	no source potential	no source potential	no source potential	no source potential
Fjerritslev Formation F-I	no source potential		no source potential	no source potential	no source potential	no source potential	no source potential	no source potential	no source potential
Gassum Formation	no source potential		no source potential	🟩	excellent source potential in parts of succession	no source potential	no source potential	no source potential	no source potential
Skagerrak Formation	▨	▨	no source potential	▨	🟩	no source potential	no source potential	no source potential	no source potential
Vinding Formation	🟦		🟦	🟩	no source potential	🟦	🟦		🟦
Oddesund Formation	🟦	no source potential	🟦	🟦	🟩	🟦	🟦		🟦
Tønder Formation	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Falster Formation	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Ørslev Formation	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Bunter Sandstone Formation	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Bunter Shale Formation	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Zechstein Group	🟦	no source potential	🟦	🟦	🟦	🟦	🟦		🟦
Rotliegend Group	🟦	🟩	🟦	🟦	🟦	🟦	🟦		🟦
Pre-Permian units	🟦	🟦	🟦	🟦	🟦	🟦	🟦	no source potential	🟦

	Gassum-1	Haldager-1	Hans-1	Hobro-1	Hyllebjerg-1	Inez-1	J-1	K-1	Kvols-1
Upper Jurassic undifferentiated	▨	▨	▨	▨	▨	▨	▨	▨	▨
Frederikshavn Formation	good source potential in parts of succession	no source potential		no source potential	marginal source potential in parts of the succession	no source potential	no source potential	no source potential	no source potential
Børglum Formation	no source potential	no source potential		no source potential	no source potential	no source potential	no source potential	no source potential	no source potential
Flyvbjerg Formation		no source potential		no source potential	no source potential			no source potential	
Haldager Sand Formation		good source potential in parts of succession		marginal source potential in parts of succession	no source potential	no source potential	marginal source potential	no source potential	no source potential
Fjerritslev Formation F-IV	no source potential	no source potential		marginal source potential in parts of the succession	marginal to good source potential		no source potential	no source potential	marginal source potential in parts of succession
Fjerritslev Formation F-III		marginal source potential in parts of succession	no source potential	marginal source potential in parts of the succession	marginal source potential		marginal to good source potential	no source potential	good to excellent source potential
Fjerritslev Formation F-II		🟦	no source potential	good to excellent source potential	good source potential in parts of succession		marginal source potential in parts of succession	no source potential	🟩
Fjerritslev Formation F-I		🟦	no source potential	no source potential	no source potential	no source potential	no source potential	no source potential	no source potential
Gassum Formation	no source potential	🟦	excellent source potential in parts of succession	no source potential	no source potential	no source potential	no source potential	no source potential	no source potential
Skagerrak Formation	🟩	🟦	🟩	▨	▨	no source potential	no source potential	no source potential	▨
Vinding Formation	🟩	🟦	▨	no source potential	no source potential	🟦	🟦	minor organic enrichment, no source potential	no source potential
Oddesund Formation	🟩	🟦	▨	no source potential	no source potential	🟦	🟦	🟦	no source potential
Tønder Formation	🟩	🟦	▨	🟦	🟦	🟦	🟦	🟦	🟦
Falster Formation	🟩	🟦	▨	🟦	🟦	🟦	🟦	🟦	🟦
Ørslev Formation	🟩	🟦	▨	🟦	🟦	🟦	🟦	🟦	🟦
Bunter Sandstone Formation	🟩	🟦	▨	🟦	🟦	🟦	🟦	🟦	🟦
Bunter Shale Formation	🟩	🟦	▨	🟦	🟦	🟦	🟦	🟦	🟦
Zechstein Group	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🟦	🟦
Rotliegend Group	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🟦	🟦
Pre-Permian units	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🟦	🟦

	Lavø-1	Mejrup-1	Mors-1	Nøvling-1	Rødding-1	Rønde -1	Skagen-2	Skive-1	Slagelse-1
Upper Jurassic undifferentiated	▨	▨	▨	▨	▨	▨	▨	▨	▨
Frederikshavn Formation		no source potential	no source potential	no source potential	no source potential	no source potential	excellent source potential in parts of succession	no source potential	
Børglum Formation		no source potential	no source potential	no source potential	no source potential	no source potential	no source potential	no source potential	
Flyvbjerg Formation		no source potential	no source potential		no source potential		marginal source potential in parts of succession	no source potential	
Haldager Sand Formation		no source potential	marginal source potential in parts of the succession				marginal source potential in parts of succession	no source potential	
Fjerritslev Formation F-IV			marginal to good source potential			excellent source potential	good source potential in parts of succession		
Fjerritslev Formation F-III		no source potential	marginal source potential		no source potential	good to excellent source potential		no source potential	
Fjerritslev Formation F-II		no source potential	marginal source potential in parts of succession	no source potential	no source potential	marginal source potential in parts of succession		no source potential	
Fjerritslev Formation F-I	no source potential	good source potential in parts of succession	no source potential	no source potential	no source potential	no source potential	marginal to good source potential	no source potential	no source potential
Gassum Formation	no source potential	marginal to good source potential	marginal source potential in parts of succession	no source potential	no source potential	no source potential	marginal source potential in parts of succession	no source potential	no source potential
Skagerrak Formation	▨	▨	▨	▨	▨	▨	no source potential	▨	▨
Vinding Formation	no source potential	good source potential in parts of succession	no source potential	marginal source potential in parts of succession	no source potential	no source potential	🟦	no source potential	marginal source potential in parts of succession
Oddesund Formation	🟦	🟦	no source potential	no source potential	no source potential	marginal source potential in parts of succession	🟦	🟦	no source potential
Tønder Formation	🟦	🟦	no source potential	no source potential	🟦	no source potential	🟦	🟦	no source potential
Falster Formation	🟦	🟦	🟩	no source potential	🟦	no source potential	🟦	🟦	no source potential
Ørslev Formation	🟦	🟦	🟩	no source potential	🟦	Contamination ?, oil-based drilling mud	🟦	🟦	no source potential
Bunter Sandstone Formation	🟦	🟦	🟩	no source potential	🟦	Contamination ?, oil-based drilling mud	🟦	🟦	no source potential
Bunter Shale Formation	🟦	🟦	🟦	no source potential	🟦		🟦	🟦	no source potential
Zechstein Group	🟦	🟦	🟦	no source potential	🟦	Contamination ?, oil-based drilling mud	🟦	🟦	no source potential
Rotliegend Group	🟦	🟦	🟦		🟦	Contamination ?, oil-based drilling mud	🟦	🟦	no source potential
Pre-Permian units	🟦	🟦	🟦	no source potential	🟦	Contamination ?, oil-based drilling mud	🟦	🟦	no source potential

	Sæby-1	Terne-1	Vedsted-1	Vinding-1	Voldum-1	Års-1
Upper Jurassic undifferentiated	▨	▨	▨	no source potential	▨	▨
Frederikshavn Formation	marginal source potential in parts of succession	excellent source potential	no source potential		marginal source potential	no source potential
Børglum Formation	no source potential	🟩	no source potential		marginal source potential	no source potential
Flyvbjerg Formation	no source potential	marginal source potential in parts of succession	no source potential			no source potential
Haldager Sand Formation	marginal source potential in parts of succession	excellent source potential	good source potential in parts of succession		no source potential	no source potential
Fjerritslev Formation F-IV	marginal to good source potential	no source potential	no source potential			marginal source potential in parts of succession
Fjerritslev Formation F-III	no source potential	marginal source potential in parts of succession	no source potential		marginal source potential in parts of succession	marginal source potential in parts of succession
Fjerritslev Formation F-II	no source potential	no source potential	marginal source potential in parts of succession		no source potential	marginal source potential in parts of succession
Fjerritslev Formation F-I	marginal source potential in parts of succession	no source potential	no source potential	no source potential	no source potential	marginal source potential in parts of succession
Gassum Formation	marginal source potential in parts of succession	no source potential	no source potential	no source potential	marginal source potential in parts of succession	marginal source potential in parts of succession
Skagerrak Formation	marginal source potential in parts of succession	🟩	no source potential	▨	▨	▨
Vinding Formation			🟦	no source potential	no source potential	no source potential
Oddesund Formation			🟦	no source potential	marginal source potential in parts of succession	🟦
Tønder Formation			🟦	no source potential	🟦	🟦
Falster Formation			🟦	no source potential	🟦	🟦
Ørslev Formation			🟦	🟦	🟦	🟦
Bunter Sandstone Formation			🟦	🟦	🟦	🟦
Bunter Shale Formation			🟦	🟦	🟦	🟦
Zechstein Group		🟩	🟦	🟦	🟦	🟦
Rotliegend Group	no source potential		🟦	🟦	🟦	🟦
Pre-Permian units	🟦	no source potential	🟦	🟦	🟦	🟦

🟦 Formation not penetrated by well

☐ Formation absent

🟩 Formation present, no data available

▨ Unit not defined in well

Criteria for assessment:

no source potential	$S2_{mean} < 2$, and $S2_{max} < 2$
marginal source potential in parts of succession	$S2_{mean} < 2$, and $2 < S2_{max} < 6$
marginal source potential	$2 < S2_{mean} < 6$
good source potential	$6 < S2_{mean} < 10$
good source potential in parts of succession	$S2_{mean} < 2$, and $6 < S2_{max} < 10$
marginal to good source potential	$2 < S2_{mean} < 6$, and $6 < S2_{max} < 10$
excellent source potential	$S2_{mean} > 10$
excellent source potential in parts of succession	$S2_{mean} < 2$, and $S2_{max} > 10$
good to excellent source potential	$6 < S2_{mean} < 10$, and $S2_{max} > 10$