DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/22

Kortlægning af grundvandsmagasiner i Ringkøbing Amt

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Indhold

Forord

Nærværende rapport indeholder 3 delrapporter: 1) Seismisk tolkning af nye seismiske linier skudt i 2004 samt en foreløbig korrelation af nye boringer i Ringkøbing Amt. 2) Distribution and thicknesses of reservoir sands in the wave-dominated Billund delta, eastern Danish North Sea and Jylland. 3) Uppermost Upper Oligocene – Miocene lithostratigraphy of Denmark.

1. delrapport

I denne rapport er der foretaget en seismisk tolkning af data fra 5 områder: Herning – Hoven, Bølling, Ørnhøj, Aulum og Ikast. Derudover er der lavet en foreløbig tolkning af 4 nye boringer (Holstebro, Ørnhøj, No, og Stensig), 5 ældre boringer (Hanning, Stauning, Lavstrup, Studsgård og Brande), samt 1 olieefterforskningsboring (Vinding-1). Resultaterne indgår i en kortlægning af grundvandsmagasiner i amtet.

Tidligere undersøgelser af seismiske data har vist at en bestemt seismisk facies svarer til sandrige grundvandsmagasiner. Dette blev testet ved Ørnhøj og gav et positiv resultat, hvor der blev anboret et grundvandsmagasin på ca. 30 m, tilhørende Bastrup sandet.
Ved Holstebro blev oplysninger fra en nyere oliefterforskningsboring (Mejrup-1) brugt til at teste om der i området var et stort grundvandsmagasin i Billund sandet. Resultatet her blev dog negativt. I den nye boring blev der kun anboret ca. 15 m sand fra Billund sandet. Det må derfor konkluderes at data fra disse ældre olieefterforskningsboringer skal bruges med forsigtighed. Resultatet fra Holstebro boringen sammenholdt med Vinding-1 boringen indikerer at man i bedste fald kan anbore 15 til 20 meter sand fra Billund sandet i Holstebro området. Til gengæld er Bastrup sandet, med en tykkelse på over 20 meter og sandsynligvis med 2 delta lober, interessant her.

Nye seismiske data indikerer et stort grundvandsmagasin i Billund sandet ved Kibæk. Området ved Ikast og nordøst herfor, rummer også store grundvandsmagasiner både fra Billund og Bastrup sandet. Den sydøstlige del af amtet (Hoven) kan ud fra ældre olieefterforskningsboringer (bedre kvalitet end nyere) samt seismiske data, specielt ved Sdr. Omme, have store grundvandsmagasiner tilhørende både Billund og Bastrup sand.

De nye data, både boringer og seismiske data, fra den nordøstlige del af amtet, indikerer at der måske skal revideres på den miocæne stratigrafi. Nogle af de dybereliggende store grundvandsmagasiner ligger måske ubeskyttet i dele af det centrale Jylland. Dette har stor betydning for udpegning af beskyttelsesområder her, samt for hele kortlægningsarbejdet af grundvandsmagasiner i det centrale Jylland.

2. delrapport

Det nedre Miocæne Billund sand blev aflejret i et bølgedomineret delta. Nærværende undersøgelse er baseret på højopløselige seismiske data, nye boringer samt blotninger langs den jyske østkyst. Deltaet blev aflejret som et typisk bølgedomineret delta med et overordnet nordvest – sydøstligt forløb. Udbygningen af deltaet skete under højt havniveau og efterfølgende fald i havniveau. Generelt aflejredes sandlag med en tykkelse på 10 – 20 m i deltakomplekset, men i forbindelse med fald i havniveau og i strukturelle lavninger aflejredes op til 100 m tykke sandlag. På seismiske data erkendes disse sandlag ved et parallelt klinoformt reflektionsmønster, med en hældning på ca. 15°. Stakningsmønsteret af denne facies indikerer om deltaudbygningen skete under stigende eller faldende havniveau og har dermed et potentiale til at forudsige større grundvandsmagasiner.

3. delrapport

Den sidste del omfatter en afrapportering af et projekt, der søger at opstille en ny litostratigrafi for den miocæne lagserie.

Der er nu defineret 5 formationer og 5 led. Disse enheder er markeret med fremhævet skrift i abstraktet nedenunder.

Vejle Fjord Formationen er revideret og opdeles nu i Vejle Fjord Sand Led og Vejle Fjord Ler Led. Brejning Ler Led opgraderes til Formation. Klinting Hoved Formationen defineres formelt. Ribe Formation revideres og inddeles i 2 nye led; Hvidbjerg Led og Billund Led. Arnum Formationen inddeles i 3 nye led, nemlig Vandel Silt Led, Sdr. Vium Led og NN Led. Odderup Formationen kommer til at inkludere Stauning Led og det kulførende Fasterholt Led. De øvre miocæne lag inddeles i Hodde -, Gram – and Marbæk Formationerne. Gram Formationen kommer også til at inkludere Glaukony Ler Led.

Seismisk tolkning af nye seismiske linier skudt i 2004 samt en foreløbig korrelation af nye boringer i Ringkøbing Amt.

Sammenfatning

I denne rapport er der foretaget en seismisk tolkning af data fra 5 områder: Herning – Hoven, Bølling, Ørnhøj, Aulum og Ikast. Derudover er der lavet en foreløbig tolkning af 4 nye boringer (Holstebro, Ørnhøj, No, og Stensig) og 5 ældre boringer (Hanning, Stauning, Lavstrup, Studsgård og Brande), samt 1 olieefterforskningsboring (Vinding-1). Resultaterne indgår i en kortlægning af grundvandsmagasiner i amtet.

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Introduktion

Nærværende delrapport omhandler en tolkning af seismiske data skudt i Ringkøbing Amt i 2004. Tolkningen er koncentreret til den miocæne lagserie; der kan dog på enkelte linier være angivet andre horisonter, både under og over den miocæne lagserie. Endvidere er der konstrueret 3 korrelationspaneler med henblik på at inddrage nye, samt ældre relevante boringer til kortlægningen af dybereliggende grundvandsmagasiner i amtet. En del af de nye boringer vil blive undersøgt ved hjælp af biostratigrafi og kan derfor være fejlagtigt tolket i nærværende rapport.

I det arbejde, der har foregået i amtet det sidste år, både med boringer i den nordøstlige del af amtet og nye seismiske data omkring Ikast, er der fremkommet tolkningsløsninger, der kan ændre den traditionelle opfattelse af den miocæne lagserie. Der er opstået nogen tvivl om tolkningen af Odderup Formationen i den østlige del af amtet, samt i Århus og Vejle amter. En ændring af stratigrafien i de nævnte område er også baseret på datering af Salten Profilet i Århus Amt. Der er i denne rapport lavet to korrelationspaneler (R7 og R8), som illustrerer dette problem.

Geologisk ramme

De Paleogene og Neogene sedimenter, der blev aflejret for 65 til 5 millioner år siden i det østlige Nordsø bassin består hovedsageligt af ler og sand. Kalkaflejringer kendes fra den tidligste del af perioden.

Paleogenet, der dækker det geologiske tidsrum fra 65 millioner år til 23 millioner år, startede med aflejring af koldtvandskarbonater. Altså, sedimenter dannet i det hav eller på havbunden i det hav som de levede i. I den østlige del af Danmark består disse karbonater hovedsageligt i form af bryozor banker og koral rev. For omkring 62 millioner år siden ændredes dette aflejringsmønster markant således at der i den resterende del af Paleogen aflejredes overvejende lerede sedimenter, som stammede fra nedbrydningen af de landområder, der omkransede den daværende Nordsø. Aflejringen skete på forholdsvist dybt vand.

For ca. 23 millioner år siden, ved begyndelsen af den periode geologerne kalder Miocæn, blev der land i det område vi i dag kender som Danmark. Landet var på det tidspunkt karakteriseret ved store deltaer og kystsletter, som byggede ud i Nordsøen fra bjergene i nord (Norge). Udbygningen af deltaer og kystsletter dominerede de første 7 millioner år af Miocæn perioden (Fig. 1). I løbet af disse 7 millioner år skete der tre markante udbygninger af deltaer, hovedsageligt fra Norge. Den første deltaudbygning nåede helt ned til Sønderjylland. Herunder aflejredes tykke sandlag kendt som Ribe Formationen. I det centrale Jylland aflejredes i en periode tykke sandlag som er blevet kaldt Billund sandet Fig. 1). Efter aflejringen af Ribe Formationen steg havet og overvejende lerede sedimenter tilhørende Arnum Formationen blev aflejret. Havet nåede ca. ind til Silkeborg området. Herefter rykkede landet igen søværts mod sydvest og sandrige deltaaflejringer blev afsat i form af Bastrup sandet. Udbygningen af Bastrup sandet nåede ikke så langt sydvest på som Ribe Formationen. En ny stigning af havet, betød at landet igen rykkede tilbage til Silkeborg området. Udbygningen af deltaer kulminerede ved overgangen fra Nedre til Mellem Miocæn, hvor store sumpområder medførte aflejringer af tykke brunkulslag i Midtjylland (Fig. 2). Disse lag er kendt som Odderup Formationen.

For ca. 15 mio. år siden, i begyndelsen af Mellem Miocæn, skete der en markant ændring mod et varmere klima der førte til at havniveauet steg og oversvømmede store landområder omkring Nordsøen. Dette store hav kaldes populært for "Gram Havet". De geologiske vidnesbyrd fra dette hav er aflejringer af marine, til tider fossilholdige, lerbjergarter kendt som Hodde og Gram Formationerne. Under denne varme periode (det midt miocæne klimatiske optimum) lå kystlinien formodentligt lidt nord for Limfjorden langs en forkastningszone kaldet Fjerritslev Forkastningen (Fig. 3). Dette er dog kun ét forslag, måske var kystlinien placeret væsentligt nordligere, og havet dækkede måske store dele af det nuværende Sverige helt op til Göteborg. Vi ved det ikke helt præcist, fordi senere istider over Danmark har slettet alle spor af Gram Havet i Nordjylland og Skagerrak–Kattegat området.

I den sidste del af Miocæn begyndte kysten igen at bygge ud i Nordsøen. Denne udbygning skete både fra nord og fra øst (Fig. 4). Ved Miocæns afslutning lå kystlinien helt ude i den centrale del af Nordsøen (Fig. 5) der langsomt var ved at være fyldt op af de nedbrydningsprodukter som igennem Miocæn var blevet eroderet bort fra de norske fjelde og de centraleuropæiske bjergkæder.

Litostratigrafi

De nyere undersøgelser af den øvre oligocæne – miocæne lagserie har vist at den tidligere litostratigrafiske opdeling er for simpel. Derfor vil der i nærværende undersøgelse blive benyttet en litostratigrafi for den miocæne lagserie, der er kraftig revideret (Dybkjær et al. 1999; Rasmussen et al. 2002)(Fig. 6 og 7).

Den ældste litostratigrafiske enhed er Vejle Fjord Formationen. Den nederste del af Vejle Fjord Formationen, Brejning Led, henregnes til oligocænet, så den miocæne lagserie starter med Vejle Fjord Leret. Vejle Fjord Leret efterfølges af Vejle Fjord Sand og Hvidbjerg sand. I det centrale og vestlige Jylland er der kortlagt et større deltakompleks, som er samtidig med Vejle Fjord Formationen. Dette benævnes Billund sand. I det sydlige Jylland aflejredes et meget sandrigt system, som er en videre udbygning af Billund deltaet, men som dog er isoleret fra Billund deltaet. Dette sandrige system hedder Ribe Formationen. Over disse enheder, der overordnet tilhører Vejle Fjord Formationen, kommer Arnum Formationen, der hovedsageligt består af lerede sedimenter. Den nederste del af Arnum Formationen, som består af sandrige sedimenter benævnes Kolding Fjord sand. De minder meget om Vejle Fjord Formationen, men er yngre og udgør ikke en del af Vejle Fjord systemet. I de nordlige og østlige egne af Jylland kiler der sig et sandlag ind i den lerede del af Arnum Formationen. Dette lag benævnes Bastrup sand. I forbindelse med en ny kystudbygning i den øverste del af Arnum Formationen aflejeredes finsand rigt på tungmineraler. Disse sandlag kaldes for Stauning sand. Over Arnum Formationen følger den sandrige Odderup Formation. Herover træffes kun lerrige sedimenter i Jylland. Disse lag er kendt som Hodde Formationen og Gram Formationen.

Der er endnu ikke konstrueret et prækvartært kort over de miocæne formationer, som omtalt ovenfor, men den overordnede fordeling af de miocæne og pliocæne i det danske område er vist i Rasmussen (2004). Her ser man at de Miocæne lag bliver ældre mod øst og nordøst. Dette er en konsekvens af den markante neogene og kvartære hævning og erosion.

Data

De seismiske data, der er tolket i nærværende rapport er: SV2, SV6, SV7, SV8, SV9, AL1, AL2, AL3, IK1, HN1, KB1,KB2,LM02 og RM2.

Boringsdatabasen omfatter 17 boringer. Disse boringer er Sdr. Vium (DGU 102.958), Lavtrup (DGU 102.673), Stauning (DGU 93.679), Stensig (DGU 93.1062), Hanning (DGU 93.549), No (DGU 83.1694), Ørnhøj (DGU 74.1140), Holstebro (DGU 64.1640), Nøvling-1 (olieefterforskningsboring), Vinding-1 (olieefterforskningsboring), Studsgård (DGU 85.360), Isenvad (DGU 86.2056), Engesvang (DGU 86.2050), Addit Mark (DGU 97.928), St. Vorslunde (DGU 104.2325), Brande (DGU 104.1964) og Lavsbjerg (DGU 95.1942).

Korrelation af boringer

I nærværende rapport er der konstrueret 3 paneler (Fig. 8), der søger at korrelerer nye og enkelte udvalgte boringer i amtet. Det skal dog understreges at der kan ske ændringer når der foreligger biostratigrafiske data fra de nye boringer. De 3 korrelationspaneler er en fortsættelse og udbygning af tidligere korrelationspaneler afrapporteret i Rasmussen (2003; 2004) og er derfor benævnt R6, R7 og R8.

R6

R6 korrelerer boringerne Sdr Vium, Lavstrup, Stauning, Stensig, Hanning, No, Ørnhøj og Holstebro (Fig. 9).

Den nederste del består af lerede sedimenter tilhørende Vejle Fjord Formationen. Ved Stensig er der dog anboret mellem til grovkornet sand ved 230 meters dybde. Dette sand tilhører formodentligt tåen af en større sandlobe, der er blevet aflejret i forbindelse med udbygningen af Billund deltaet. Over Vejle Fjord Formationen følger sandede sedimenter fra Billund sandet. I den sydlige del, ved Sdr. Vium, er denne del benævnt Ribe Formationen i det vi her er syd for det sandrige bælte af Billund sand, som løber tværs over Jylland. Over Ribe Formationen og Billund sandet følger lerede aflejringer fra nedre Arnum Formation. Det er muligt at der ved Stensig og Hanning er aflejret/bevaret sandede og lerede sedimenter fra Kolding Fjord Formationen? Arnum Formationen følges af Bastrup sandet. Dette sandlag er dog meget tyndt i Sdr. Vium boringen og mangler i No boringen. Lagserien i No boringen er noget forskellig fra en typisk Arnum succession (se logmønsteret), og det må vente en nærmere biostratigrafisk undersøgelse før det kan afgøres om det er omlejrede miocæne sedimenter eller kvartære sedimeter. I den nordlige del af profilet, ved Holstebro og Ørnhøj, kiler der sig sandede sedimenter ind i Arnum Formationen. Disse sandlag tilhører Bastrup sandet. Distale lag af Bastrup sandet er også erkendt i Stauning og Lavtrup boringerne. Over Bastrup sandet følger lerede aflejringer fra øvre Arnum Formationen. Indlejret i Arnum Formationen findes finkornede sandlag, rige på tungmineraler, i den sydlige del af profilet. Disse finkornede sandlag korrelerer til Stauning sandet. Arnum Formationen overlejres af sandede sedimenter fra Odderup Formationen. Specielt ved Holstebro og Ørnhøj, er der erkendt lignit i Odderup Formationen som svarer til Fasterholt Ledet. Odderup Formationen følges af lerede sedimenter tilhørende Hodde og Gram Formationerne.

R7

R7 korrelerer boringerne St. Vorslunde (Vejle Amt), Brande (Petersborg), Lavsbjerg, Isenvad og Engesvang (Fig. 10).

Nederste del består af lerede sedimenter tilhørende Vejle Fjord Formationen. Disse overlejres af sandrige sedimenter fra Billund sandet. Billund sandet er tykkest mod nord og opnår en tykkelse på ca. 70 meter i Isenvad boringen. Over Billund sandet følger en 10 til 20 meter tyk nedre Arnum Formation, der består af overvejende lerede sedimenter. Herover følger Bastrup sandet, som er veludviklet langs profilet. Bastrup sandet er lige som Billund sandet mest veludviklet mod nord, men er mægtigt i hele området og har ekstremt gode reservoiregenskaber. Bastrup sandet overlejres af lerede sedimenter tilhørende øvre Arnum Formation. Herover følger sandede sedimenter fra Odderup Formationen. I Odderup Formationen er der erkendt brunkulsholdige sedimenter, som tilhører Fasterholt Ledet. Herover følger lerede sedimenter fra Hodde og Gram formationerne.

R8

R8 korrelerer Nøvling, Studsgård, Isenvad, Engesvang og Addit Mark boringerne (Fig. 11).

Den nederste del af profilet er domineret af lerede sedimenter tilhørende Vejle Fjord Formationen. Disse dominerer meget i den vestlige og østlige del af profilet. Forholdsvis tykke sandlag fra Billund sandet, er anboret i Isenvad og Engesvang boringerne. Over Billund sandet følger lerede sedimenter fra nedre Arnum Formationen. De lerede sedimenter dominerer i Nøvling boringen, men det skal dog fastslås at Nøvling er en gammel olieefterforskningsboring og at man derfor ikke helt kan regne med sediment beskrivelserne fra denne boring. De lerede sedimenter fra nedre Arnum Formation overlejres af sandede sedimenter tilhørende Bastrup sandet. Herover følger lerede sedimenter fra øvre Arnum Formation. Ved Nøvling og Studsgård overlejres øvre Arnum Formation af sandede sedimenter tilhørende Odderup Formationen og ved Studstup er der anboret brunkulsholdige lag fra Fasterholt Ledet.

Seismisk tolkning

I 2004 blev der indsamlet seismiske data fra 5 områder i amtet. De 5 områder er: Aulum, Ørnhøj, Ikast, Bølling og Herning – Hoven. Tolkningen af de seismiske data fra de enkelte områder vil blive præsenteret herunder.

Tolkningen af de seismiske data består i en inddeling i sekvenser, der er vist i figur 7 og beskrevet i Rasmussen (2004). Endvidere er der også konstrueret temakort, som viser forskellige seismiske facies, der er relevant i kortlægningen af grundvandsmagasiner.

Kvaliteten af de seismiske data er generelt høj. Der er dog i Ørnhøj-området konstateret områder, hvor det ikke har været muligt at få tilstrækkelig energi ned i undergrunden til at opnå gode data. Kvaliteten i den øverste del af de seismiske data, der er anvendt i denne rapport, er dårlig.

Herning – Hoven (HN1, KB1 og KB2)(Fig. 12)

Der er erkendt 3 sekvenser i den miocæne lagserie: B, C og D (Fig. 13a, b og c).

Basis af sekvens B er tolket ved en kontinuert, højamplitude reflektor. Sekvens B er karakteriseret ved svagt hældende clinoformer, som dykker mod syd. Hældningen på clinoformerne er målt til 0.7^{o}. Imellem skudpunkt 9000 og 14000 ses et område, der er karakteriseret ved et parallelt klinoformt reflektionsmønster (markeret med gult). Hældningen er mod syd og ca. 7^{o}. Enheden kiler ud mod øst (Fig. 13b).

Sekvens C er karakteriseret ved et noget kaotisk reflektionsmønster, med lav kontinuitet og noget varierende amplituder. Der er dog i visse områder erkendt clinoformer, der hælder mod syd.

Sekvens D har et kaotisk og delvist transparent reflektionsmønster. Den øvre grænse af sekvens D er svær at fastlægge på baggrund af datakvaliteten, men der er observeret enkelte nedskårede dale.

Den seismiske linie skærer ingen boringer, men 2 vigtige stratigrafiske gode boringer, Studsgård og Eg-3, ligger tæt på linien. I Studsgård boringen, der er forskudt ca. 7 km, er en næsten komplet Miocæn lagserie fra terræn og ned til toppen af Billund sandet. Tolkning af den seismiske linie, med hensyn til placeringen af top Bastrup og top Billund, understøttes kraftigt af boringen. Bastrup sandet er godt 40 m tykt ifølge Studsgård boringen. Tykkelsen af Billund sandet kan ikke estimeres ud fra boringen, da denne ikke gennembore Billund sandet. Eg-3 borigen, der er en gammel olieefterforskningsboring, ligger i en afstand af ca. 5 km fra skudpunkt 24500. En tolkning af denne boring er vist i Rasmussen (2003). Boringen er tolket til at gennembore tykke sandlag, både i sekvens B og C. Hvis denne tolkning er korrekt, svarer det svagt hældende klinoforme reflektionsmønster til en deltaudbygning mod syd med sandrige aflejringer. Sandrige, tykke aflejringer er kendt fra delta enheden i sekvens B (se part 2 i nærværende rapport), men erfaringer fra boringer i Billund området viser at sandrige aflejringer med gode egenskaber som grundvandsmagasiner er associeret med et parallelt klinoformt reflektionsmønster, som er erkendt nord for Eg-3 boringen. På en seismisk linie lige øst for Eg-3 boringen, ved Sdr Omme (Ribe Amt), er der erkendt både Billund sand og Bastrup sand, så det er sandsynligt at der findes grundvandsmagasiner tilhørende både Billund sand og Bastrup sand i området omkring Hoven.

På grund af liniens begrænsede udstrækning mod syd er det ikke muligt præcist at sige, hvor stor udstrækning deltaet/deltaerne har mod syd. Tidligere undersøgelser indikerer dog at deltafronten/fronterne ligger i den sydlige del af linien for deltaerne i både sekvens B og C. Det er ikke muligt at tolke distinkte aflejringsmiljøer i sekvens D på basis af kvaliteten i den øverste del af den seismiske linie. De mod syd hældende klinoformer indikerer en udbygning af Bastrup sandet, hvilket også er anboret i Eg-3 og boringen ved Studsgård (Fig. 13a). Det må derfor antages at der er Bastrup sand af høj kvalitet i området.

Bølling (LM02 og RM2)(Fig. 15)

Der er erkendt 3 sekvenser i den miocæne lagserie: Sekvens B, C og D (Fig. 16a og b).

Basis af sekvens B er placeret ved en højamplitude og kontinuerlig reflektor, som kan følges regionalt. Generelt er sekvens B karakteriseret ved et parallelt reflektionsmønster. I den nordlige del ses svagt hældende reflektorer i den nederste del af sekvensen. Reflektorene hælder mod syd. Der kan erkendes pålap på den enhed (Fig. 16a). Øverst i sekvensen ses små konkave (opad) reflektorer.

Basis af sekvens C er placeret ved en reflektor der er kontinuerlig og med en høj amplitude. Lige under grænsen ses ofte de små konkave (opad) reflektorer, der karakteriserer den øverste del af sekvens B. Internt, er sekvens C karakteriseret ved et parallelt til subparallelt reflektionsmønster, med noget varierende amplitude.

Basis af sekvens D er placeret ved en kraftig, men diskontinuert reflektor. Sekvensen er domineret af et transparent reflektionsmønster med enkelte høj amplitude reflektorer.

Den øvre del af seismikken er svær at tolke, men større nedskårede elementer kan erkendes.

Det seismiske survey i området kan korreleres til en række boringer; Hanning, Stensig (Fig. 9, 16a), Rækker Mølle og Borris (Rasmussen 2003). Speciel gennembore Stensig boringen næsten hele den miocæne lagserie (Fig. 16a). Det svagt hældende reflektionsmønster i den nordlige del kan tolkes til at repræsentere en sandrig lobe tilhørende Billund deltaet. Det parallelle reflektionsmønster, der ellers karakteriserer sekvens B, korrelerer til lerdominerede aflejringer. I forbindelse med den pålappende enhed nederst i sekvensen er der aflejret sandede sedimenter, som gradvist bliver finere opad. De små konkave reflektorer øverst i sekvensen kan tolkes som nedskårede dale med sandfyld, som for eksempel er gennemboret i Rækker Mølle boringen (Rasmussen 2004). Alle de ovenfor nævnte boringer, gennemborer sekvens C. Disse boringer gennemborer både tykke og tynde sandenheder uden at det seismiske reflektionmønster direkte kan relateres til sandlagene. Den øverste del af seismikken kan kun opdeles i en enkelt seismisk sekvens. Boringer viser dog at sekvenserne D, E og F (Rasmussen 2004) er repræsenteret og at både Odderup, Hodde og Gram Formationerne dermed findes i området.

Ikast (IK1)(Fig. 17)

Der er erkendt 3 sekvenser i den miocæne lagserie: Sekvens B, C og D (Fig. 18). Generelt hælder de miocæne lag mod syd.

Basis af sekvens B er placeret ved en højamplitude, kontinuerlig reflektor. Internt er sekvensen karakteriseret ved et noget kaotisk reflektionsmønster. I den nordlige del af sektionen er der erkendt et parallelt, klinoformt reflektionsmønster i den midterste del af sekvensen (markeret med gult). I den sydlige del, mellem skudpunkt 6150 og 10100, ses en meget iregulær, højamplitude reflektor. Øverst i sekvensen ses en del højamplitude, tildels konkave opad reflektorer.

Basis af sekvens C er placeret ved en høj amplitude, delvist kontinuerlig reflektor. Nederst i sekvensen erkendes en markant, højamplitude, kontinuerlig reflektor. Herover er der i den nordlige del af sektionen en serie af subparallelle til svagt mod syd hældende reflektorer. Ellers er sekvens C karakteriseret ved et transparent reflektionsmønster.

Basis af sekvens D er placeret ved en højamplitude, kontinuerlig reflektor. Internt er sekvensen karakteriseret ved et kaotisk refeltionsmønster.

Den seismiske linie kan korreleres til Isenvad boringen (Fig. 18). Sekvens B korrelerer her til Vejle Fjord Formationen og Billund sandet. Denne boring gennemborer 70 meter Billund sand og ca. 30 meter lerede sedimenter fra Vejle Formationen. Det klinoforme reflektionsmønster korrelerer til den nederste del af Billund sandet (Fig. 18), men generelt er sekvensen, ifølge boringen, meget sandet i den øverste del. Den irregulære, højamplitude reflektor i den sydlige del af sektionen kan tolkes til at repræsentere en erosionsflade. Sandlaget i den øverste del af Billund sandet viser en finende opad tendens, hvilket er i overensstemmelse med udfyldning af en dal. På en seismisk linie lige vest for Ikast dominerer det klinoforme reflektionsmønster (Fig. 19), hvilket tyder på at dette område ikke har været udsat for erosion som ved Isenvad. Udbredelsen af det parallelt reflektionsmønster er vist på figur 20. Over Billund sandet følger lerede sedimenter tilhørende nedre Arnum Formation. Dette interval korrelerer til det højamplitude, parallelt reflektionsmønster nederst i sekvens C. Herover følger veksellejrende sand og ler aflejringer fra Bastrup sandet. Denne del korrelerer til det subparallele til svagthældende reflektionsmønster i den nordlige del af sektionen. En udkiling af lerlagene mod syd bekræftes af Lavsbjerg boringen, der ligger tæt på den sydlige del af sektionen (Fig. 18). Sekvens D er pga. hældningen af lagserien bedst repræsenteret i den sydlige ende af sektionen. Her korrelerer sekvensen til Odderup Formationen og Fasterholt Ledet. Sekvens D trunkeres mod nord.

Ørnhøj (SV2, SV6, SV7, SV8 og SV9)(Fig 21)

Der er erkendt 3 sekvenser i den miocæne lagserie: Sekvens B,C og D (Fig. 22a, b, c, d og e).

Basis af sekvens B er placeret ved en højamplitude og kontinuerlig reflektor, som kan følges regionalt. Generelt er sekvens B karakteriseret ved et parallelt, delvist lavamplitude reflektionsmønster. I den nederste del af sekvensen ses en mere høj amplitude, gennemgående reflektor.

Sekvens C er defineret ved en kontinuerlig, men svag reflektor. Herover følger en tynd zone karakteriseret ved et parallelt reflektionsmønster. Dette følges, i den nordlige ende af et lavamplitude, subparallelt reflektionsmønster, der har en svag hældning mod syd. En udkiling af enheden ses ved skudpunkt 2600. Den øverste del af sekvens C er karakteriseret ved et lavamplitude, parallelt reflektionsmønster.

Basis af sekvens D er placeret ved en kontinuerlig, lavamplitude reflektor. Den nederste del af sekvens D er karakteriseret ved et lavamplitude, delvist transparent, parallelt til subparallelt reflektionsmønster. Den øvre del er karakteriseret ved et noget højere amplitude mønster. Ved selve grænsen erkendes ofte smalle konkave opad reflektorer.

Den øverste del af den seismiske sektion er meget transparent og den øvre grænse af sekvens D kan være svær at erkende. Der er dog erkendt markante nedskæringer i området.

Der er ingen boringer i området, der gennemborer hele den miocæne lagserie. På basis af borehuls korrelationer (Fig. 9), er det mest sandsynlig at den nederste del og måske det meste af sekvens B, består af lerede sedimenter tilhørende Vejle Fjord Formationen. Ørnhøj (Vind) boringen anborer måske sandede sedimenter fra den øverste del af sekvensen. Dette kan dog først afklares når der foreligger en biostratigrafisk rapport. Sekvens C er til gengæld anboret i Ørnhøj (Vind) boringen. Her korrelerer den nederste del af sekvensen til lerede sedimenter fra nedre Arnum (Fig. 22a), boringen afsluttes dog i et sandlag, der kan tolkes som en distal lobe af en tidligere Bastrup udbygning. En alternativ tolkning er at det tilhører Kolding Fjord Formationen. Dette følges af ca. 30 meter Bastrup sand. Over Bastrup sandet følger ca. 10 meter lerede sedimenter fra nedre Arnum Formation. Ved selve sekvensgrænsen mellem sekvens C og D er der et gruslag med korn op til 3 cm i diameter. Den nedre del af sekvens C består af øvre Arnum ler. Den øvre del, der seismisk er karakteriseret ved et relativt højamplitude, parallelt reflektionsmønster, korrelerer til sandede sedimenter fra Odderup Formationen og lignitholdige lag tilhørende Fasterholt Ledet.

Aulum (AL1, AL2 og AL3)(Fig. 23)

Der er erkendt 3 sekvenser i den miocæne lagserie: Sekvens B, C og D (Fig. 24a, b og c).

Basis af sekvens B er placeret ved en højamplitude og kontinuerlig reflektor, som kan følges regionalt. Generelt er sekvens B karakteriseret ved et parallelt til subparallelt reflektionsmønster. I den nederste del af sekvensen ses en mere høj amplitude, gennemgående reflektor. I den sydlige del erkendes en mindre trunkering internt i sekvensen (Fig. 24a).

Sekvens C er defineret ved en kontinuerlig, men svag reflektor. Herover følger en tynd zone karakteriseret ved et parallelt reflektionsmønster. Dette følges af et lavamplitude, subparallelt reflektionsmønster. Den øverste del af sekvens C er karakteriseret ved et parallelt reflektionsmønster med enkelte områder med en serie af konkav opad? reflektorer.

Basis af sekvens D er placeret ved en kontinuerlig, lavamplitude reflektor. Den nederste del af sekvens D er karakteriseret ved et lavamplitude, delvist transparent, parallelt til subparallelt reflektionsmønster.

Den øverste del af den seismiske sektion er meget transparent og den øvre grænse af sekvens D kan ikke erkendes. Der er dog erkendt markante nedskæringer i området.

De seismiske linier kan via ADK85 survey korreleres til Vinding-1 boringen (Fig. 25, 26). Vinding-1 boringen gennemborer en tyk kvartær lagserie, men det tyder på at også hele sekvens B er gennemboret. Den nederste del korrelerer til lerede sedimenter tilhørende Vejle Fjord Formationen. Fra ca. 140 meter og op ad, forekommer hyppige indslag af sand, specielt i den øverste del. Dette sand blev også gennemboret ved Holstebro (Fig. 9). Her blev anboret ca. 15 meter sand ved selve sekvensgrænsen, hvor de øverste 10 meter tilhører Kolding Fjord Formationen. Herunder var der kun indslag af tynde sandlag i Holstebro boringen. Der er muligvis mægtigere sandlag i Vinding området, men denne antagelse bygger på en gammel Vinding boringen (gammel olieefterforskningsboring). På grund af den kvartære dal ved Vinding-1, kan sekvens C ikke korreleres til boringer, men både i Holstebro og ved Ørnhøj (Fig. 9) er der anboret Bastrup sand øverst i sekvensen. Ligeledes gennembores normalt sandrige sedimenter fra Odderup Formation, hvor sekvens D er tilstede.

Sammenfatning af seismisk tolkning

På baggrund af nærværende undersøgelse samt tidligere tolkning af seismiske data i Ringkøbing Amt og data indsamlet i de andre jyske amter, er der fremstillet et temakort, der gør rede for udbredelsen af potentielle miocæne grundvandsmagasiner i Jylland. I vise områder er data af en sådan kvalitet og tæthed at tykkelsen og udbredelsen kan angives ret nøjagtigt (Hansen og Rasmussen part 3).

På figurene 27, 28 og 29 er vist udbredelsen af Billund og Bastrup sandet. Endvidere er der angivet, hvor et parallelt klinoformt reflektionsmønster er identificeret. Af speciel interesse for Ringkøbing Amt, er der for Billund sandet fundet den seismiske facies ved Kibæk, Ikast og ved Stauning. For Bastrup sandet er det kun identificeret ved Ørnhøj, men Bastrup sandet er generelt tykt nordøst for en linie der går fra Videbæk og ned mod Hoven.

Konklusion

Nærværende rapport er baseret på en tolkning af nye seismiske data samt udvalgte boringer i Ringkøbing Amt. Undersøgelsen viser at erfaringer med tidligere seismiske studier kan bruges til at finde grundvandsmagasiner. Dette blev testet ved Ørnhøj og gav et positiv resultat, hvor der blev anboret et grundvandsmagasin på ca. 30 m, tilhørende Bastrup sandet.

Ved Holstebro blev oplysninger fra en nyere oliefterforskningsboring (Mejrup-1) brugt til at teste om der i området var et stort grundvandsmagasin i Billund sandet. Resultatet her blev dog negativt. I den nye boring ved Holstebro, blev der kun anboret ca. 15 m sand fra Billund sandet. Dette resultat sammenholdt med Vinding-1 boringen indikerer at man i bedste fald kan anborer 15 til 20 meter sand fra Billund sandet i Holstebro området. Til gengæld er Bastrup sandet, med en tykkelse op over 20 meter interessant i området.

Nye seismiske data indikerer et stort grundvandsmagasin ved Kibæk. Området ved Ikast og nordøst herfor, rummer også store grundvandsmagasiner både fra Billund og Bastrup sandet. Den sydøstlige del af amtet (Hoven) kan ifølge ældre data fra olieefterforskningsboringer (bedre kvalitet end nyere) samt seismiske data, specielt ved Sdr. Omme, have store grundvandsmagasiner tilhørende både Billund og Bastrup sand.

De nye data, både boringer og seismiske data, fra den nordøstlige del af amtet indikerer at der måske skal revideres på den miocæne stratigrafi. Nogle af de dybereliggende store grundvandsmagasiner ligger måske ubeskyttede i dele af det centrale Jylland. Dette har stor betydning for udpegning af beskyttelsesområder her, samt for hele kortlægningsarbejdet af grundvandsmagasiner i det centrale Jylland.

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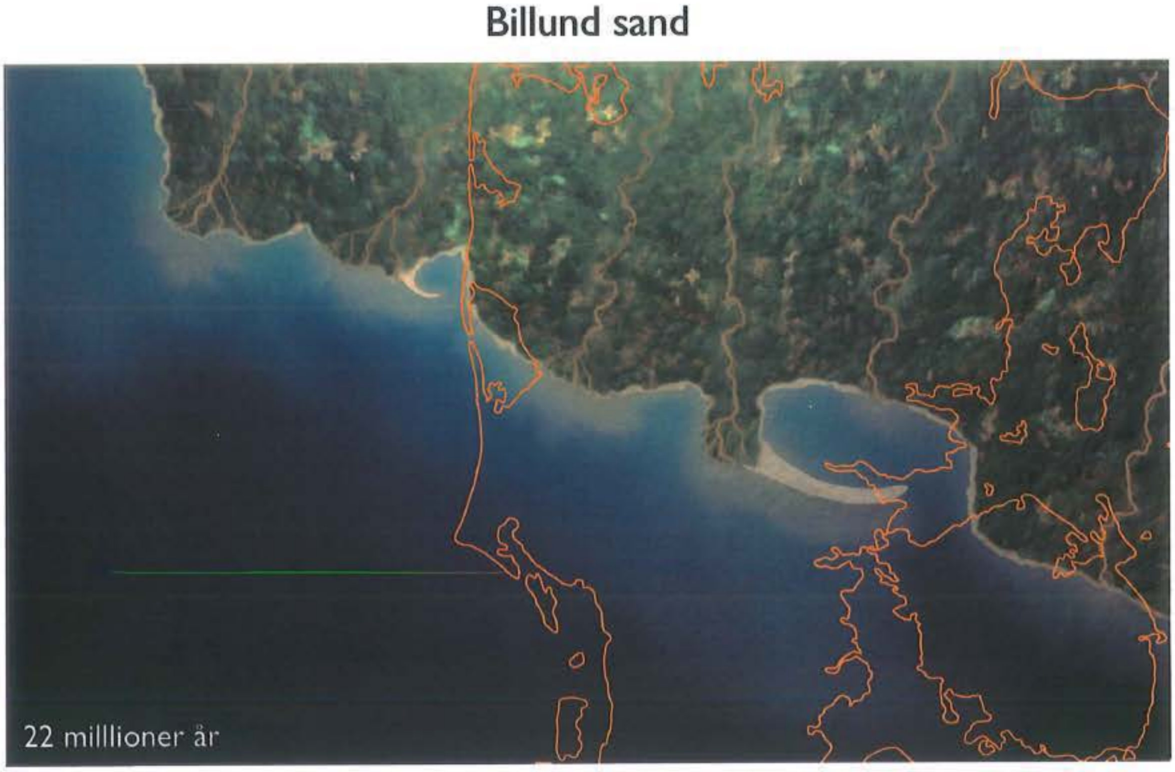


Fig. 1: Palæogeografisk rekonstruktion af Danmark for ca. 22 millioner år siden i Miocæn.

Odderup Formation - brunkul

Fig. 2: Palæogeografisk rekonstruktion af Danmark for ca. 15 millioner år siden i Miocæn.

Gramhavet

Fig. 3: Palæogeografisk rekonstruktion af Danmark for ca. 12 millioner år siden i Miocæn.

Gramhavet

Fig. 4: Palæogeografisk rekonstruktion af Danmark for ca. 10 millioner år siden i Miocæn.

Fig. 5: Palæogeografisk rekonstruktion af Danmark for ca. 7 millioner år siden i Miocæn.

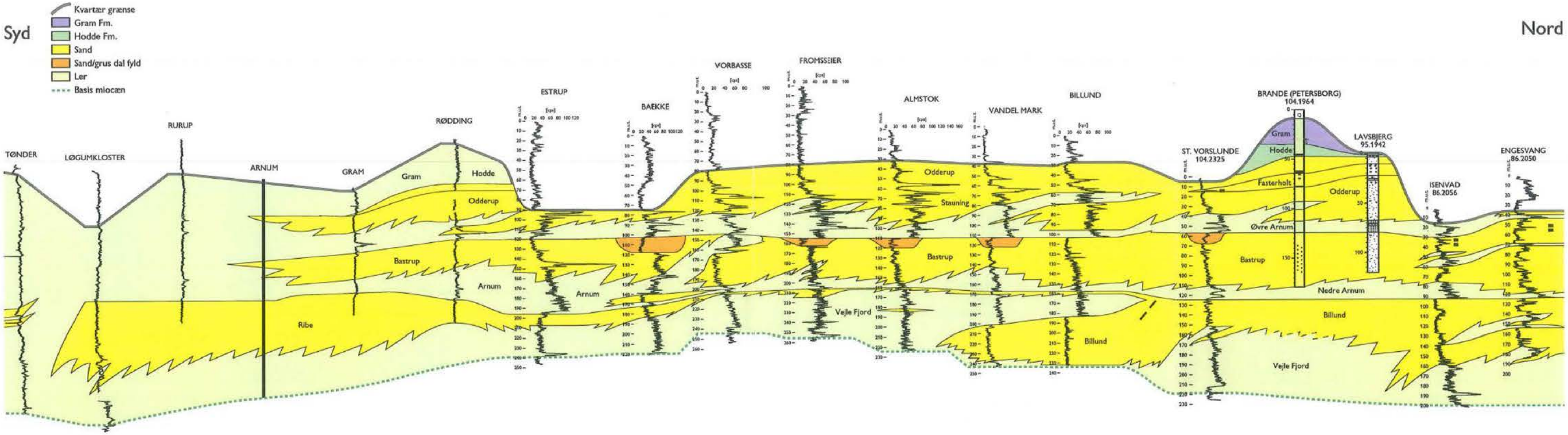
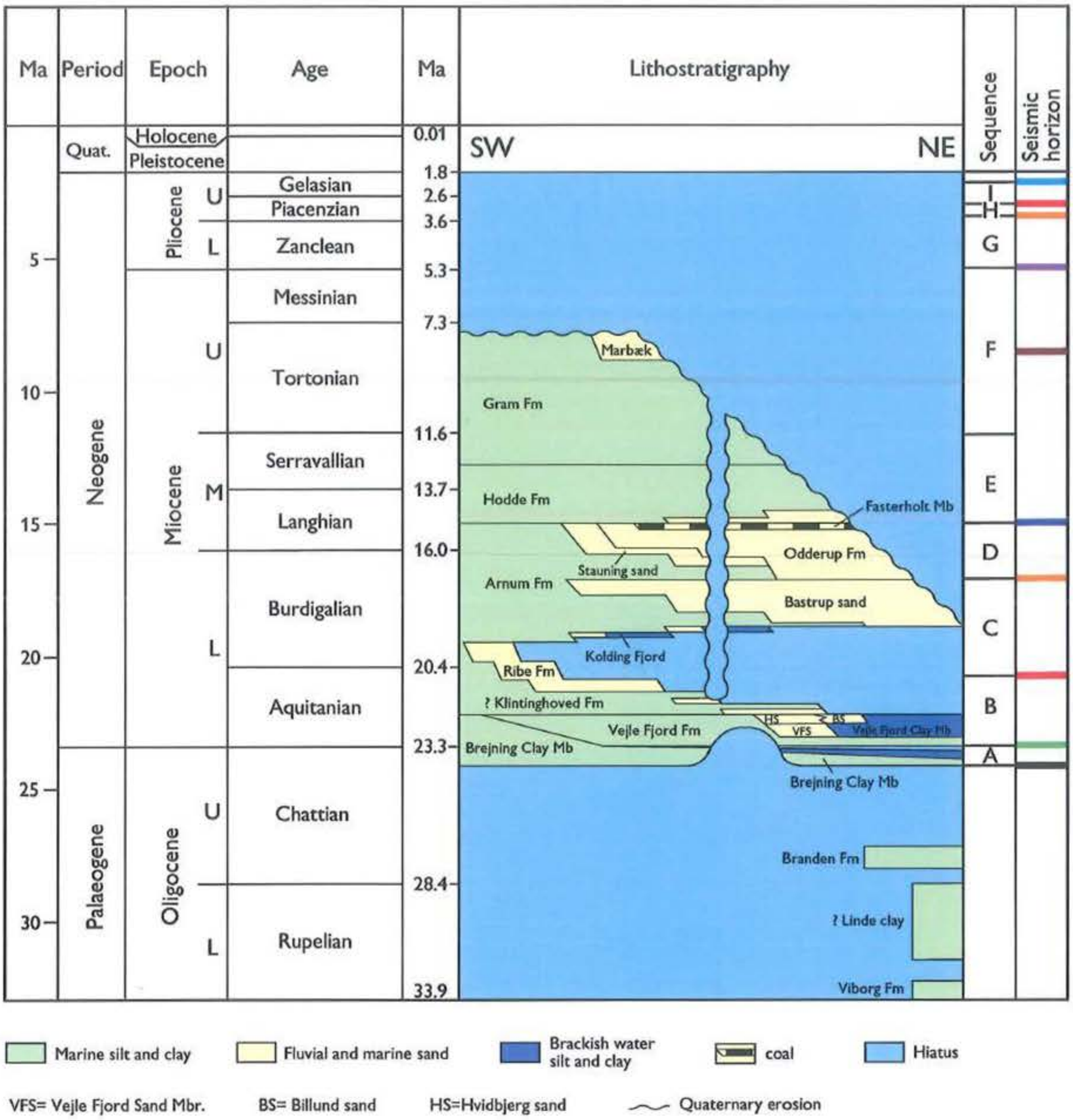


Fig. 6: Korrelationspanel af boringer fra Sønderjylland og det centrale Jylland.



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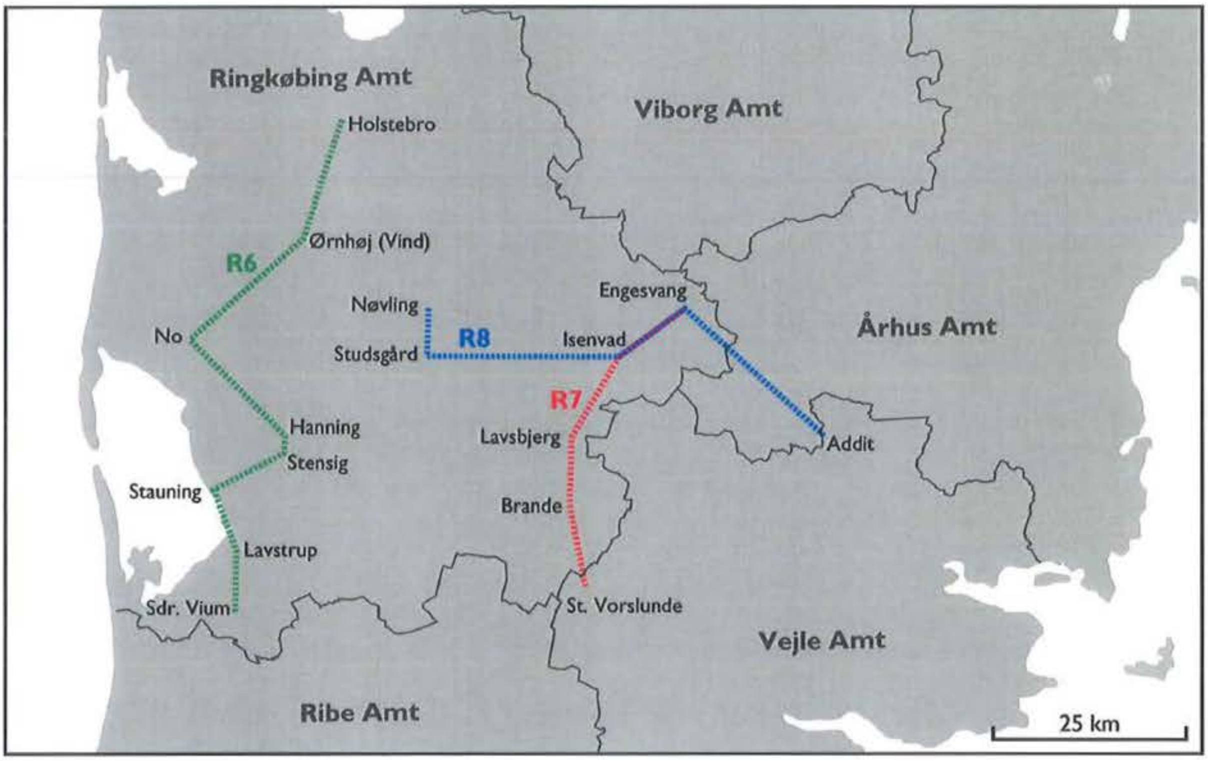


Fig. 8: Placering af korrelationspaneler i amtet.

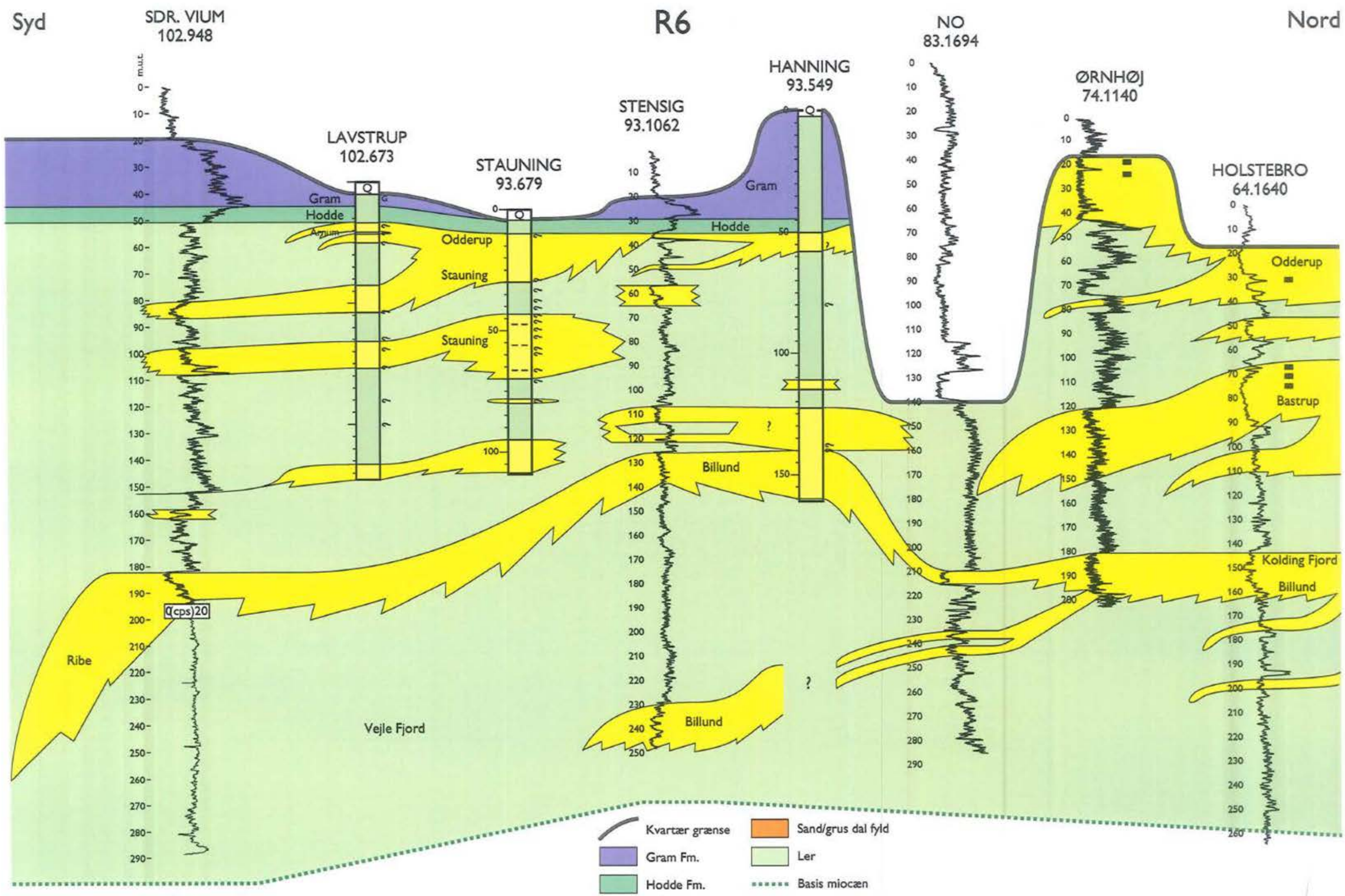


Fig. 9: R6-korrelationspanel.

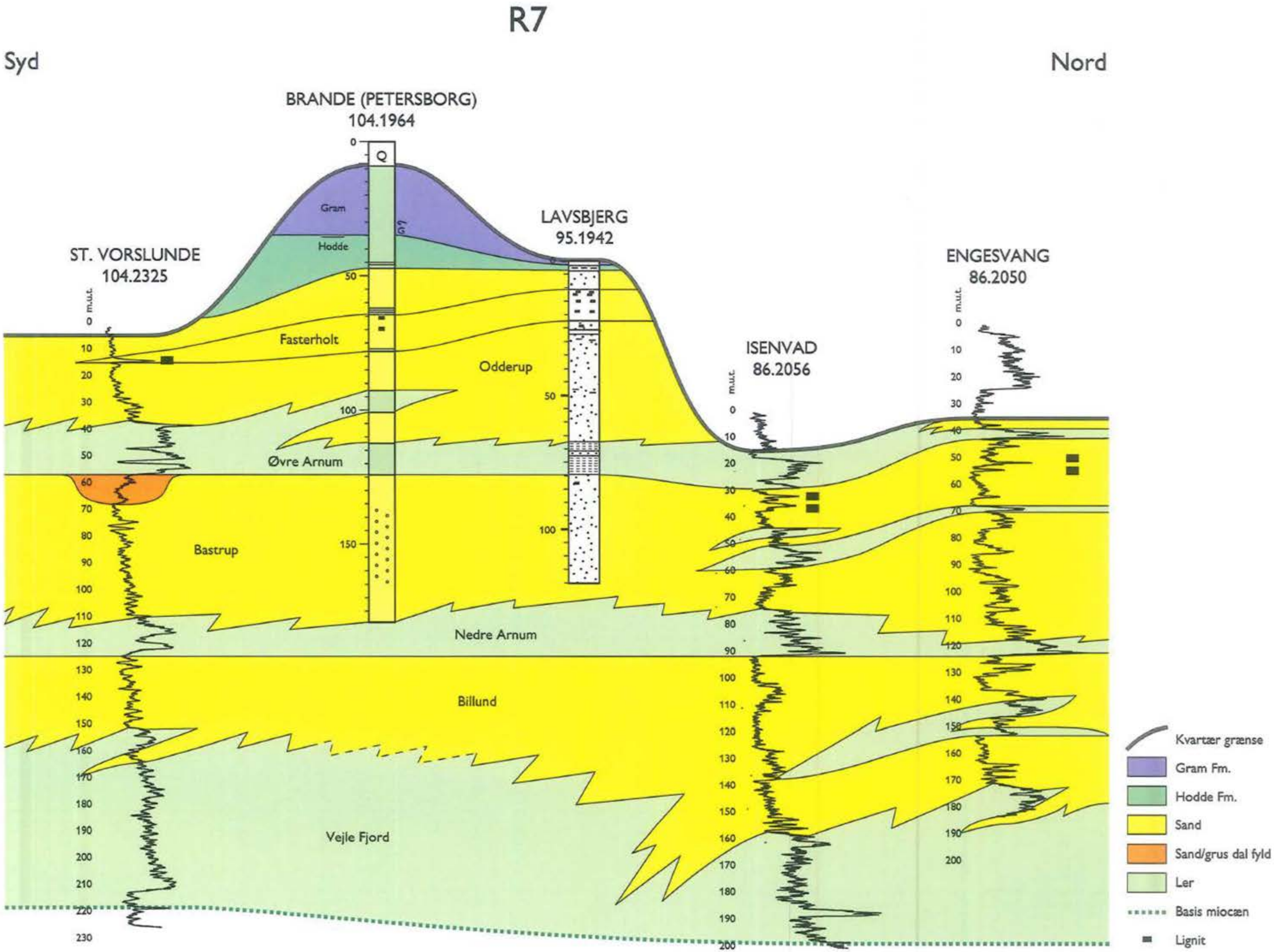


Fig. 10: R7-korrelationspanel.

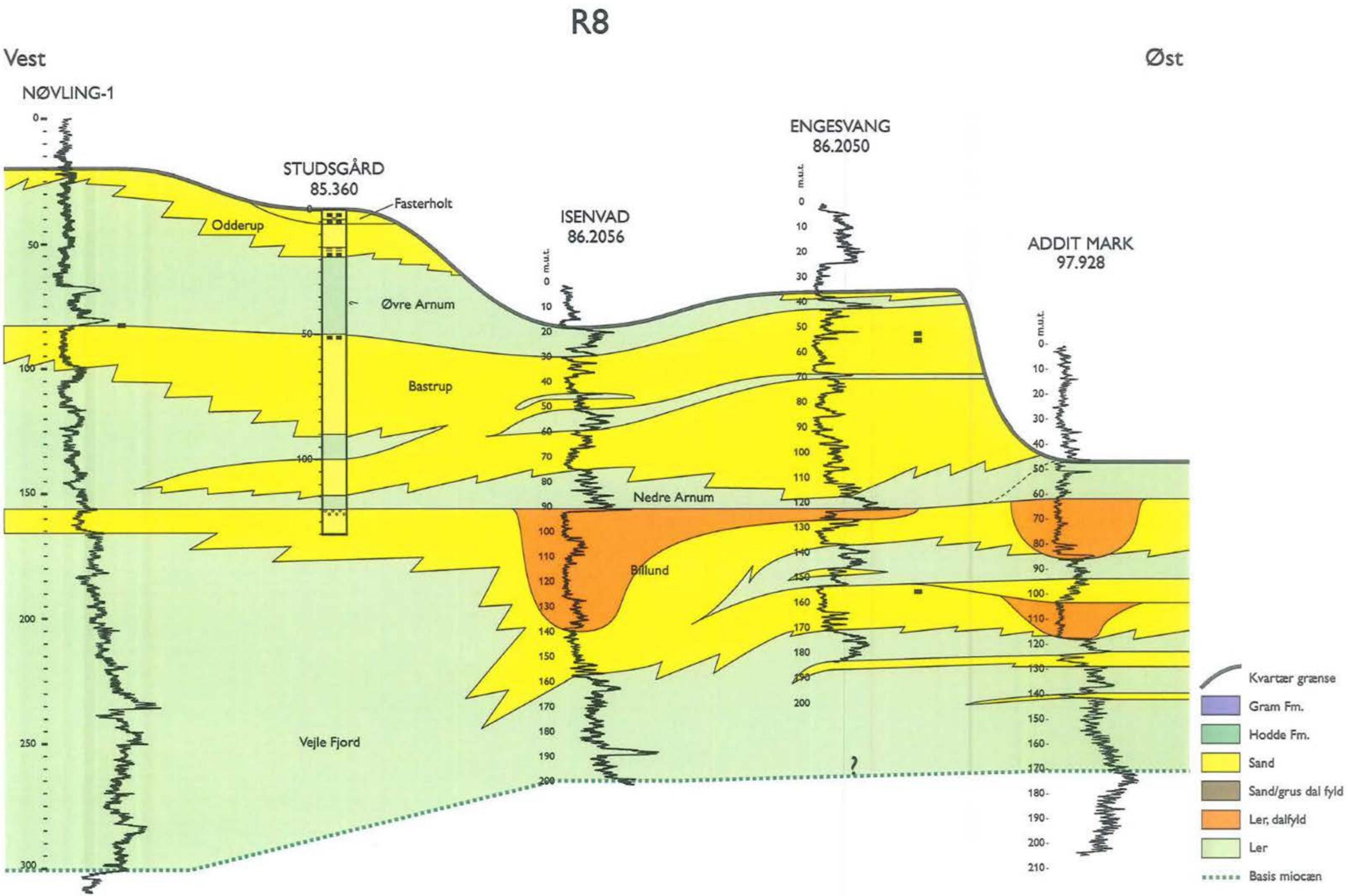
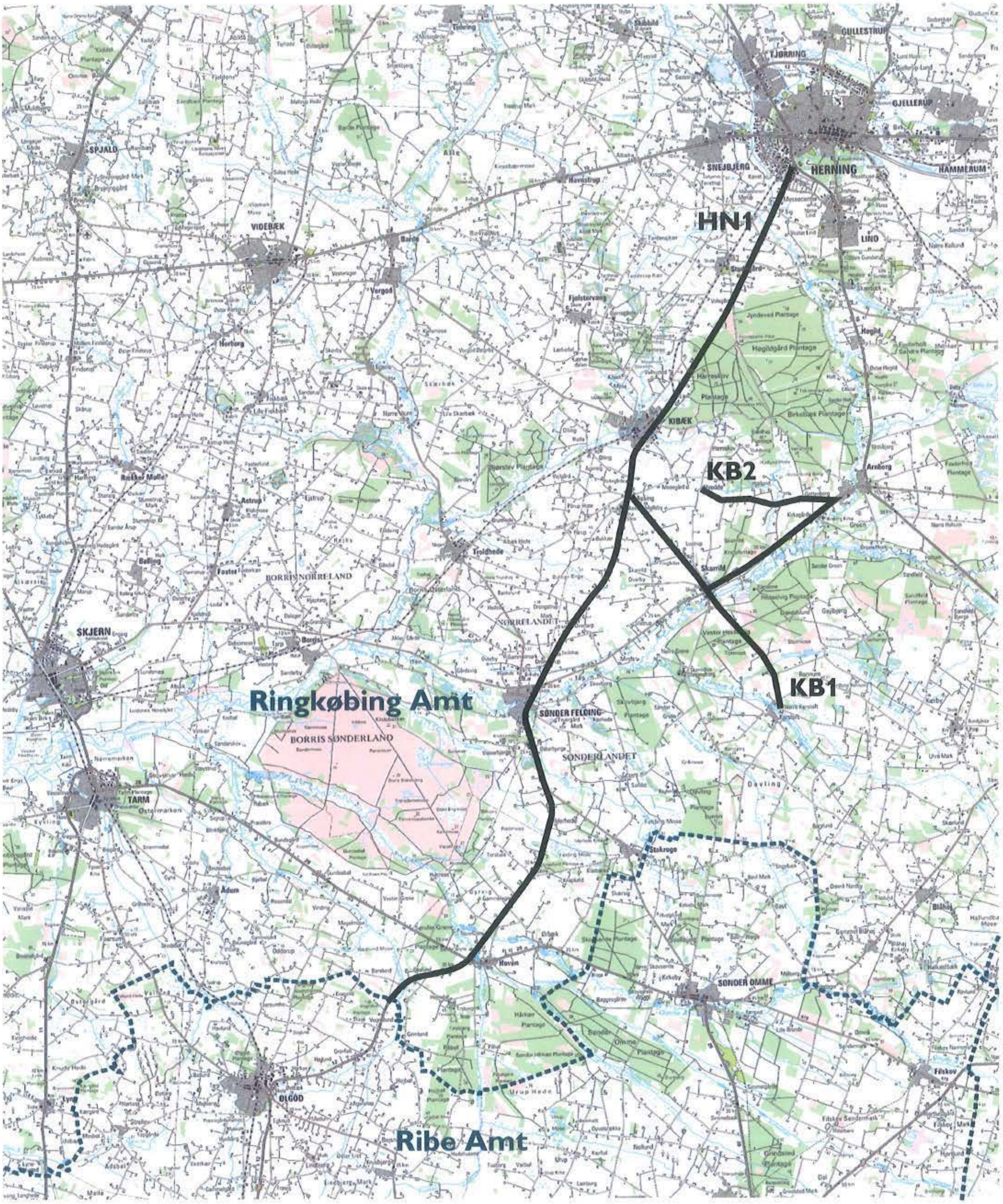


Fig. 11: R8-korrelationspanel.



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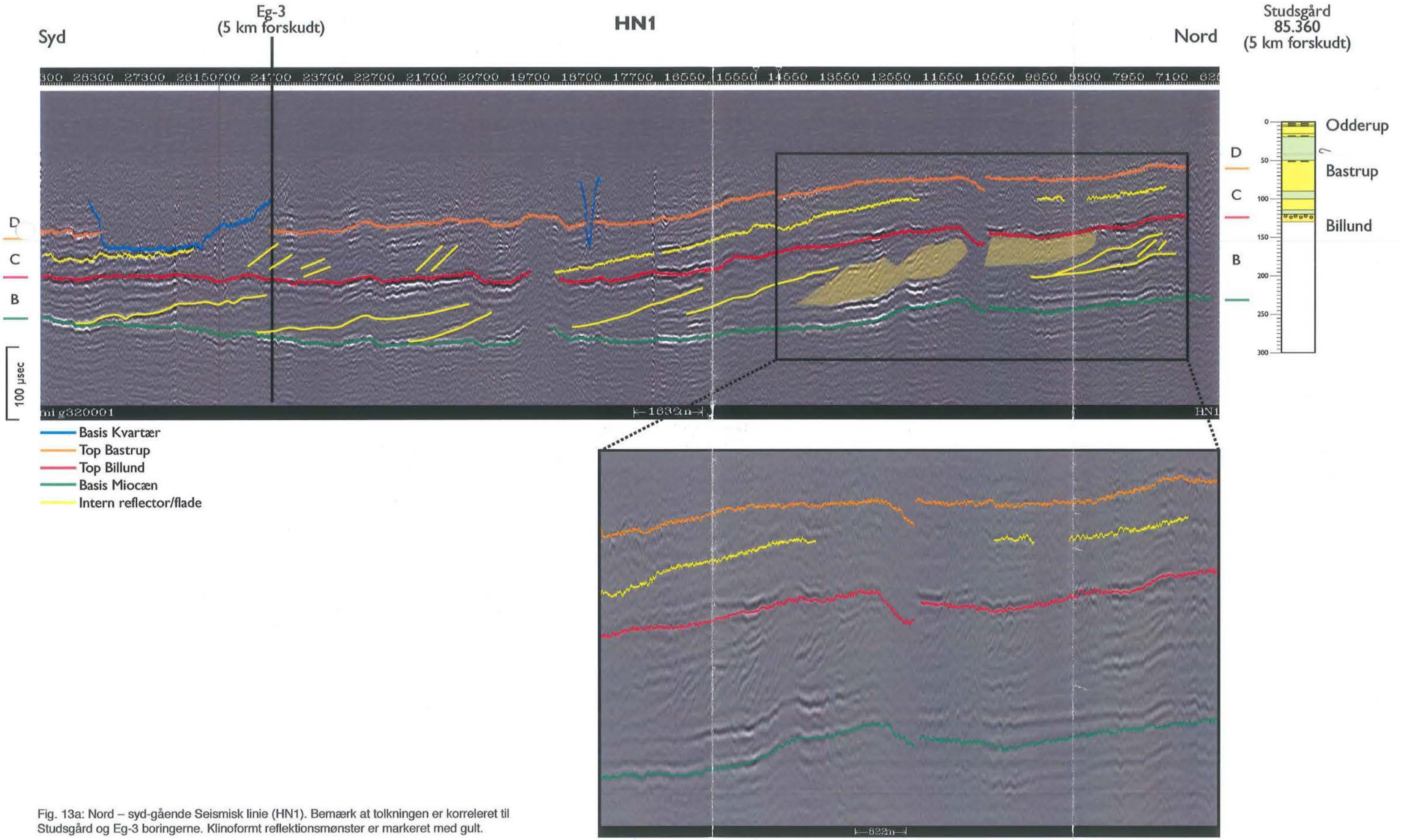

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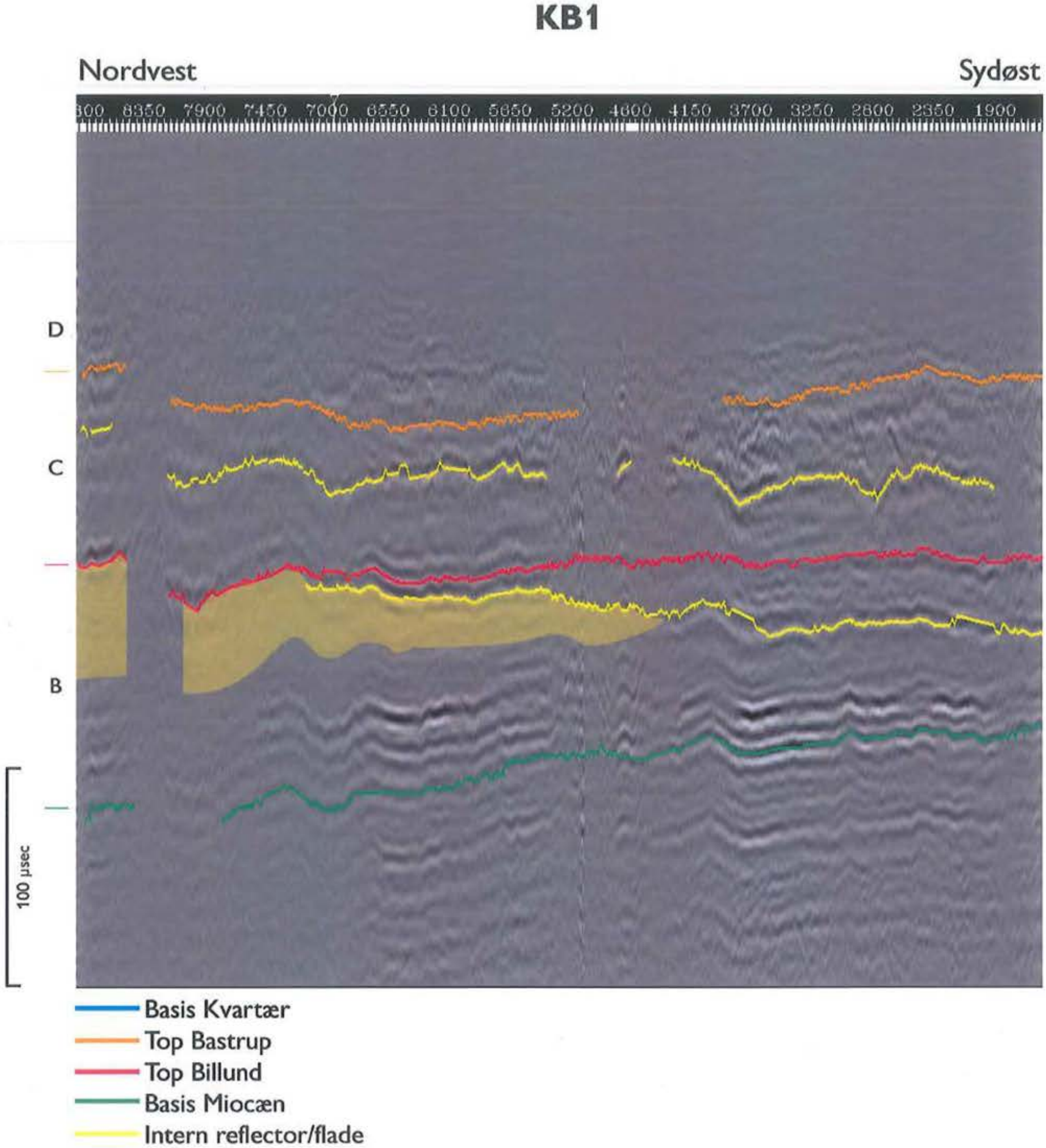


Fig. 13b: Nordvest – sydøst-gående linie ved Kibæk (KB1). Bemærk at det gule felt markerer området, som korrelerer det klinoforme reflektionsmønster på HN1.

KB2

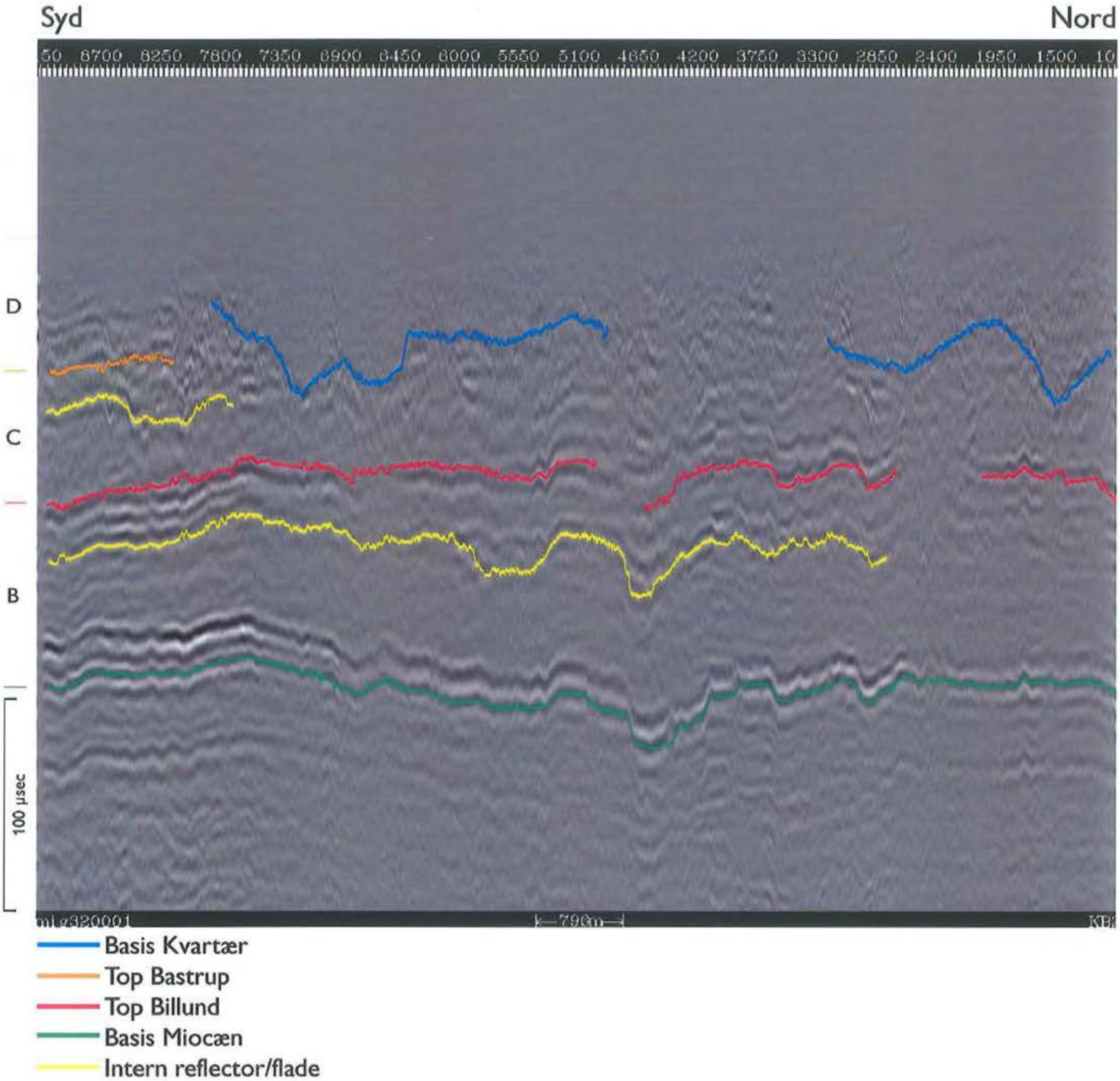
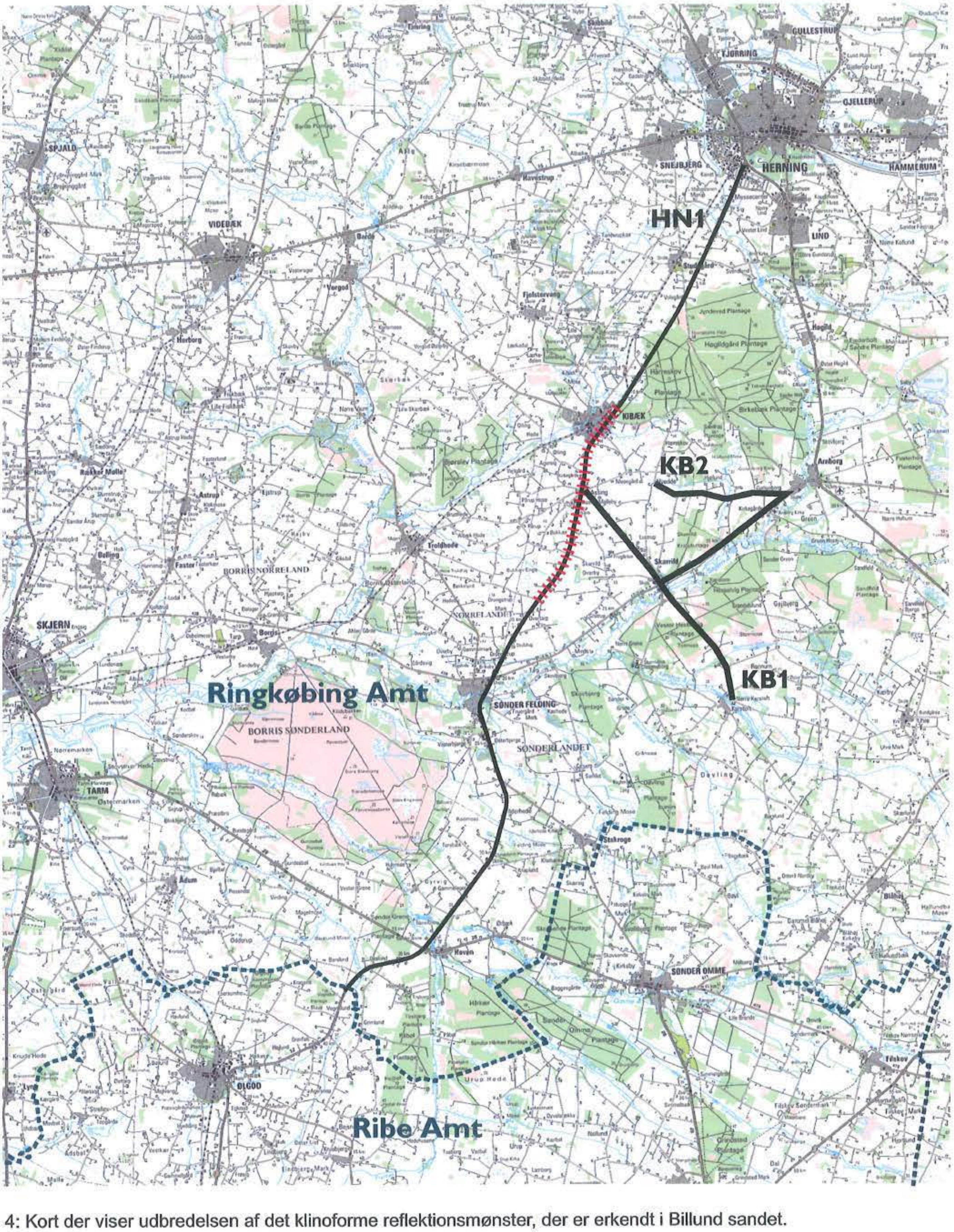


Fig. 13c: Seismisk linie ved Kibæk (KB2).



4: Kort der viser udbredelsen af det klinoforme reflektionsmønster, der er erkendt i Billund sandet.

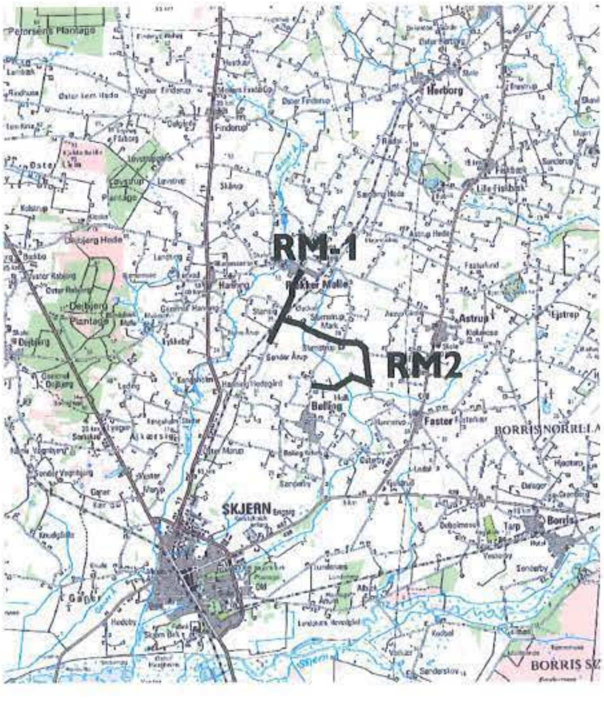


Fig. 15: Kort over seismiske linier ved Rækker Mølle.

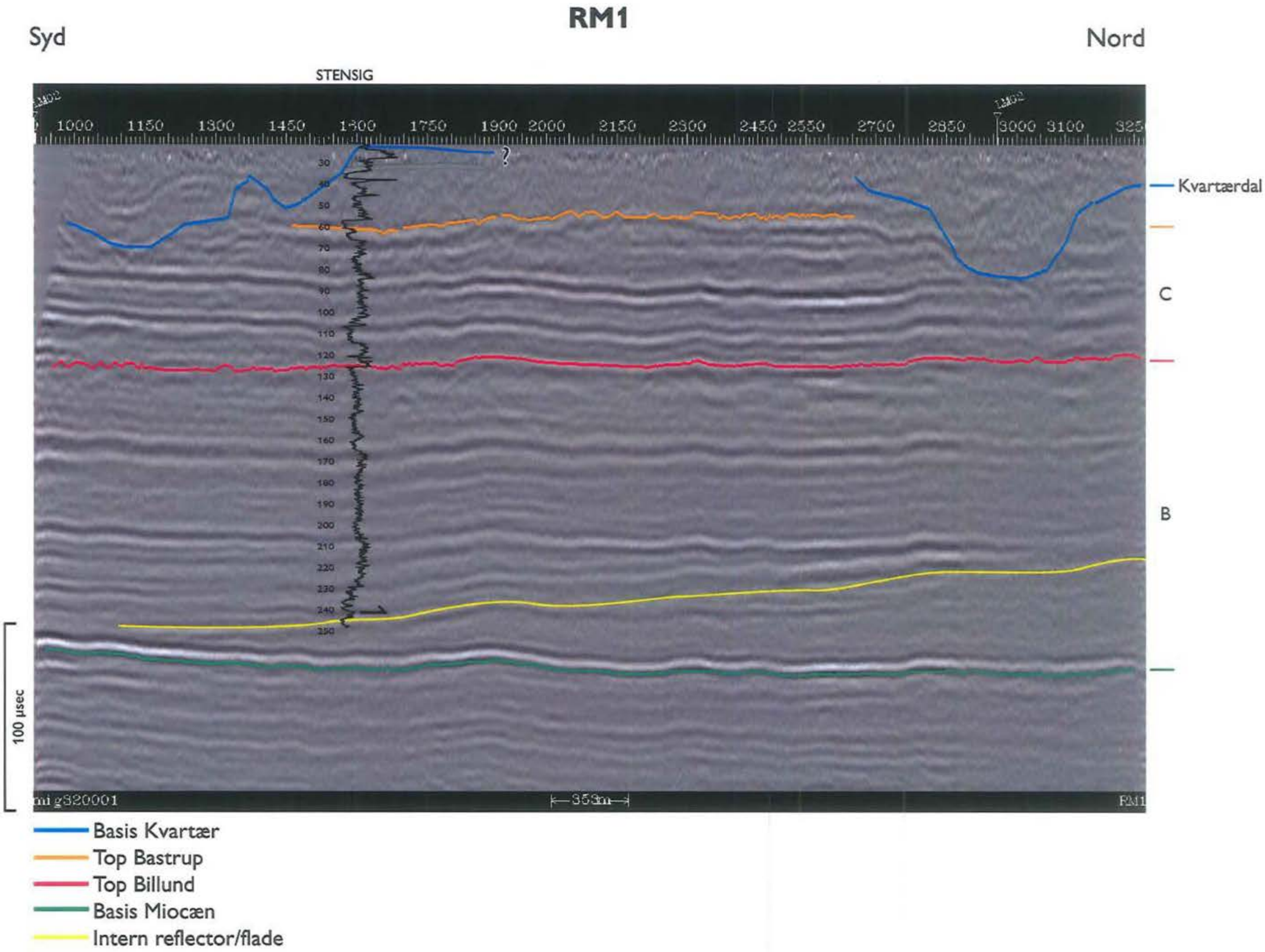
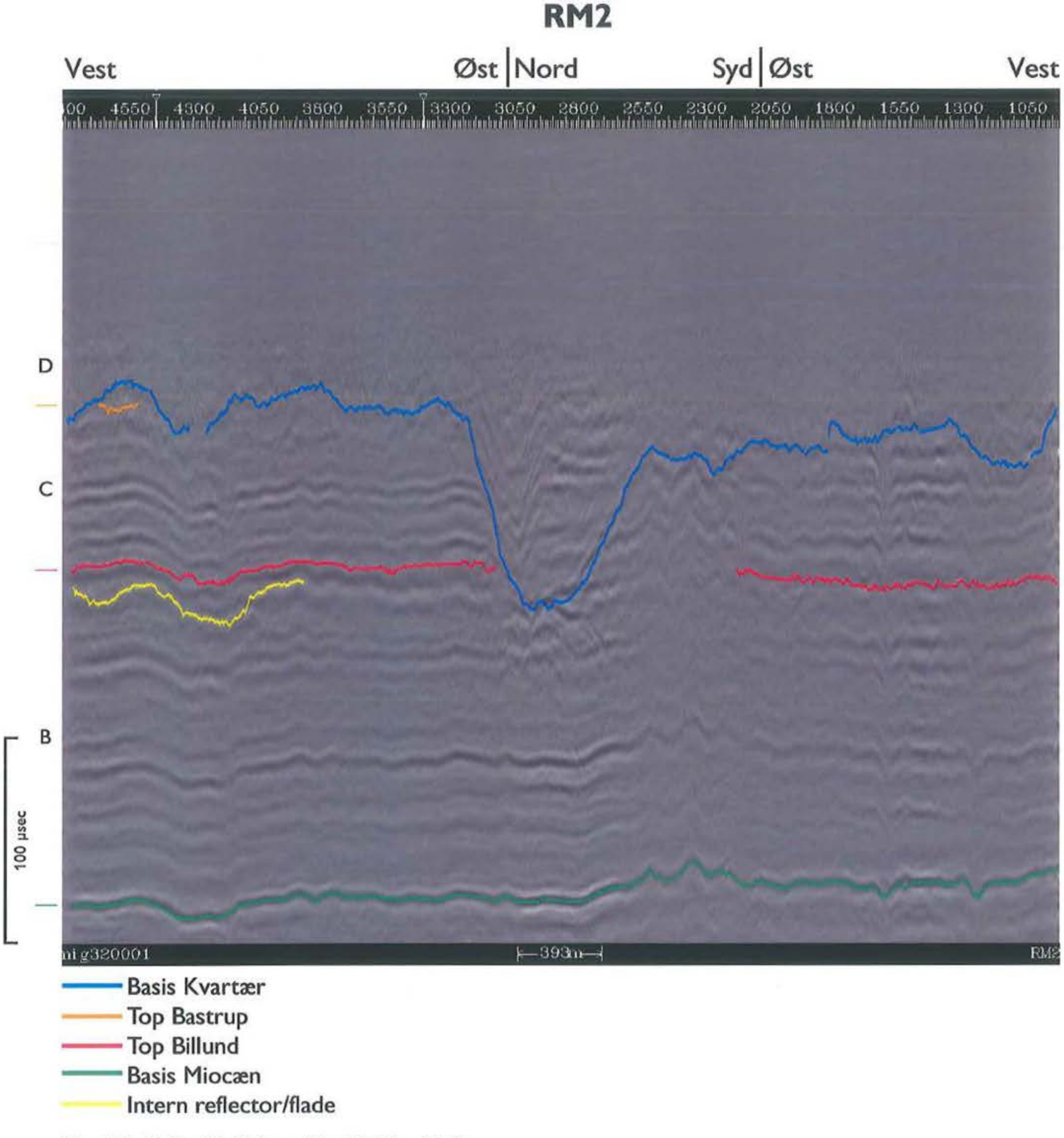


Fig. 16a: Nord – syd-gående seismisk linie, der gå gennem Stensig boringen.



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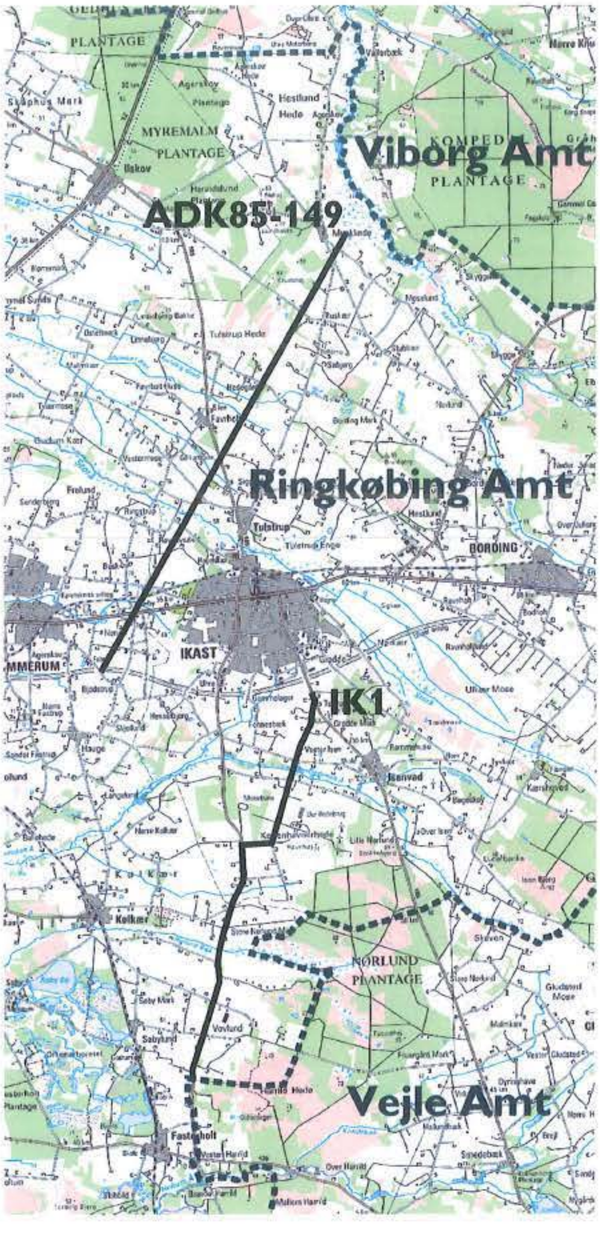

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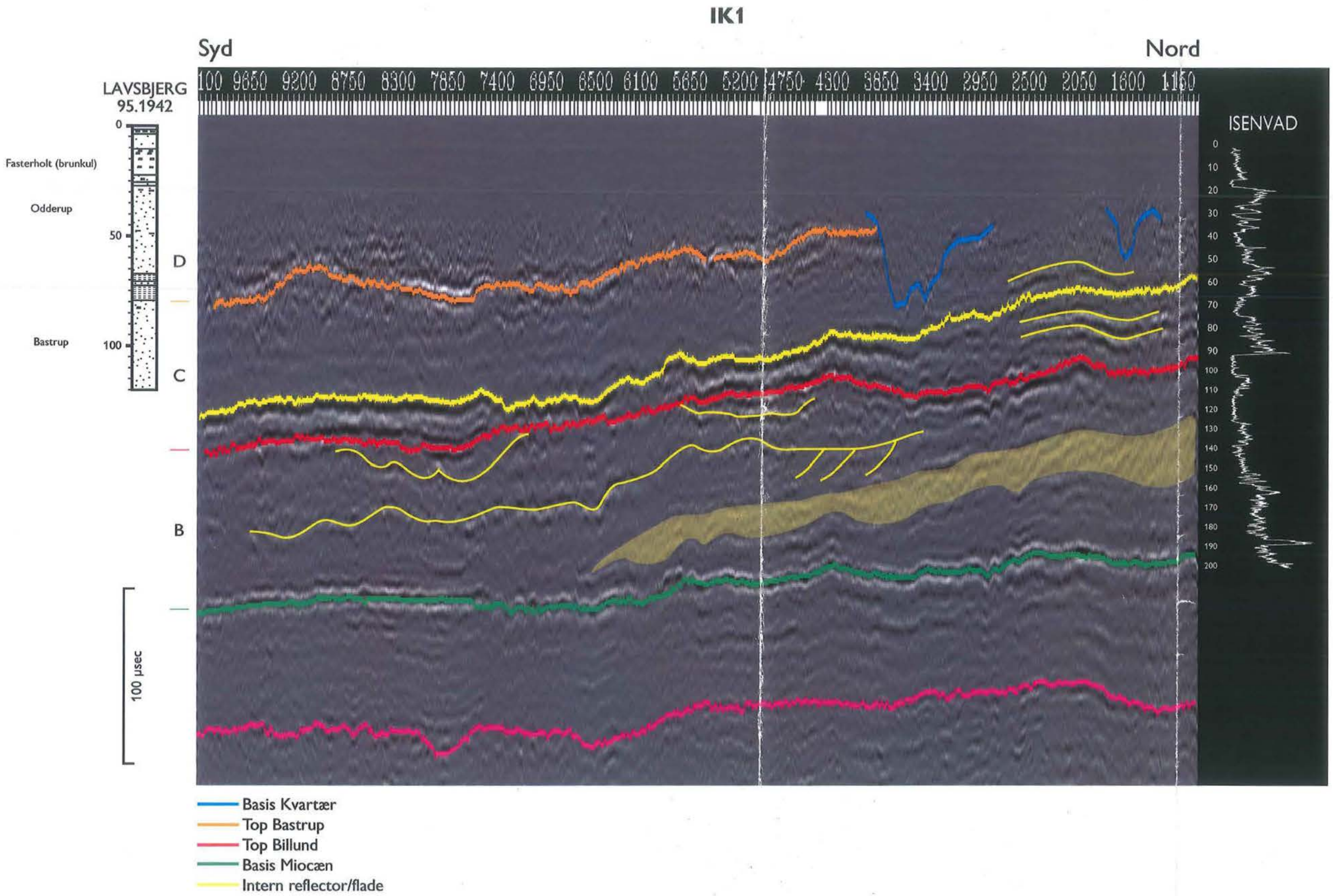


Fig. 18: Nord – syd-gående seismisk linie syd for Ikast. Linien forbinder Isenvad boringen nær grusgraven og området ved Fasterholt med brundkulslejrene. Boringen, Lavsbjerg, er indsat på linien. Bemærk det klinoforme reflektionsmønster, der er markeret med gult og markante erosionsflader i sekvens B.

ADK85-149

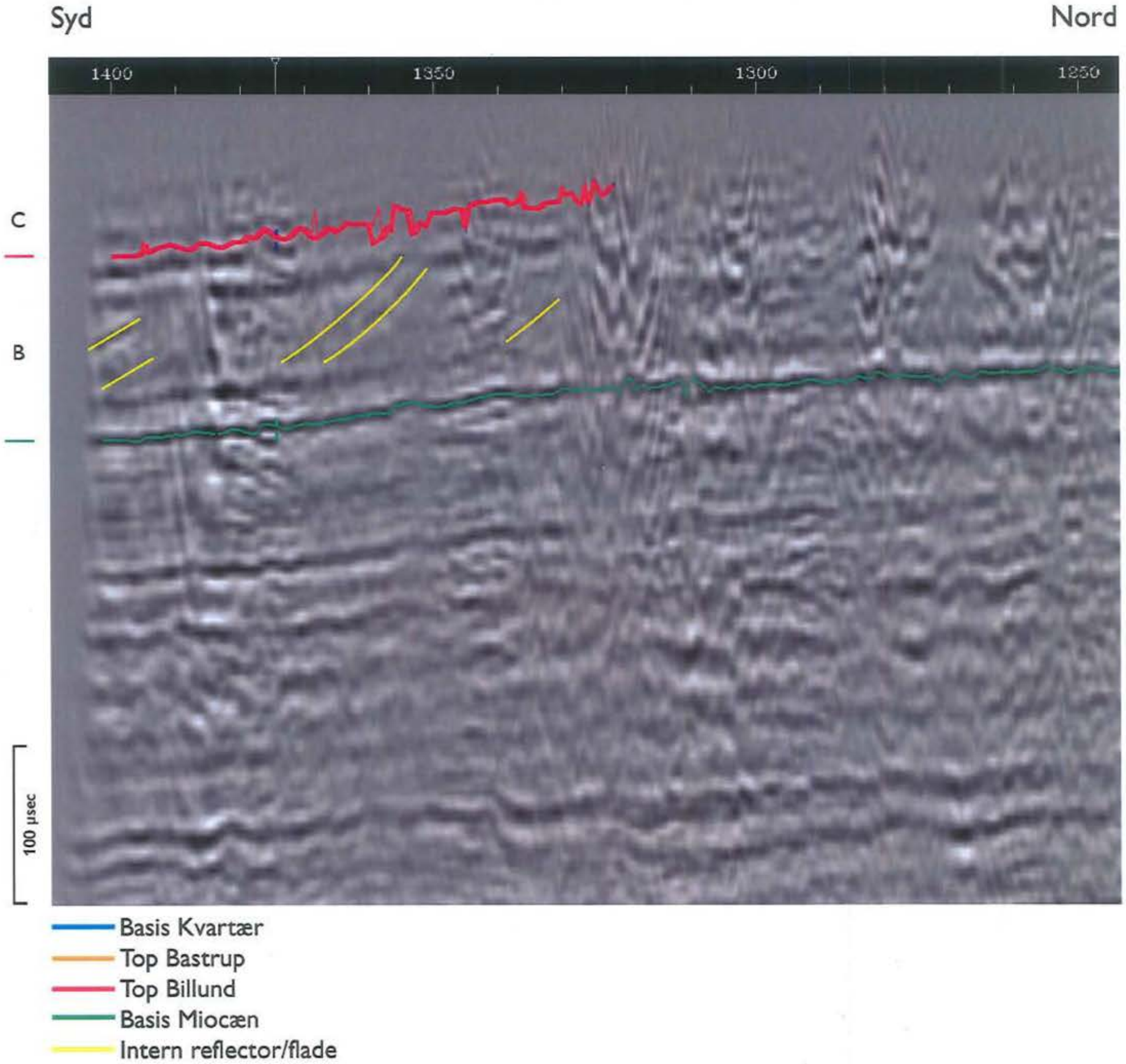


Fig. 19: Nord – syd-gående seismisk linie ADK85-149 lige vest for Ikast. Bemærk at der er en antydning af et parallelt-klinoformt reflektionsmønster i sekvens B.

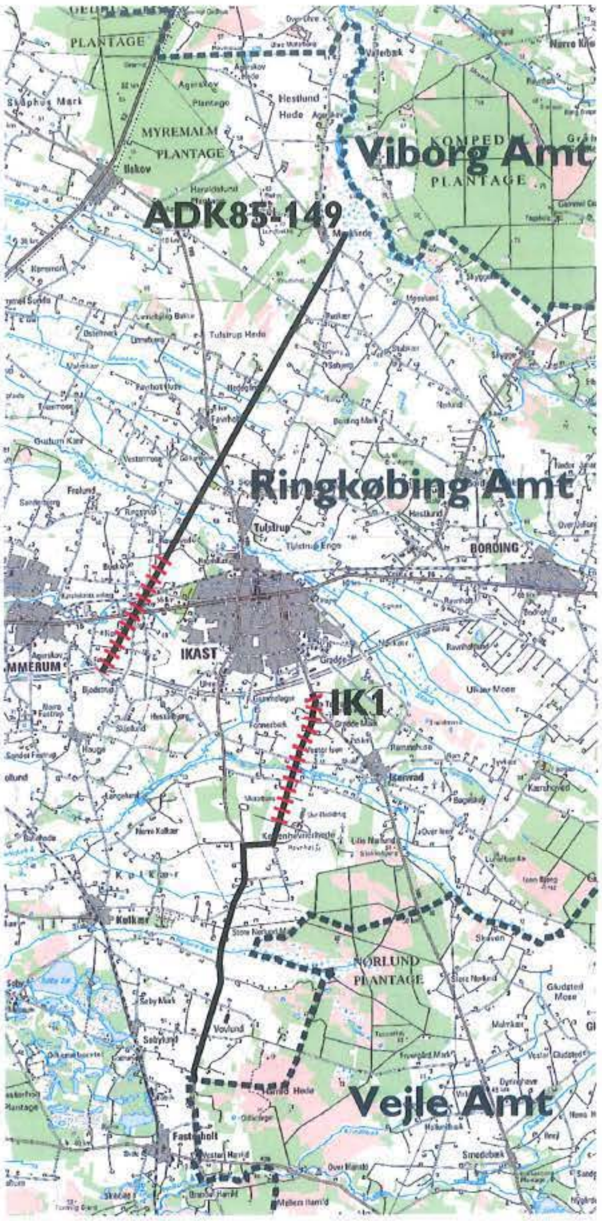


Fig. 20: Kort over udbredelsen af parallelt-klinoformt reflektionsmønster.

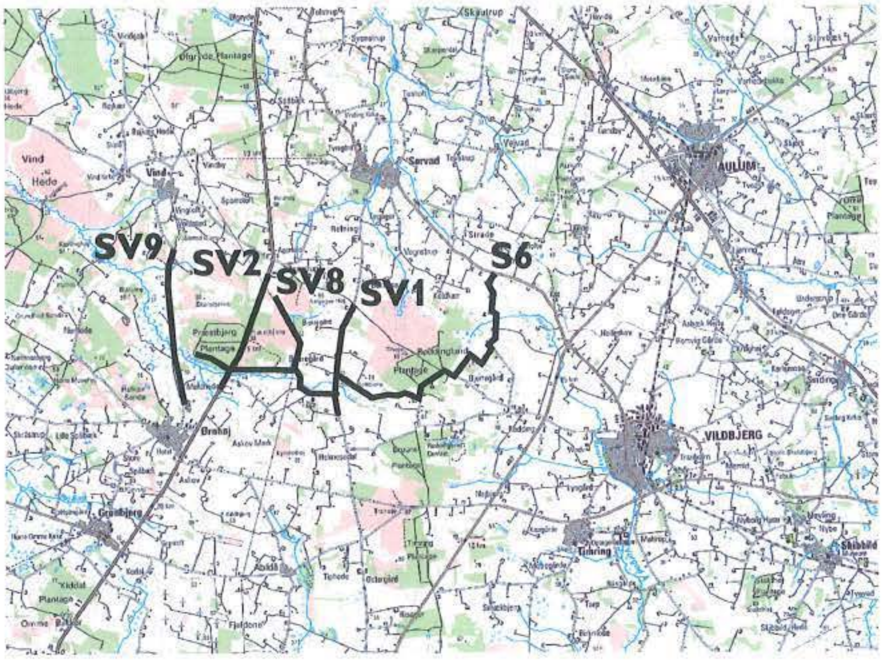


Fig. 21: Kort over seismiske linier ved Ørnhøj.

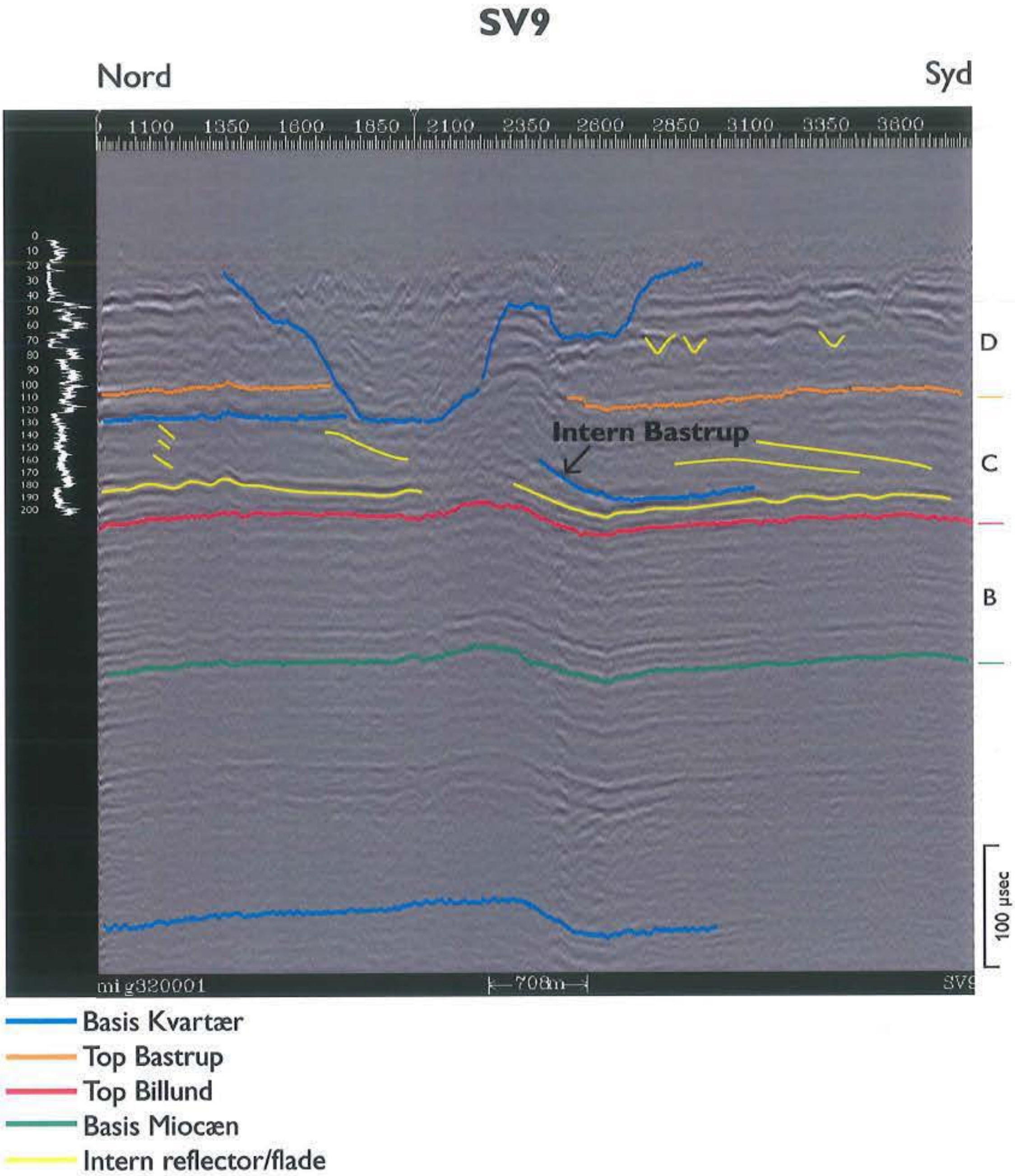


Fig. 22a: Nord – syd-gående seismisk linie nord for Ørnhøj. Linien korrelerer Ørnhøj (Vind) boringen. Bemærk at sandlaget anboret i 125 – 155 korrelerer til klinoformer angivet med gule streger og at det nederste sandlag ved ca. 180 m korrelerer til højamplitude reflektionsmønster.

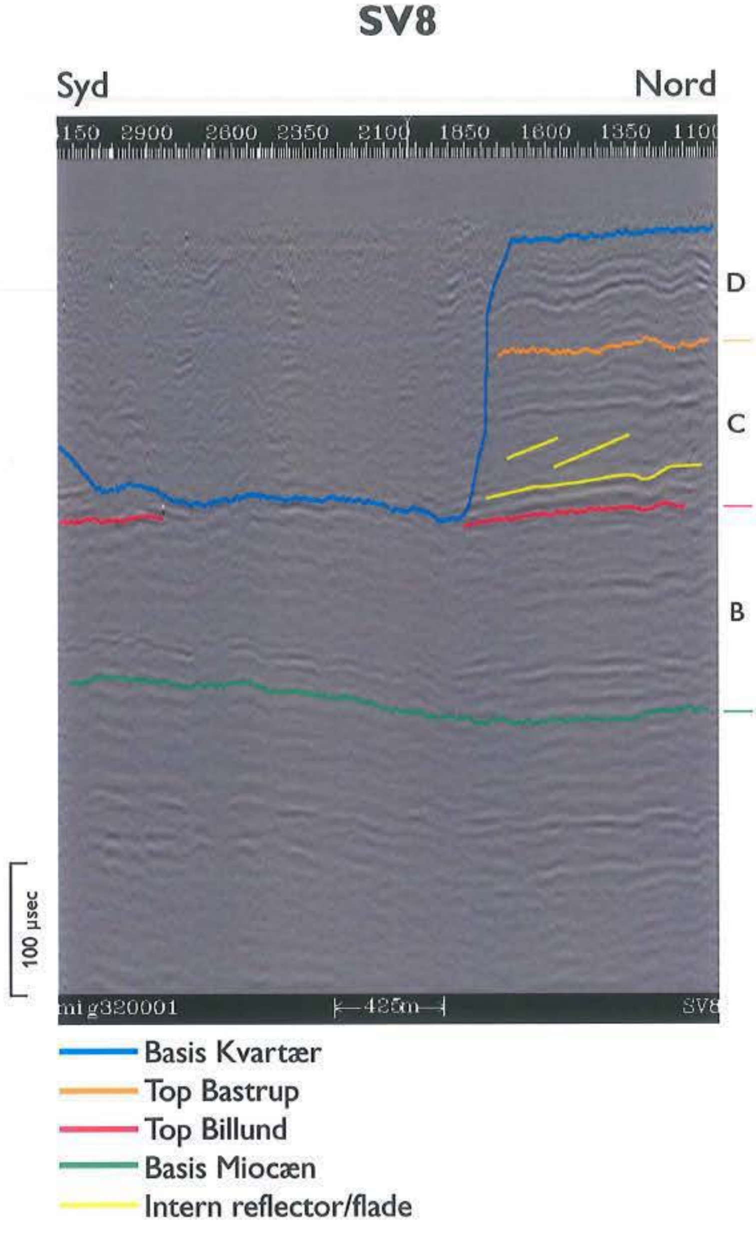
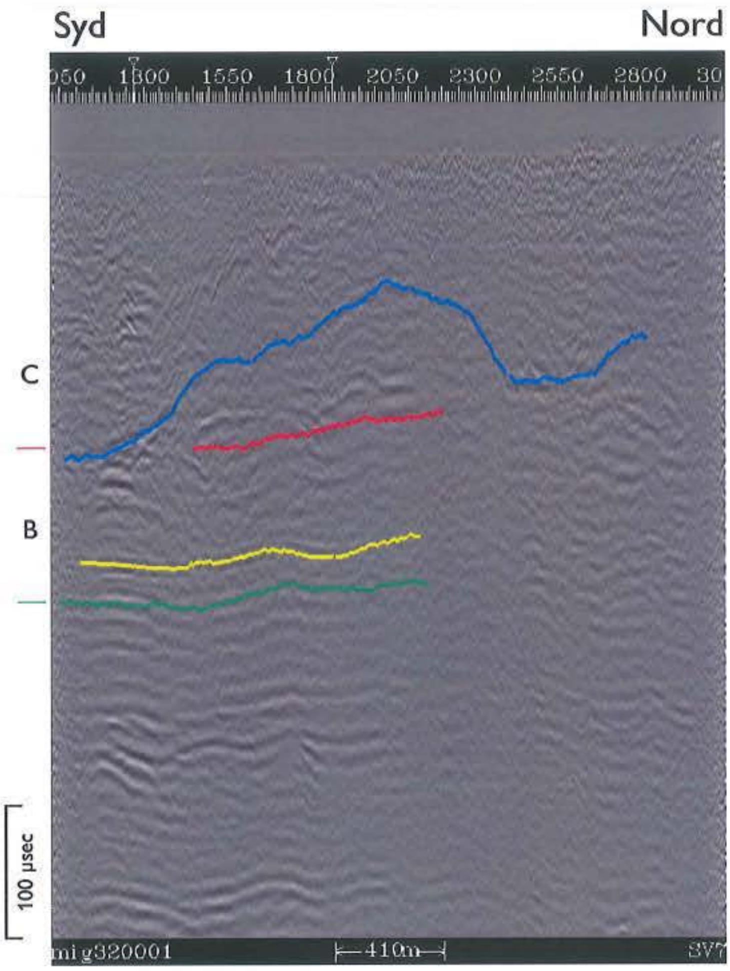


Fig. 22b: Nord – syd-gående seismisk linie nordøst for Ørnhøj.

SV7



Basis Kvartær
Top Bastrup
Top Billund
Basis Miocæn
Intern reflector/flade

Fig. 22c: Nord – syd-gående seismisk linie nord for Ørnhøj.

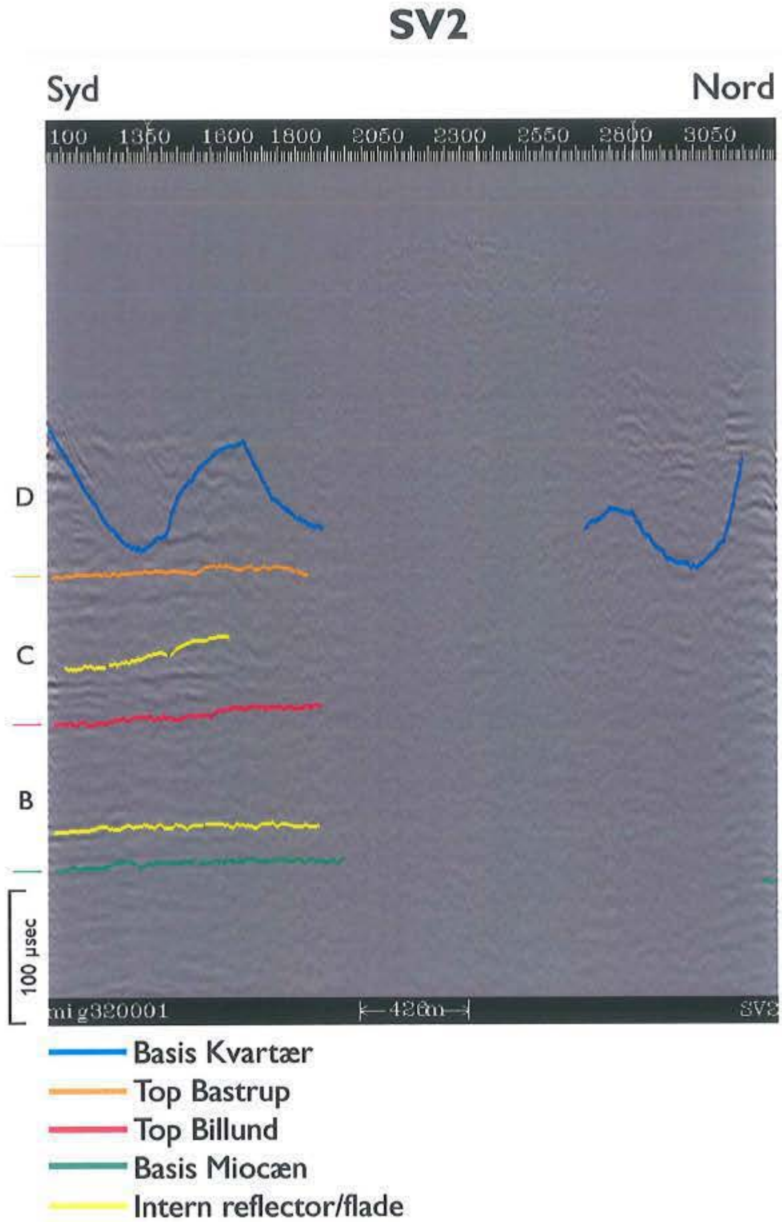


Fig. 22e: Nord – syd-gående seismisk linie øst for Ørnhøj.

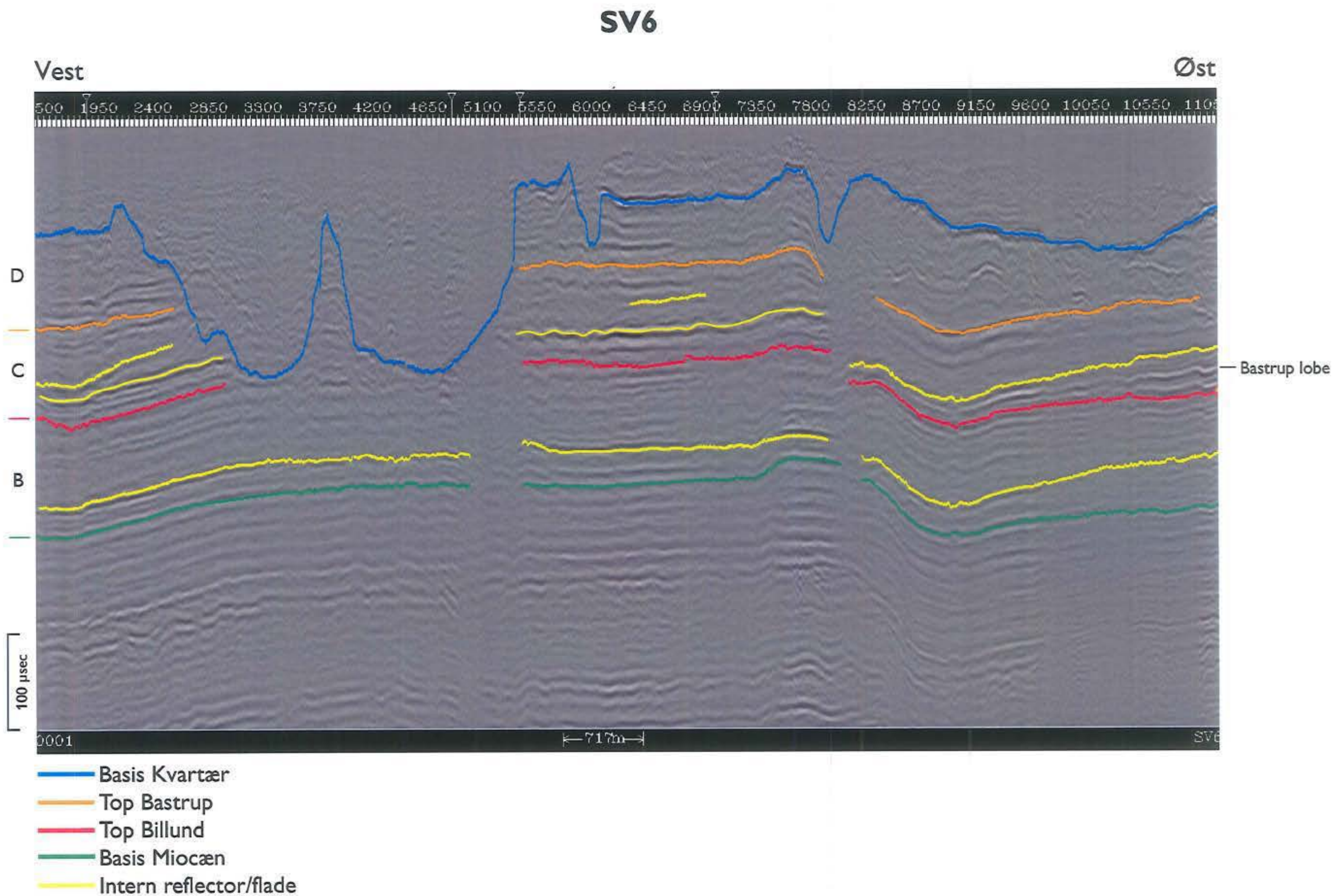


Fig. 22d: Øst – vest-gående seismisk linie øst for Ørnhøj.

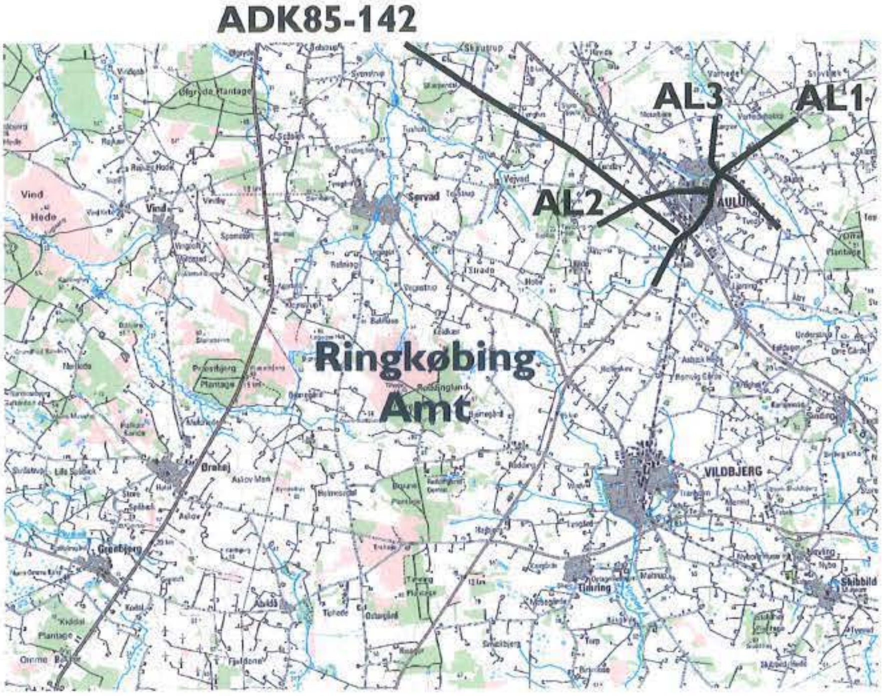


Fig. 23: Kort over seismiske linier ved Aulum.

AL 1

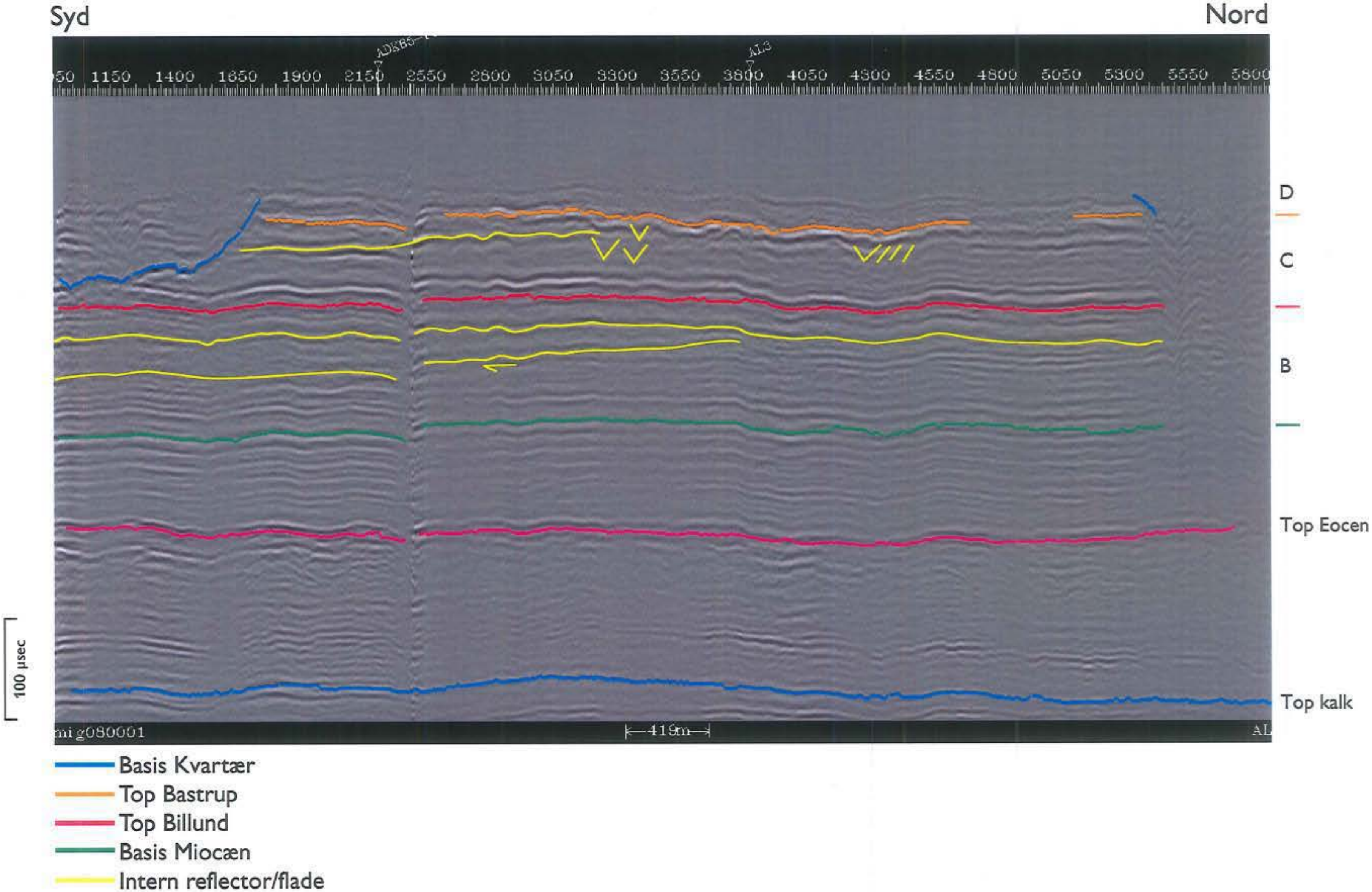


Fig. 24a: Nord – syd-gående seismisk linie ved Aulum (AL1). Bemærk de konkave opad strukturer øverst i sekvens C. Dette kan tolkes som kanaler øverst i Bastrup sandet.

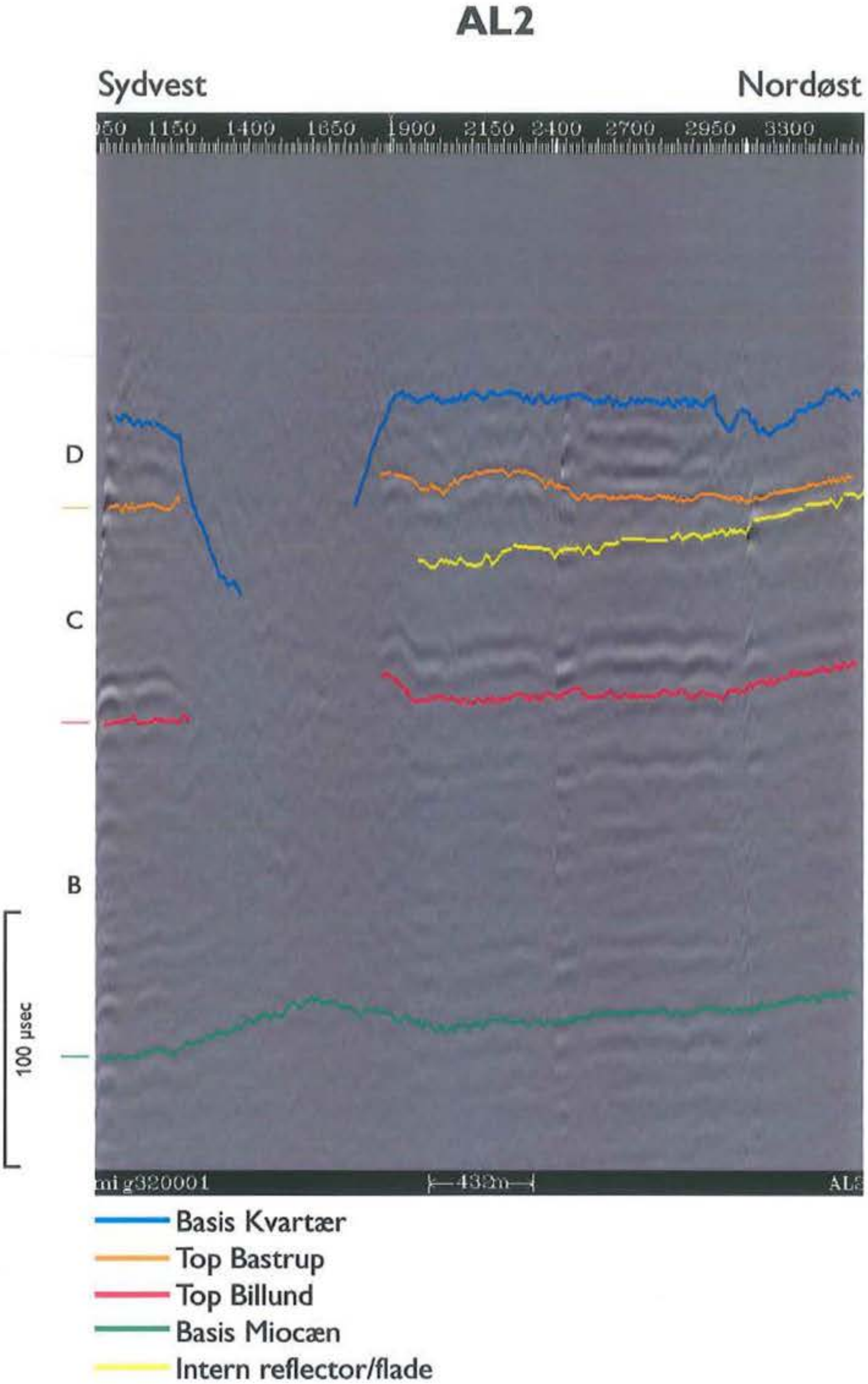
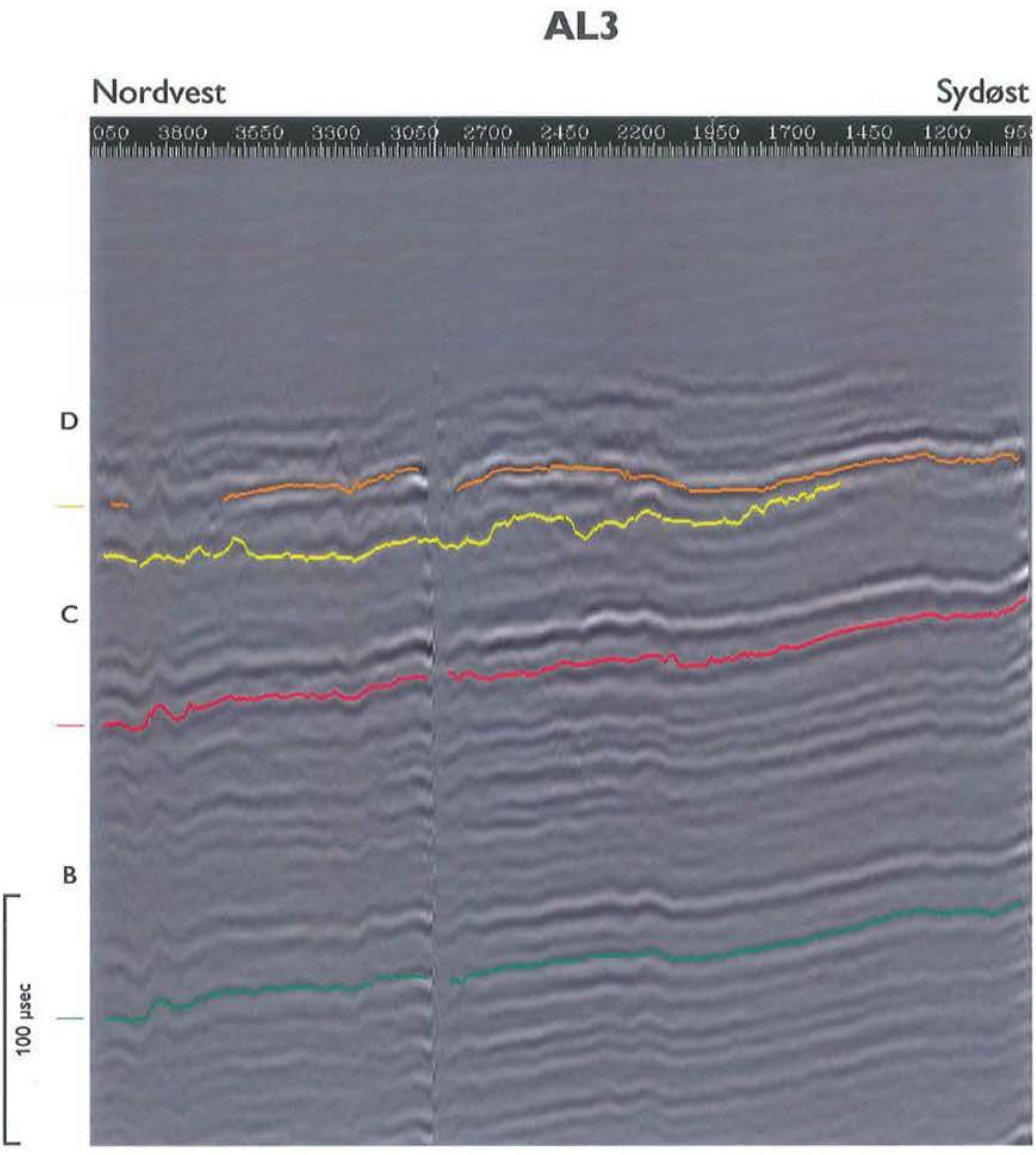


Fig. 24b: Sydvest – nordøst-gående seismisk linie ved Aulum (AL2).



Basis Kvartær
Top Bastrup
Top Billund
Basis Miocæn
Intern reflector/flade

Fig. 24c: Nordvest – sydøst-gående seismisk linie ved Aulum (AL3).

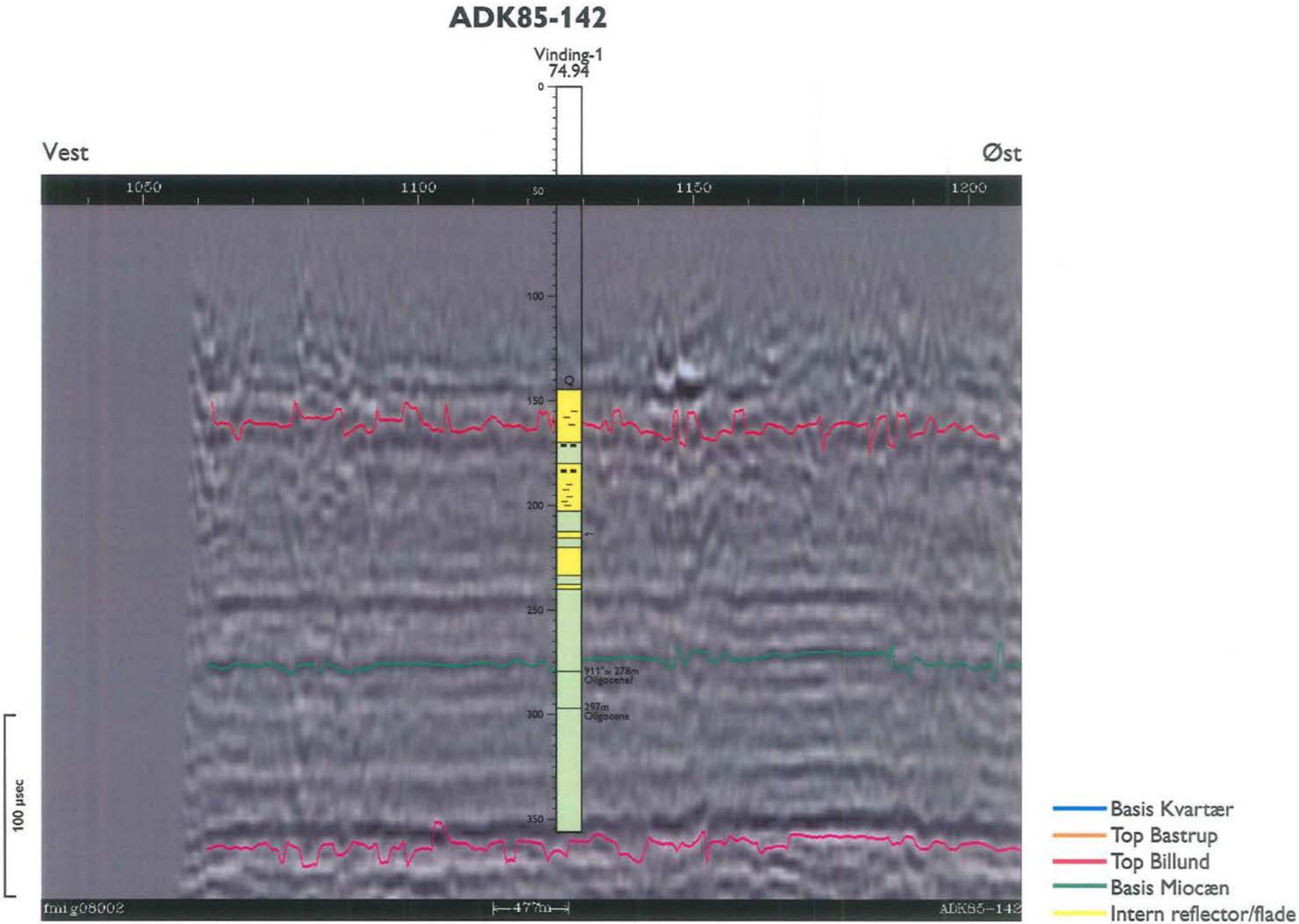


Fig. 25: Øst – vest-gående seismisk linie, der korrelerer til Vinding-1 boringen.

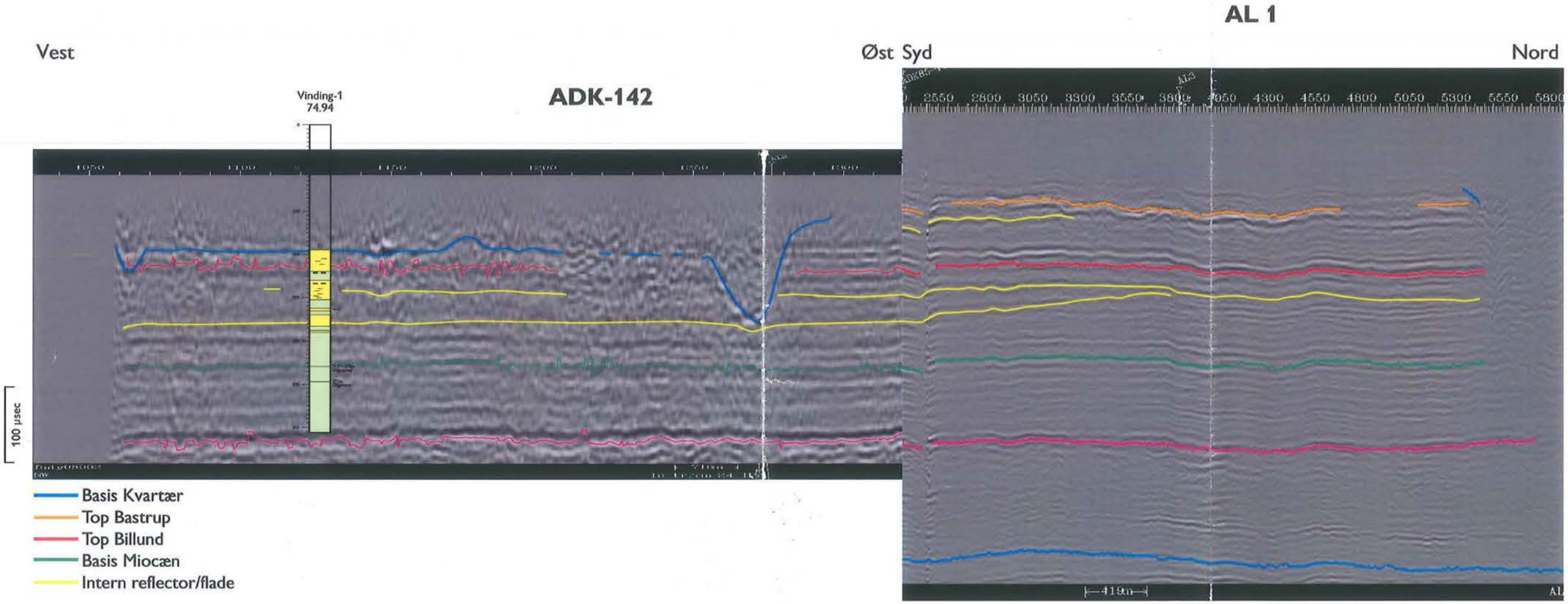


Fig. 26: Sammensat seismisk linie, der viser korrelationen mellem ny og gammel seismik, samt Vinding-1 boringen.

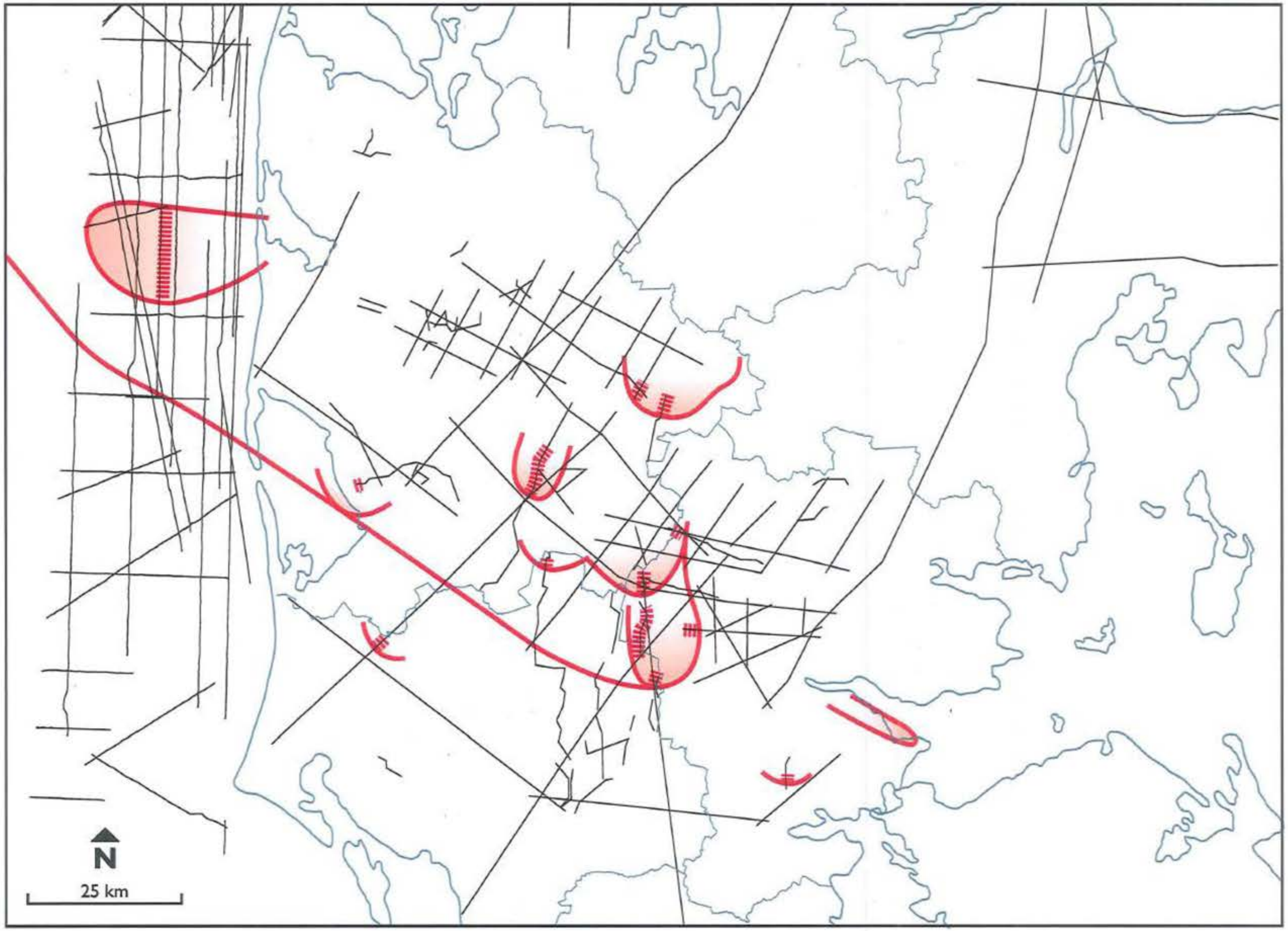


Fig. 27: Kort over deltalober og oddekomplekser i Billund sandet (sekvens B), samt placeringen af kystlinien under den sidste fase af Billund sandet.

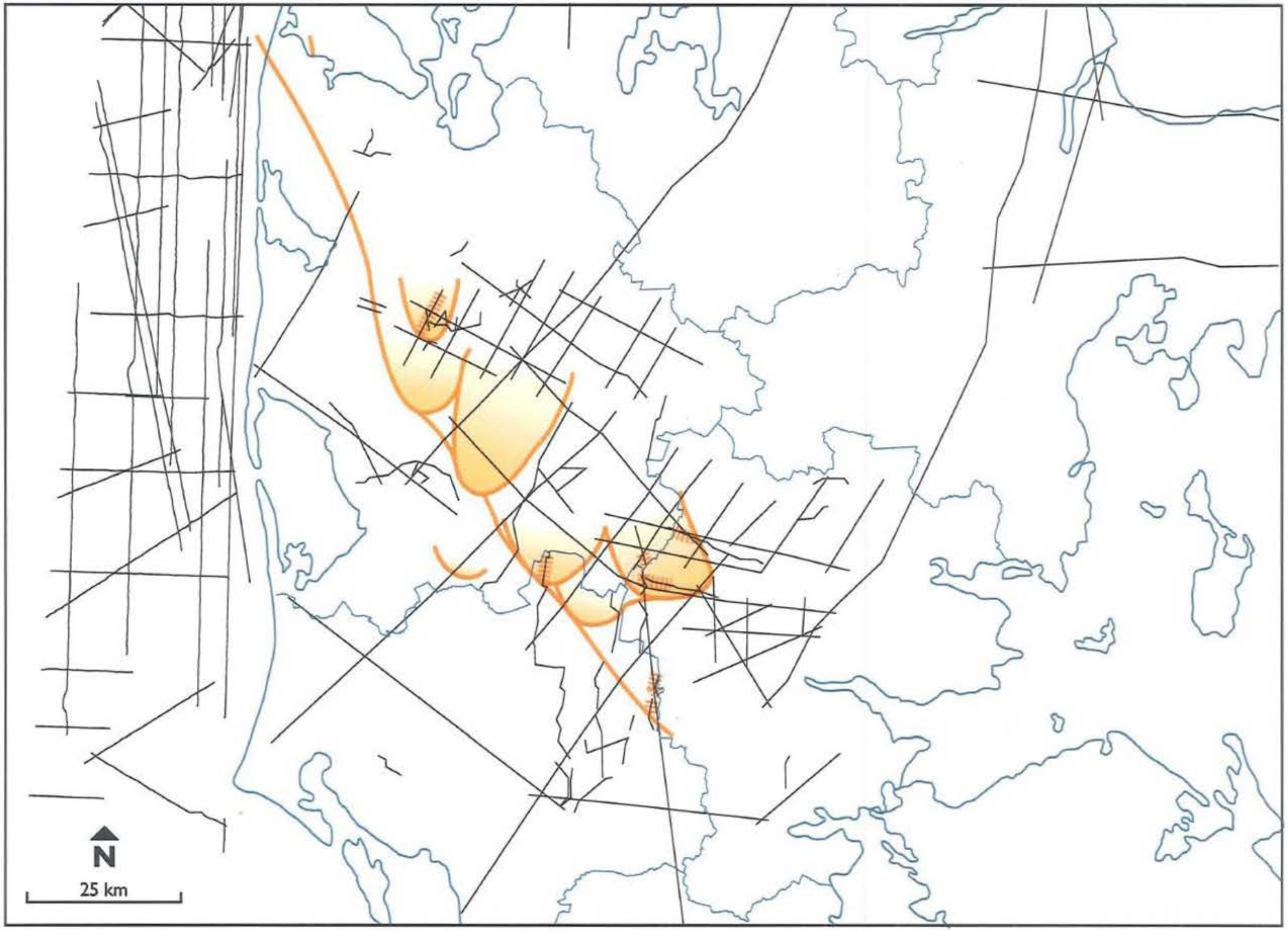


Fig. 28: Kort over deltalober i Bastrup sandet (sekvens C), samt placeringen af kystlinien under den sidste fase af Bastrup sandet.

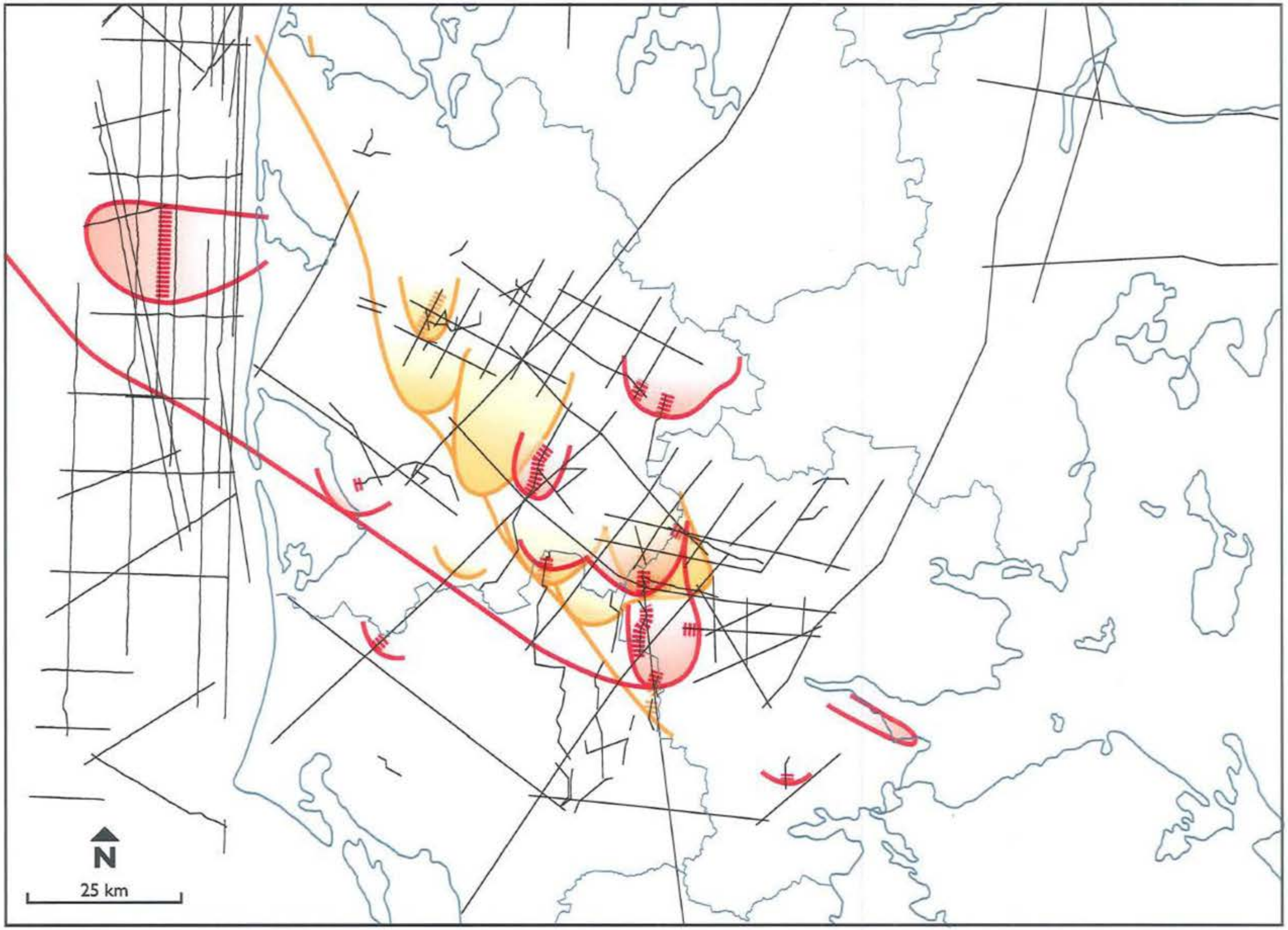


Fig. 29: Sammensat kort over sandrige enheder i Billund og Bastrup sandet. Bemærk at et parallelt klinoformt reflektionsmønster er angivet med henholdsvis røde og gule streger.

Distribution and thicknesses of reservoir sands in the wave-dominated Billund Delta, eastern danish North Sea and Jylland

Abstract

The lower Miocene Billund sand of Jylland, Denmark, provides an excellent opportunity to study the distribution of sands in a wave-dominated delta. This study is based on new high-resolution seismic data, nine stratigraphic boreholes, and outcrops along the fjords in eastern Jylland. The Billund delta was deposited in the eastern North Sea Basin during the Early Miocene and is on the available data recognized as a NW–SE trending feature. It forms a typically wave-dominated delta with thick sand bodies deposited in the up-drift area and sands and clays associated with a spit/lagoonal complex in the down-drift area. In the delta front alternating sands and clays were laid down, the sands mainly associated with storm events. Coarse-grained intervals mainly represent storm deposits in front of the delta. Progradation of the studied part of the delta occurred during high sea level and a subsequent fall in sea level that was caused by a eustatic fall during the mid Aquitanian (Early Miocene). Although 10–20 m thick sand intervals are common throughout the delta complex, the thickest (up to 100 m) and cleanest sand is found in units deposited during periods of forced regression and in narrow bands within structural lows. On seismic sections the sand-rich parts correlate with parallel clinoformal seismic facies, in which the clinoforms dip 7° – 10°. The stacking pattern of this seismic facies also indicates whether the progradation occurred during rising or falling sea level by displaying an ascending or descending shoreline trajectory, respectively. The Billund delta may be an excellent analogue for hydrocarbon-bearing, wave-dominated deltas, and seems to exhibit similarities to Jurassic deposits in the North Sea area.

Introduction

Delta systems are commonly classified into a tri-plate scheme including fluvial, tidal and wave-dominated deltas (Galloway 1975). Bhattacharya & Giosan (2003) focuses on the morphology and distribution of sands in a number of wave-dominated deltas such as the Sf. Gheorghe lobe of the Danube delta, the Brazos delta and the Damietta lobe of the Nile delta. Here thick sands were mainly deposited on the updrift side of the delta, sourced by sands reworked from other parts of the delta or additional sources updrift of the delta front and not directly from the fluvial-transported material. Spit/barrier complexes and associated lagoonal sediments and river-borne muds were formed in the downdrift area.

The multidisciplinary approach of this paper is to use both 2D seismic data, sedimentological outcrop studies and borehole data in order to provide detailed information on the spatial distribution of reservoir sands in the Billund delta (Fig. 1). The Billund delta complex is composed of sediments that prograded southwards from the Fennoscandian Shield during the Early Miocene (Rasmussen 2004). It covers an area of ~10000 km^2 and is part of an even larger delta complex that is normally referred to as the Ribe Formation (Sorgenfrei 1951; Rasmussen 2004). This part of the Ribe Formation is an exploration target for drinking water reservoir units and a large seismic and well database is therefore available.

The results presented here are not only of direct interest in the search for clean drinking water, but also indirectly for oil exploration as the delta may be an excellent analogue for hydrocarbon-bearing deltaic sediments in, for example, the Viking and Central Grabens.

Geological setting

The Early Miocene Billund delta covers the present day central Jylland onshore and the offshore area west of Ringkøbing Fjord. The main structural framework of this area includes the southernmost part of the Norwegian–Danish Basin and the northern part of the Ringkøbing–Fyn High. In Permian time the structural framework of the North Sea was dominated by the E-W trending northern- and southern Permian basins separated by the Mid North Sea High and the Ringkøbing–Fyn High (Cartwright 1990; Ziegler 1990; Vejbæk 1997). Thick successions of Zechstein evaporites (mainly halite) were deposited in both of these basins (Ziegler 1990; Vejbæk 1997). Later remobilization of the evaporites in the Norwegian–Danish basin played an important role in determining the depositional pattern of the Cenozoic succession (Madsen & Clausen 1995; Clausen et al. 1999; Rasmussen et al. in press). Over the Ringkøbing–Fyn High, evaporite deposits are only observed in marginal areas and the depositional pattern is mainly controlled by topography changes associated with the N–S trending Horn Graben and the Brande Trough (Best et al. 1983; Vejbæk 1990, Ziegler 1990; Clausen & Korstgård 1993).

Mesozoic rifting in the Central Graben area was followed by late Mesozoic and Cenozoic regional thermal subsidence. Several periods of inversion were probably caused by the Alpine Orogeny and ridge push related opening of the Atlantic Ocean (Vejbæk & Andersen 1987; 2002; Ziegler 1993; Deeks & Thomas 1995). The inversion was focused at older structural lineaments in the Central Graben and along the Sorgenfrei–Tornquist zone (Liboriussen et al. 1987; Vejbæk & Andersen 1987, 2002; Ziegler 1993). Inversion tectonics is, however, only believed to have exerted minor influence on the structural lineaments within the Horn Graben. Several periods of renewed activation of faults took place in Late Eocene, Late Oligocene and Early Miocene (Clausen et al. 1999). Tectonic activity during the Oligocene, along older structural lineaments, amplifies the subdivision of the Danish North Sea sector into two basins separated by the Ringkøbing–Fyn High. The fault activity and salt remobilisation within the Norwegian–Danish basin are believed to have influenced seabed morphology and subsequently the depositional pattern during Cenozoic times (Madsen & Clausen 1995; Clausen et al. 1999; Rasmussen, 2004).

In the early Cenozoic the North Sea basin was strongly affected by Paleocene uplift of the adjacent land area which changed the sediment input from Cretaceous – early Paleocene pelagic chalk deposits to more siliciclastic-dominated sediments (Gry 1935; Spjeldnæs 1975; Heilmann-Clausen 1995). This is represented by Upper Paleocene and Eocene fine-grained hemipelagic sediments derived from the adjacent Shetland Platform, and to some extend also the Scandinavian platform (Jordt et al. 1995; Michelsen et al. 1998; Ahmadi et al. 2003). The fine-grained sediments are inter-bedded with mass flow-derived coarser grained sediments some of which have excellent hydrocarbon reservoir potential (Hartog et al. 1993; Danielsen & Thomsen 1995; Underhill 2001; Hamberg et al. in press).

The first recognizable, large scale Cenozoic sediment progradation observed in the Danish part of the North Sea was initiated during the Oligocene. The general progradation direction of the fine-grained clastic wedges was towards the south from the Fennoscandian Shield (Jordt et al. 1995; Michelsen et al. 1995; Michelsen et al. 1998; Huuse et al. 2001; Rasmussen 2004). The direction of progradation from to the SSW continued in the Early Miocene and early Mid Miocene with three major depositional pulses of delta and shoreline progradation represented by the Ribe Formation, the Bastrup sand and the Odderup Formation (Fig. 2) (Rasmussen 2001, Rasmussen et al. 2002). The depositional reflects an early Aquitanian eustatic fall in sea level (Rasmussen 2004). The area in front of the slope is characterized by deposits controlled by a possible bottom current as suggested by Hansen et al. (2004).

During the Mid Miocene the depositional environment changed from coastal and deltaic to the more open marine conditions represented by the Gram and Hodde Formations (Fig. 2), as a result of an eustatic rise in sea level (Laursen & Kristoffersen 1999) and from increased subsidence in the basin areas (Clausen et al. 1999). During late Miocene the main depocentre moved progressively from the Norwegian–Danish Basin towards the Central Graben area (Sørensen et al. 1997). The Ringkøbing–Fyn High influenced the depositional pattern in the area (Sørensen et al. 1997; Rasmussen et al. 2002). The sediment input direction gradually changed during the Miocene and by Late Miocene–Pliocene the delta was primarily prograding from the Baltic area from east to west (Clausen et al. 1999; Overeem et al. 2001). The amount of sediment input from the north-east was, however, still considerable (Gregersen et al. 1998).

Data and methodology

The study is based on high resolution vibro-seismic data from the onshore area (GI and STR) and shallow-seismic offshore data from the eastern part of the Danish North Sea (Dana 95, 96, GR 97, 98 and FL 99). Conventional multi-channel 2D seismic, acquired for oil exploration, has also been used for regional seismic correlation. The survey frequency spectra are different from one survey to another. The conventional seismic data have a dominant frequency of about 40 Hz, the high-resolution data from the North Sea have a dominant frequency of about 65 Hz and the youngest onshore lines have a dominant frequency of about 100 Hz. Assuming that the interval velocity of the sediment is about 1800 m/s this gives a vertical seismic resolution ($\lambda/4$ sensu Yilmaz (1987)) of 11 m, 7 m and 5 m respectively. Studies of nine new stratigraphic boreholes: Engesvang, Isenvad, Store Vorslunde, Billund, Vandel Mark, Løvlund, Almstok, No and Stensig form the sedimentological and biostratigraphic database (Fig. 1). More than 10 on- and offshore wells drilled for hydrocarbon exploration have also been used for log correlation (Fig. 1).

Interpretation of seismic facies and reflector termination are based on the principles of seismic analysis described by Brown & Fisher (1977) and Mitchum et al. (1977a). Seismic facies are defined by the reflector pattern, amplitude and reflector continuity. The termination nomenclature is used to describe and define the top and bottom of seismic units. The sequence stratigraphic approach follows that of Hunt & Tucker (1992; 1995). Their model is based on the principles of Mitchum et al. (1977b) and other workers in the Exxon Group, where a sequence is defined as a stratigraphic succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities. However, the Hunt and Tucker model differs from the Mitchum et al. (1977b) model by placing the sequence boundary above of the allochthonous debris at the basin floor instead of below it. The concept of shoreline trajectories as introduced by Helland-Hansen & Gjeldberg (1994) is used here to describe shoreline and clinoform migration patterns. Shoreline trajectories describe the path of the shoreline migration in cross-sections along the depositional-dip (Helland-Hansen & Gjeldberg, 1994).

Seismic interpretation

Seismic interpretation has concentrated on a major prograding complex that can be followed both on- and offshore (Figs. 3 and 4). The system is bounded towards the south by relatively horizontal and parallel successions of reflections that prograding complex. The system displays an overall NW–SE orientated trend (Fig. 4). Its thickness varies from 300 ms (TWT) in the northwestern part to c. 150 ms (TWT) in the central area down to less than 30 ms (TWT) in the easternmost part. The seismic expression of the Billund delta has been subdivided into two seismic facies types. These facies types have been named the *parallel* clinoform facies and the *sigmoidal* clinoform facies on the basis of seismic reflection geometries described by Brown & Fisher (1977).

Parallel clinoform facies

The parallel clinoform facies is characterised by high frequency steep parallel clinoformal reflection patterns (Fig. 3 and 5). The lower boundary is relatively sharp and is sometimes defined by bottomset terminations on an erosional surface. The upper boundary is also sharp and sometimes defined by erosional truncations (Figs. 2 and 5a). The amplitude is high, especially in the upper part of the facies where the clinoforms are steepest, probably are a result of the effect of amplitude-stacking of reflections from a steep surface. The magnitude of the amplitude decreases with clinoform dip until it reaches the bottomset interval. The clinoform reflections are, in general, closely-spaced with a relative high wavelet frequency. The clinoforms are, in general, 75–100 m high and dip up to 7^0 – 10° towards the south.

The parallel clinoform facies units extend about 1–5 km from north to south, but where they are arranged in amalgamating sets of parallel clinoform packages, they reach 10 km (Fig. 3). The pinchout distance of a prograding shoreline, or the process-controlled pinchout distance, as defined by Løseth & Helland-Hansen (2001), is measured to be between 0.5

and 1 km. The stacking pattern of each package (of the parallel clinoform facies) is in general upward prograding but some of them display downwards prograding (Fig. 3).

Sigmoidal clinoform facies

The sigmoidal clinoforms are characterized by being less steep and more curved than the parallel clinoform facies (Figs. 3 and 5b). The reflection amplitude is medium with relatively low frequency. The upper boundary of the clinoforms is sharp, often with erosional truncations, al though some topset development can be recognized in seismic cross-sections. The erosional truncations are most pronounced in the most southerly parts of the unit where the clinoform breakpoint (if not eroded) would have been expected. The lower boundary is also sharp and sometimes seems to be defined as an erosional surface with erosional truncations of the reflections defining the underlying succession. Bottomset can be recognized in some cross-sections (Fig. 3). The sigmoidal clinoform facies unit are up to 100 m high and thin to the north where the reflections become more parallel and horizontal. The sigmoidal clinoform facies stack in units of 5–10 km in length from north to south. The dip of the clinoforms is approximately 1°–3°. The process-controlled pinchout distance is measured to be 1.5 to 2.6 km. The sigmoidal clinoform packages generally exhibit an upward prograding seismic pattern.

Parallel horizontal facies

The parallel horizontal facies is characterized by parallel to sub-parallel reflection pattern (Fig. 5). The reflection amplitude is medium to low with relatively low frequency. The upper boundary is characterized by a high amplitude reflector and may show erosional erosion. The lower boundary is also characterized by a high amplitude reflector. The parallel facies is up to 150 m high. The parallel horizontal facies may have a lateral extension of over 20 km.

Clinoform facies distribution

The distribution and thicknesses of the parallel clinoformal seismic facies can be seen in Figure 7. It has been impossible to construct a detailed facies map of the sigmoidal clinoformal facies because of the scattered nature of the data.

In the western part of the study area, the parallel clinoform facies is developed to the north of the sigmoidal clinoform facies. Eastwards they become intercalated. The parallel clinoform facies is thickest in the area west of Ringkøbing Fjord where it reaches 100 meters. Here the facies can be traced in an approximately 20 km long and 5 km wide zone before it reaches the present-day shoreline. The thick area west of the Ringkøbing Fjord is referred to as the Ringkøbing Fjord lobe.

The facies is also widely developed in the area of the Brande Trough where it is subdivided into a number of amalgamating units. The largest coherent packages occur the south where they have a thickness of about 80 m in a semicircular area with a diameter of approximately 10 km. Two other, significantly smaller, facies packages are recognized north of the first facies area. All the three packages are separated by areas of sigmoidal clinoform facies and are jointly referred to as the Brande lobe.

Lithology

The Billund complex has been penetrated by six new boreholes (Fig. 1). A few older water supply boreholes and oil wells penetrated the delta complex both onshore and offshore. The associated spit system east of the Billund area outcrops along fjords in east Jylland. This system has recently been intensively studied with respect to sedimentology and palynofacies (Dybkjær & Rasmussen 2000, Dybkjær 2004).

Borehole and well description

The Brande lobe, which formed the eastern part of the delta complex, is penetrated by the Engesvang, Isenvad, Store Vorslunde, Billund, Vandel Mark and Løvlund Boreholes (Fig. 1). Sands of varying thicknesses and quality have been found in these boreholes.

The Engesvang borehole penetrates 60 m of medium to coarse sand with some intercalation of clayey silt layers (Fig. 9). In the Isenvad borehole ca. 100 m of deltaic deposits has been penetrated. The lowermost 30 m consists of clayey silt which is capped by 70 m of medium to coarse sand interval. The lower part of the sand interval shows a clear coarsening upward trend.

The succession penetrated at Store Vorslunde is 80 m thick. The lower part is characterised by 50 m of clayey silt and the upper part by clayey silt intercalated with sand stringers. The deltaic succession is here capped by 30 m of medium- to coarse-grained sand. The uppermost sand-rich part correlates with the parallel clinoformal reflection pattern on the seismic section (Fig. 8A). In the Billund borehole the succession is characterized by 40 m of medium to coarse-grained sand sharply overlies older Eocene deposits. This sand-rich succession correlates with the parallel clinoform facies on the seismic section (Fig. 8B). At Vandel Mark the lower part consists of c. 10 m silty clay with thin fine- to medium-grained sand beds (Fig. 9). This is sharply overlain by 30 m of medium-grained sand with a few intercalations of clay layers. The succession at Løvlund is characterised by fine- to medium-grained sand interbedded with thin clay layers (Fig. 8C). This is topped by approximately 15 m of alternating clayey silt and sand layers. The succession at Løvlund correlates with the sigmoidal clinoform facies on the seismic section (Fig. 8C).

West of the Brande Lobe in Stensig borehole penetrate the deltaic succession characterised by parallel horizontal facies. The succession here correlates to clayey silt with increasing intercalation of sand layers upwards.

East of the Brande lobe the Gadbjerg and Remmerslund boreholes penetrate a distinctively thinner succession of the Billund complex. The succession at Remmerslund is 31 m thick and is composed of organic-rich, clayey silt with few sand lenses (Fig. 10). A 42 m thick succession has been penetrated at Gadbjerg. The sequence is characterised by laminated clayey silt capped by 2 m of medium- to coarse-grained sand (Fig. 11).

Data from two older hydrocarbon exploration; Eg-3 and C-1 (Fig. 11), have been used to confirm the deposits of the Billund complex in the central and western part of the study area. However, the description of the lithology is speculative as the main target of these wells was deeper-seated Paleocene and Cretaceous deposits. Approximately 100 m of sand have been reported in the Eg-3 well (Completion report Eg-3). This thick sandy interval correlates with a clinoformal reflection pattern on older seismic data (Rasmussen & Dybkjær in press). The succession in the C-1 well consists of alternating clay and sand, which become slightly coarser and thicker upwards. This part correlates to a clinoformal reflection pattern which however has only been observed on older multi-channel seismic data with low resolution.

Outcrop desciption

A detailed study of the outcrops is given by Rasmussen & Dybkjær (in press); a summary is presented here:

The succession that outcrops at Dykjær in east Jylland, in the northern part of the study area, is characterised by organic-rich, clayey silts, with some intercalations of fine-grained sand. Thick sands and gravel may occur locally (Fig. 12A and B). In the central part of the Hvidbjerg locality, the succession is dominated by thick sand, in places up to 26 m thick (Fig. 12C). The sand is clean and medium-grained and dominated by thick to planar sand beds capped by wave ripples and the beds are dipping gently towards the south-east (Fig. 12D). The sedimentary structures at the Pjedsted locality are dominated by thick to planar sand beds locally with tidal bundles and double clay layers are common (Fig. 12E). The cross-beds of the tidal bundles dip towards the south-west. Alternating sand and clay beds dominate in the southern part of the study area, represented by a compound section referred to as Lillebælt (Fig. 12F). The succession here shows a thickening- and coarsening-upward trend and amalgamation of sand layers is common in the upper part of the interval (Fig. 12G). Sedimentary structures in the sand beds are dominated by hummocky and swaley cross-stratification; gutter casts occur in the upper part of the succession. The succession that outcrops in east Jylland is erosively capped by a gravel layer with lasts up to 3 cm. The thickness of the gravel layer varies but it rarely exceeds 1 m.

Interpretation

Correlation of seismic facies with boreholes indicates that the parallel clinoform facies ties to sand-rich sediments, as in the upper part of the complex in the Store Vorslunde and Billund boreholes (Figs. 6A, and B). The sigmoidal reflection pattern correlates with alternating sand and clay layers, as best demonstrated in the Løvlund borehole (Fig. 8C), but also in the lower part of the Store Vorslunde borehole (Fig. 8A). The succession penetrated in the boreholes show an overall coarsening-upward trend. In the Store Vorslunde borehole the palynomorphs indicate progressively decreasing marine influence upwards. The influx of fresh water alga is high. The uppermost sand in this borehole was deposited in a terrestrial environment (Dybkjær & Rasmussen 2000). Studies of the succession that outcrops in east Jylland (Friis et al. 1998; Dybkjær & Rasmussen 2000; Rasmussen & Dybkjær in press) indicate a marginal marine depositional environment. As a consequence, the clinoformal reflection pattern generally indicates progradation of a siliciclastic wedge into the basin and the overall lobate morphology of the complex is therefore interpreted as representing a deltaic environment (cf. Brown & Fisher 1977; Orton & Reading 1993; Bhattacharya & Giosan 2003). A pinchout distance of less that 2 km characterised the delta (Fig. 3). The pinchout distance in prograding systems is highly dependent on the kind of sediment input to the system (gravel, sand and clay) and the type of delta (wave-, tidal- or fluvial-dominated as defined by Galloway (1975) and Løseth & Helland-Hansen (2001)). The pinchout distance generally becomes shorter the coarser the input material and shorter in wave-dominated deltas compared to tidal- and fluvial-dominated deltas (Løseth & Helland-Hansen 2001).

The study of boreholes and outcrops indicate that it is a mixed sand-mud system, and the grain size rarely exceeds coarse-grained sand (Friis et al. 1998; Rasmussen & Dybkjær in press). Sedimentary structures in the associated spit complex in the eastern part of the study area are dominated by hummocky and swaley cross-stratified sand and wash-over fans (Rasmussen & Dybkjær in press) all structures indicative of a wave-dominated depositional environment. Some tidal influence is implied by tidal bundles and double clay layers (Friis et al. 1998; Rasmussen & Dybkjær in press), but tidal influence is subordinate. Sedimentary structures in east Jylland, such as climbing ripples and anisotropic hummocky cross-stratified sand beds, indicate a predominance of westerly winds (Rasmussen & Dybkjær in press). The study of Friis et al. (1998) also suggests a dominance of westerly winds based on palaeogeographical considerations. It is therefore emerges that along-shore sediment transport towards the south-east probably took place during formation of the Billund delta which resulted in the deposition of sands mainly on the western side of delta lobes and spit/barrier with associated clayey lagoonal deposits to the east of the main delta. The marked erosion on the Ringkøbing lobe (Fig. 6A) may consequently be a result of erosion of a former tongue of the delta complex. The eroded material was subsequently transported eastwards and deposited updrift on the Brande lobe or at the location of the Eg-3 well where a thick package of sand has been penetrated (Fig. 7).

Where the parallel clinoform facies shows an aggradational stacking pattern, or is overlain by the sigmoidal clinoform facies, it is interpreted as having been deposited during sea level rise and thus forms the highstand systems tract of the delta complex. Where parallel clinoform facies units progressively move towards the south, show amalgamation and erode into the underlying succession, the progradation is interpreted to have occurred during falling sea level. Similar observations have been made by Hampson & Storms (2003) for a wave-dominated shore face-shelf system where the forced regressive shoreline trajectories are marked by amalgamation of erosional discontinuity clinoform surfaces into regressive surfaces of marine erosion.

Predictions of sands

The Billund delta provides a good example of distribution of the sands in a wave-dominated delta. According to Bhattacharya & Giosan (2003), thick sands are deposited in front of the delta as amalgamated sand ridges if the wave action is normal to the delta front. In wave-dominated deltas influenced by strong long-shore currents, sands are deposited in the up-drift part of the delta front and the downdrift part is characterised by deposition of spit/lagoonal complexes. The calibre of the sediments transported to the delta environment is also important for the morphology and distribution of sediments within the delta (Orton & Reading 1993). In addition to this, progradation of the delta during changing sea level is also thought to control the distribution of sands (Dominquez & Wanless 1991). The use of shoreline trajectories as a predictive tool has recently been developed by Bullimore et al. (2004) and Bullimore & Helland-Hansen (2004) and can also be used successfully in this study.

The Billund delta shows a seismic facies pattern of alternating parallel clinoformal and sigmoidal seismic facies. This alternation is interpreted as reflecting lateral delta lobe switching due to autocyclicity. The parallel clinoform facies corresponds to sand-rich central delta lobe deposits and the sigmoidal facies reflects delta lobe margin deposits of alternating sand and clay deposits. The influence of sea level changes can, however, be recognised in the overall trajectory trends of the delta complex. Progradation during rising sea level is reflected in an ascending shoreline trajectory (Fig.11B) (Helland-Hansen & Martinsen 1996). Progradation during stable sea level results in a horizontal trajectory (Fig. 12B) and finally progradation under falling sea level is illustrated in a descending trajectory (Fig. 13C) (Helland-Hansen & Martinsen 1996).

Progradation of the Billund delta during an ascending and stable trajectory is demonstrated around and to the north of the Store Vorslunde borehole (Fig. 14). Both seismic facies are recognised on the seismic section. The lateral distribution of the parallel clinoformal facies is relatively confined, less than 5 km. This seismic facies alternates with the sigmoidal seismic facies. The stacking pattern for this part of the succession is aggradational and progradational (ascending trajectory). At the Store Vorslunde borehole, 30 m of clean sand was penetrated, corresponding to the height of the clinoforms interpreted on seismic cross-sections (Fig. 8). The sigmoidal clinoform facies correlates with clay sediments interbedded with thin sand layers in. The deltaic succession correlates with spits and barrier complexes in the eastern part of the study area (Rasmussen & Dybkjær in press). The main spit complex here consists of up to 26 m of well-sorted and clean fine- to medium-grained sand. The thickness of the sand decreases rapidly south of the spit to ~15 m where it consists of mainly fine-grained sand with numerous intercalations of clay, especially in the lower part of a parasequence (Rasmussen & Dybkjær in press). Clayey lagoonal deposits with some fine-grained sand layers are present to the north of the main spit system. Thicker sand sedimentation may have occurred as washover fan deposits adjacent to the spit.

Progradation of the Billund delta, characterised by descending trajectory, indicates construction of the delta during falling sea level. This is illustrated south of the Store Vorslunde borehole (Fig. 14). The transitional phase from ascending to descending trajectory is seen as a change from alternating parallel clinoform facies and sigmoidal facies to a marked amalgamation of the parallel clinoform facies; this facies then completely dominates the seismic reflection pattern. Furthermore, in some areas, successively deeper erosion is recognised at the base of the parallel clinoform facies, which further supports the association of progradation with falling sea level. However, this pattern sometimes change to shallower erosional depth at the base of the clinoforms (e.g. at shot point 3450, Fig. 3), but still with amalgamation of the parallel clinoform facies. This is interpreted as being due to delta lobe switching under falling sea level. The succession, characterised by the amalgamated parallel clinoform facies on the seismic sections, has been penetrated by the Billund borehole. Here 50 m of clean medium- to coarse-grained sand corresponds to the height of the clinoforms observed on the seismic data. If the height of clinoforms can be applied as an indication of lithological thickness, up to 75 m of sand may be expected in some parts of the Billund delta (Fig. 7). The succession characterised by descending parallel clinoform reflection patterns correlates with a major hiatus in the eastern part of the study area (Rasmussen 1998; Dybkjær & Rasmussen 2000). In outcrops the hiatus is marked by a distinct erosional surface overlain by a conglomerate with pebbles up to 5 cm (Rasmussen 1998; Rasmussen & Dybkjær in press). Rasmussen (1996, 1998) and Rasmussen & Dybkjær in press) interpreted the gravel layer as having been deposited in a fluvial depositional environment during a major regression in the Early Miocene. Coarse-grained fluvial deposits were therefore laid down in the eastern part of the study area during the period with forced regression as indicated by the descending trajectory recognised in the late phase of construction of the Billund delta complex.

In addition to sea level changes, the physiography of the basin played a significant role in the distribution of sand-rich delta lobes and associated spit systems of the Billund delta. In Figure 16 the mapped delta lobes and the Hvidbjerg spit are compared with the Top Pre–Zechstein structural elements in the basin. Both the Brande and Ringkøbing lobes are associated with structurally-defined topographic lows. The Brande lobe is confined to an N–S trending graben structure (the Brande Trough) in the central part of the study area (Fig. 15). The Ringkøbing lobe is located within the foot-wall section of a minor half graben just off the coast of Jylland (Fig. 15). The WNW–ESE trending Ringkøbing–Fyn High also seems to have influenced the southernmost positions of the Ringkøbing lobe as the termination of this lobe coincides with the northern rim of the Ringkøbing–Fyn High (Fig. 15). The Brande lobe has a more southerly location, possibly due to its position within the Brande Trough (Fig. 15). The relatively thick sand in the Eg-3 borehole does not seem to be associated with any structural element. One explanation for this may be that initial progradation was controlled by the topography of the basin and the succeeding location of lobes was controlled by inter-lobe filling. An alternative explanation is that the Eg-3 well is located west of the Brande lobe and that the sand here represents a succession deposited on its updrift side.

An important structural element in the Early Miocene is the eastern fault of the Brande Trough, which separated an elevated area east of the fault from lower lying areas to the west. In principle, this fault controlled the distribution of the main delta, deposited in relatively deep water (c. 100 m), and the associated spit/barrier systems deposited in shallower water in the eastern part of the study area. However, smaller structural elements also control the distribution of sand and clay. For instance, the spit system at Hvidbjerg follows the WNW–ESE trend of minor faults on the Ringkøbing–Fyn High (Fig. 15). Rasmussen &

Dybkjær (in press) suggest that the location of spits and barriers, deposited during the Early Miocene, was strongly controlled by structural elements in a similar fashion to the Lower Cretaceous Jydegård and Robbedale Formations on Bornholm (Noe-Nygaard & Surlyk 1988).

The higher topography east of the Brande Trough also played a role for development of the delta complex during falling sea level. Here the area was subaerially exposed and gravel and sand were deposited in fluvial environments (Rasmussen 1998) while thick sands were laid down in deltas within the deeper-lying Brande Trough. The fluvial deposits were, however, reworked during a succeeding transgression in the Early Miocene, so they now form a more or less tabular layer of gravel above a ravinement surface (Rasmussen & Dybkjær in press).

Remobilisation of the salt structures north of the Ringkøbing lobe (Japsen & Langtofte 1991) probably influenced development of the western part of the delta complex. The sigmoidal clinoform facies is found in the southern part of the delta and that it is placed on top of an erosional surface above the parallel clinoform facies. The location above an erosional surface suggests that the unit was deposited after a relative fall in sea level, succeeded by a relative sea level rise as implied by the progradational pattern of the facies. However, this development cannot be recognised in the eastern part of the delta complex and may therefore be a local phenomenon. Consequently, this may reflect a local change in relative sea level due to salt movements resulting in local erosion of the tip of the delta lobe. Tectonic movements in the Early Miocene, described by Rasmussen (2004), may have triggered the salt tectonism giving rise to local warping around the structure.

Conclusions

The Billund delta, that covers an area of 10000 km^2, prograded south-westwards during the Early Miocene. Two discrete lobes of this delta have been identified, the Brande and Ringkøbing lobes, on the basis of high resolution seismic data, new boreholes and outcrop sections.

The study of seismic data and sedimentary structures from outcrops in east Jylland indicate that the delta was wave-dominated with thick sand deposited preferentially in the updrift part of the delta lobes. The sand supply to the delta-lobes originated partly from erosion of former lobes located in the western part of the delta complex, and partly from deltas or other sources located northwest of the study area. In the eastern part of the study area, spit complexes with associated lagoonal deposits were formed during normal regression.

The seismic facies study indicates that parallel clinoforms with a dip of $7^0 - 10^\circ$ are indicative for more homogeneous sand layers. The stacking patterns (ascending or descending trajectories) of the clinoforms indicate whether progradation occurred under rising or falling sea level. The thickest sand deposits are characterised by amalgamation of the parallel clinoformal facies and successive deeper erosion in the substratum. In the eastern part of the delta complex, which developed in a topographically elevated position on the Ringkøbing–Fyn High, gravels were deposited during the period of forced regression.

The most sand-rich delta lobes were preferentially deposited in topographic lows such as the N–S trending Brande Trough, during progradation. The location of the downdrift spit system was controlled by minor WNW–ESE striking faults arranged en echelon to the main boundary fault of the Brande Trough.

This investigation illustrates that a combined study of the depositional environment (fluvial-, tidal- or wave-dominated), sea level changes and the physiography of the basin is needed in order to predict the spatial distribution of thick sands in a deltaic setting.

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Figure captions

Figure 1. *Study area with location of boreholes and wells (white dots). Locations of correlation panels are indicated by a stippled line. Main structural elements are from Vejbæk & Britze (1994).*

Figure 2. *Lithostratigraphy of the upper Oligocene and Miocene succession, Denmark. Teh lower Miocene Billund sand is indicated in bold.*

Figure 3. *Three N–S orientated seismic lines through the Billund delta complex. The parallel clinoformal seismic facies is shown in orange and the sigmiodal facies in yellow. For location of the seismic section see Figure 4. (Seismic data courtesy of COWI and H. Lykke-Andersen).*

Figure 4. *Isochore map of the Billund delta. Note that the thickest part of the delta is located in the north-western part of the study area. Much thinner deltaic deposits cover the eastern part of Jylland. The deltaic succession pinches out towards the south. Seismic sections in Figure 3 are shown as bold lines.*

Figure 5. *Enlarged seismic sections showing the three seismic facies. (A) Note the dense pattern of dipping reflectors within the parallel clinoformal seismic reflection facies (orange). The dip of the reflectors is c. 150. (B) The maximum dip of the clinoforms within the sigmoidal seismic reflection facies (yellow) rarely exceeds 50. (C) The parallel horizontal facies is shown in green. The location of the seismic line is illustrated in Figure 4 (Seismic data courtesy by COWI and H. Lykke-Andersen).*

Figure 6. *Details of seismic sections from the Billund delta. The upper section shows erosion of the delta front of the Ringkøbing lobe. The lower shows a horizon-flattened seismic section at Løvlund. The influence of the antecedent topography is evident on the horizon-flattened section can be seen. The structural elevation in the southern part is the Ringkøbing–Fyn High.*

Figure 7. *Thicknesses of the sand within the delta complex as indicated from measurements of the height of the clinoforms with parallel clinoform facies (from seismic cross-sections). Sand thicknesses in selected boreholes are also indicated.*

Figure 8. *Lithological section and gamma log data from the Store Vorslunde, Billund and Løvlund stratigraphic boreholes compared with the seismic section which runs through the borehole. Correlation of sand-rich intervals within the borehole with seismic facies is indicated with a red line. (Seismic data courtesy COWI).*

Figure 9. *N–S gamma log correlation panel from four boreholes. Engesvang, Isenvad, Store Vorslunde, Billund and Vandel Mark are located on the Brande lobe and the Almstok borehole in front of the Billund delta. Note the influence of the Ringkøbing–Fyn High (elevation towards Almstok) also shown in Figure 6. The location of the correlation panel is shown in Figure 1.*

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Figure 11. *E–W trending correlation panel of the Billund delta. Note that thick deltaic sands were laid down west of the main Brande Trough fault and dominantly clayey sediments with some thicker sand bodies (Hvidbjerg spit system) east of the fault. The Billund delta complex pinches out towards the west approaching the R-1 well.*

Figure 12. *Photographs of Billund delta outcrops in east Jylland. A) Lagoonal muds and upper shoreface sands at Dykjær. B) Flood-dominated tidal bar (main current direction towards the NE) deposited north of the spit system. C) Panorama view of the Hvidbjerg spit system. D) Details of the Hvidbjerg sand showing a planar-laminated sand bed capped by wave ripples. E) Tidal bundles from the sand pit just south of Hvidbjerg. The cross-stratified sand beds dips SW, perpendicular to the strike of the shoreline. Note the three double clay drapes in the exposed section. F) Hummocky cross-stratified sand beds at Lillebælt deposited in the lower shoreface in front of the Hvidbjerg spit. G) Swaley cross-stratified sand beds in the outcrop at Lillebælt.*

Figure 13. *Schematic illustration of development of the Billund delta complex during rising, stable and falling sea level. The progradation of the delta is reflected by alternation of parallel clinoformal seismic reflection patterns and sigmiodal seismic reflection pattern, which is interpreted as due to delta lobe switching. Ascending shoreline trajectory indicates progradation under rising sea level. A stable shoreline trajectory indicates no change in sea level and a descending shoreline trajectory indicates progradation under falling sea level. Extensive and thickest sands were deposited during falling sea level that is indicated by a descending shoreline trajectory and deep erosion into the unconsolidated Miocene substratum and incision into the proximal part of the delta complex. Based on the concepts of Helland-Hansen & Gjelberg (1994).*

Figure 14. *A sketch of the seismic section through the Brande lobe (Fig. 3c), showing the alternation of the two seismic facies during progradation. Note that the initial progradation occurred during rising sea level as indicated by ascending shoreline trajectory and the simple alternation between the two facies. The final progradation (south of Store Vorslunde borehole) occurred under falling sea level as shown by a descending shoreline trajectory. Note also the marked erosion into the Miocene substratum and amalgamation of the parallel clinoform facies that occurred during this stage.*

Figure 15. *Sand-rich lobes of the Billund delta superimposed on the structural framework from Vejbæk & Britze (1994). Note that the Ringkøbing and Brande lobes are confined to structural lows. Note also that the trend of the Hvidbjerg sand in eastern Jylland is similar to that of minor faults on the Ringkøbing–Fyn High.*

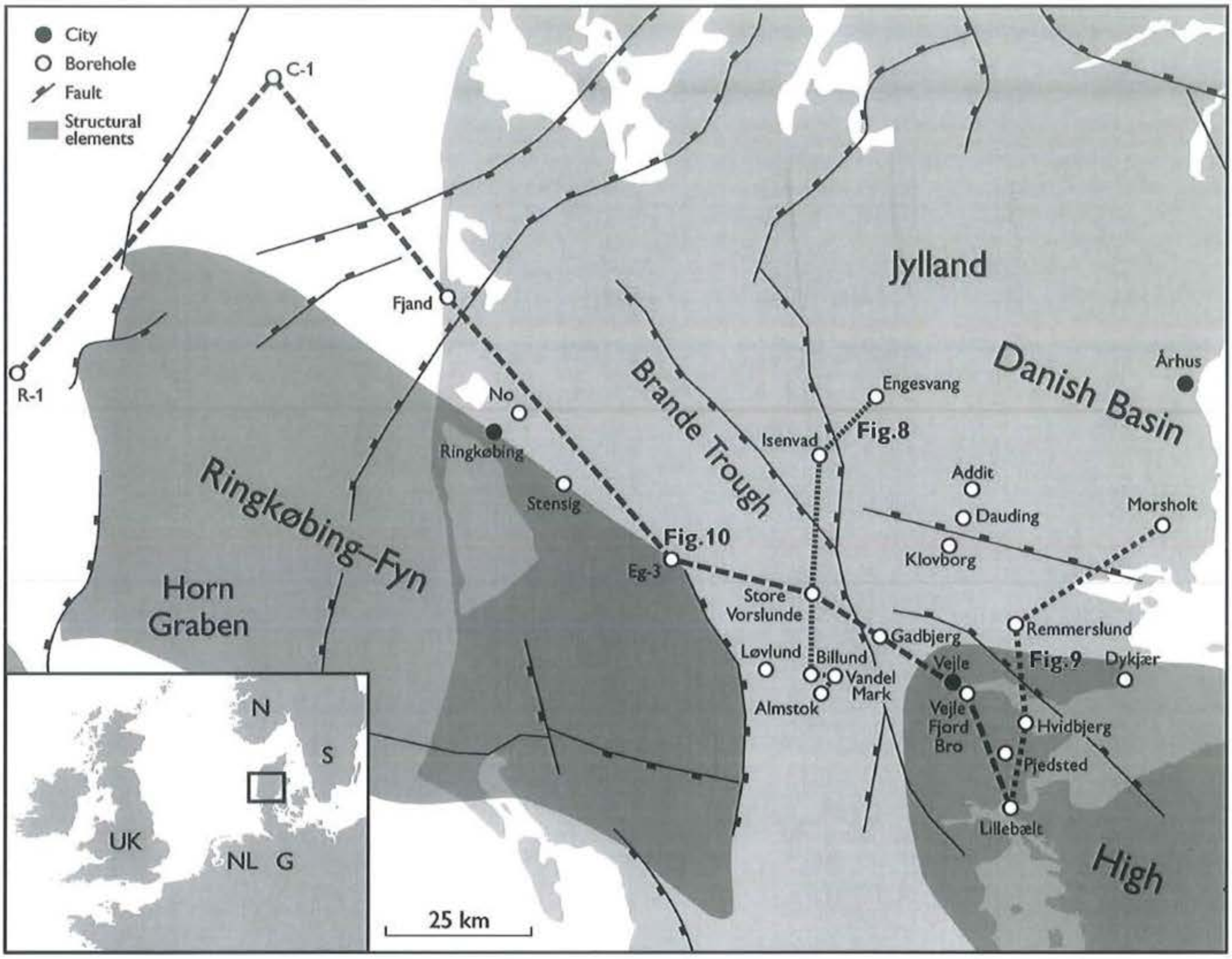


Figure 1: Study area with location of boreholes and wells (white dots). Locations of correlation panels are indicated by a stippled line. Main structural elements are from Vejbæk & Britze (1994).

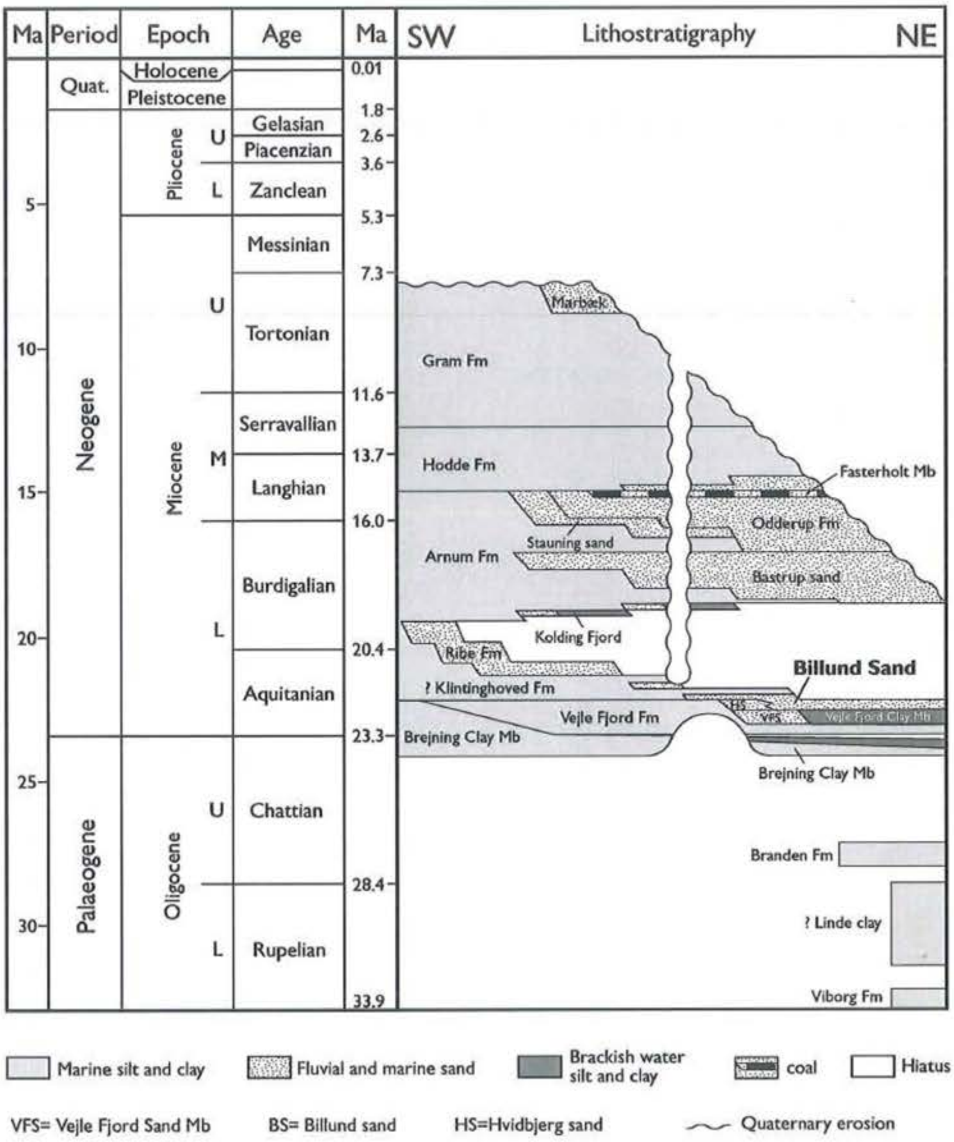


Figure 2: Lithostratigraphy of the upper Oligocene and Miocene succession, Denmark. The lower Miocene Billund sand is indicated in bold.

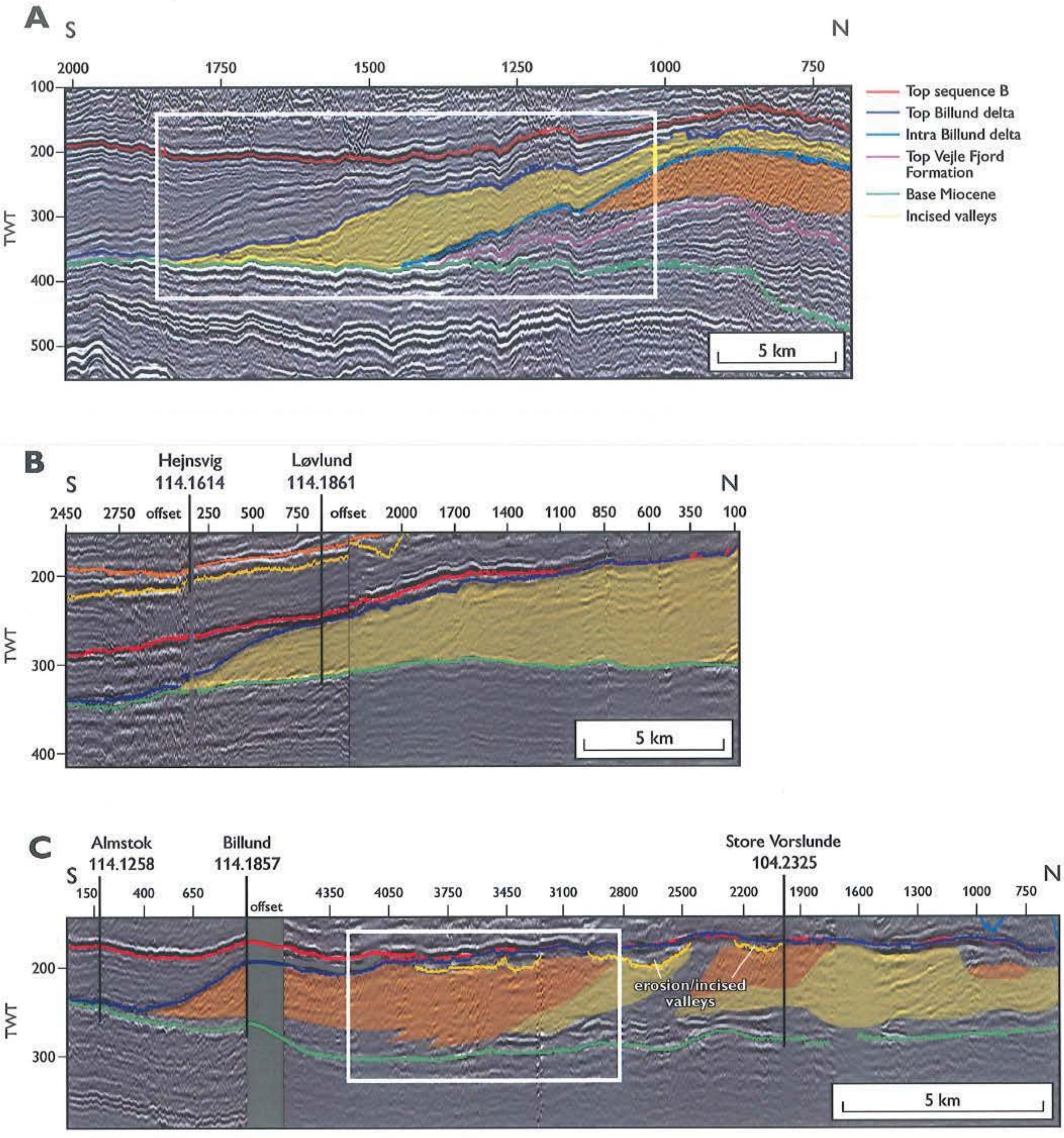
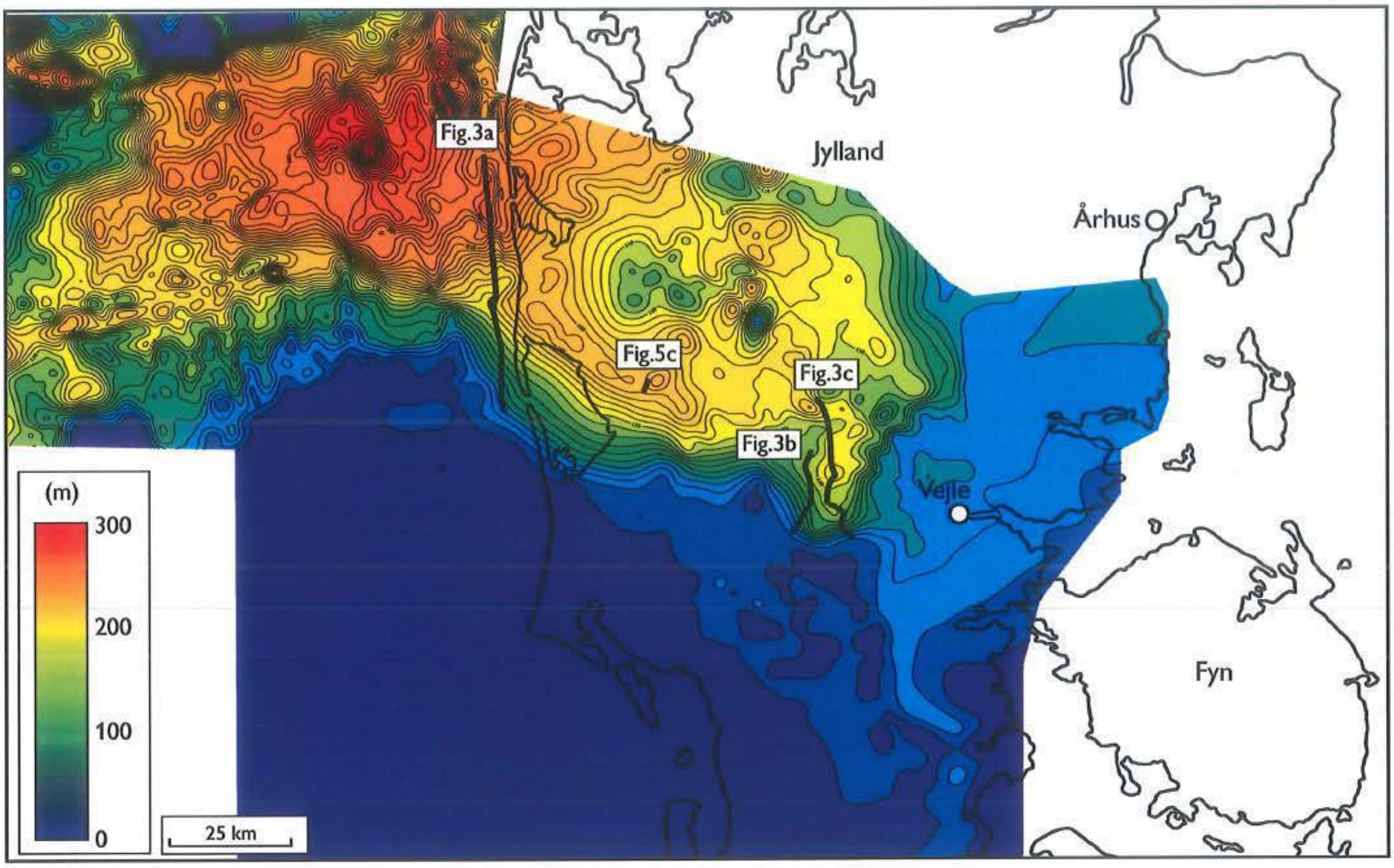


Figure 3: Three N---S orientated seismic lines through the Billund delta complex. The parallel clinoformal seismic facies is shown in orange and the sigmiodal facies in yellow. For location of the seismic section see Figure 4. (Seismic data courtesy of COWI and H. Lykke-Andersen).



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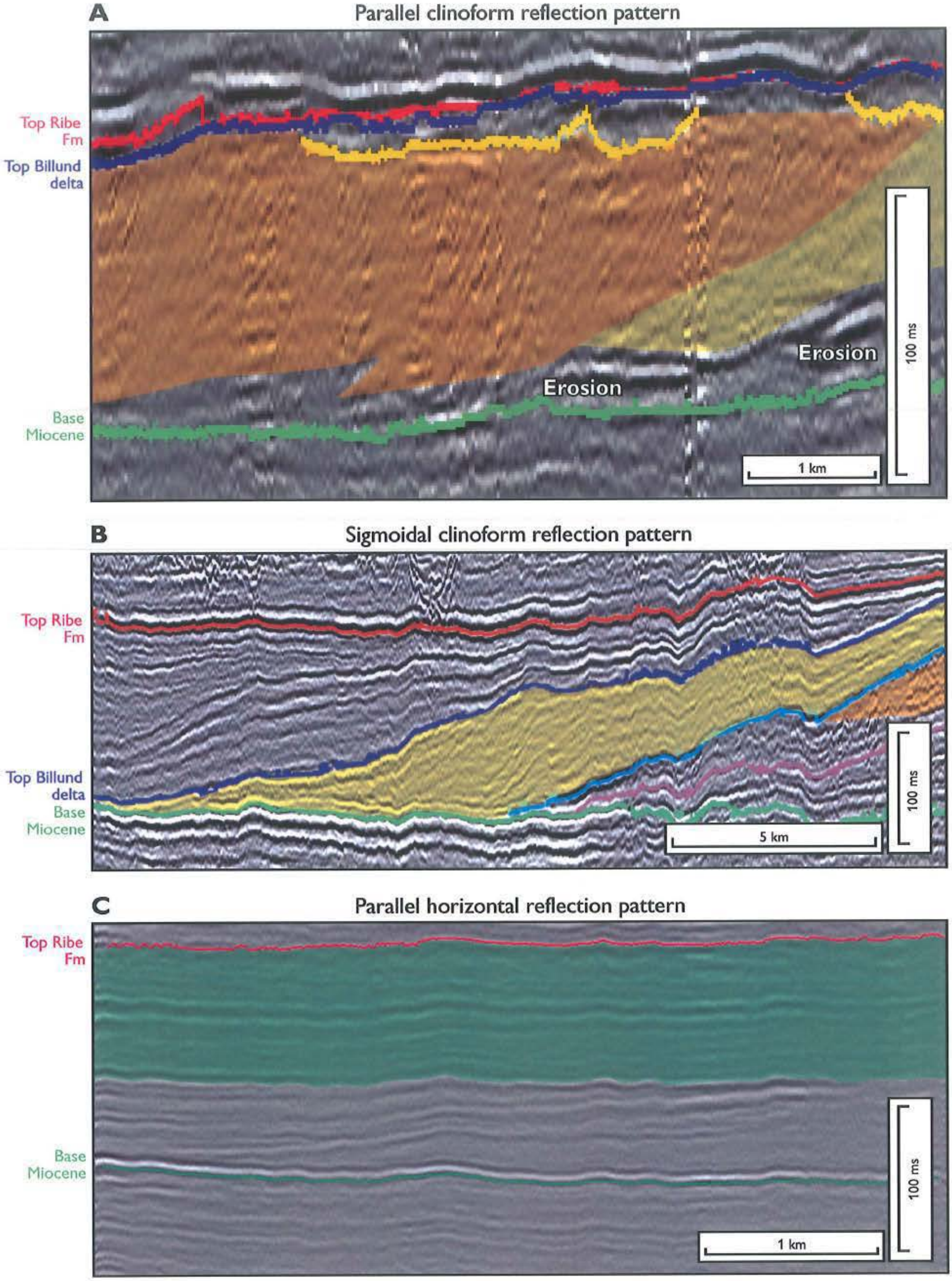

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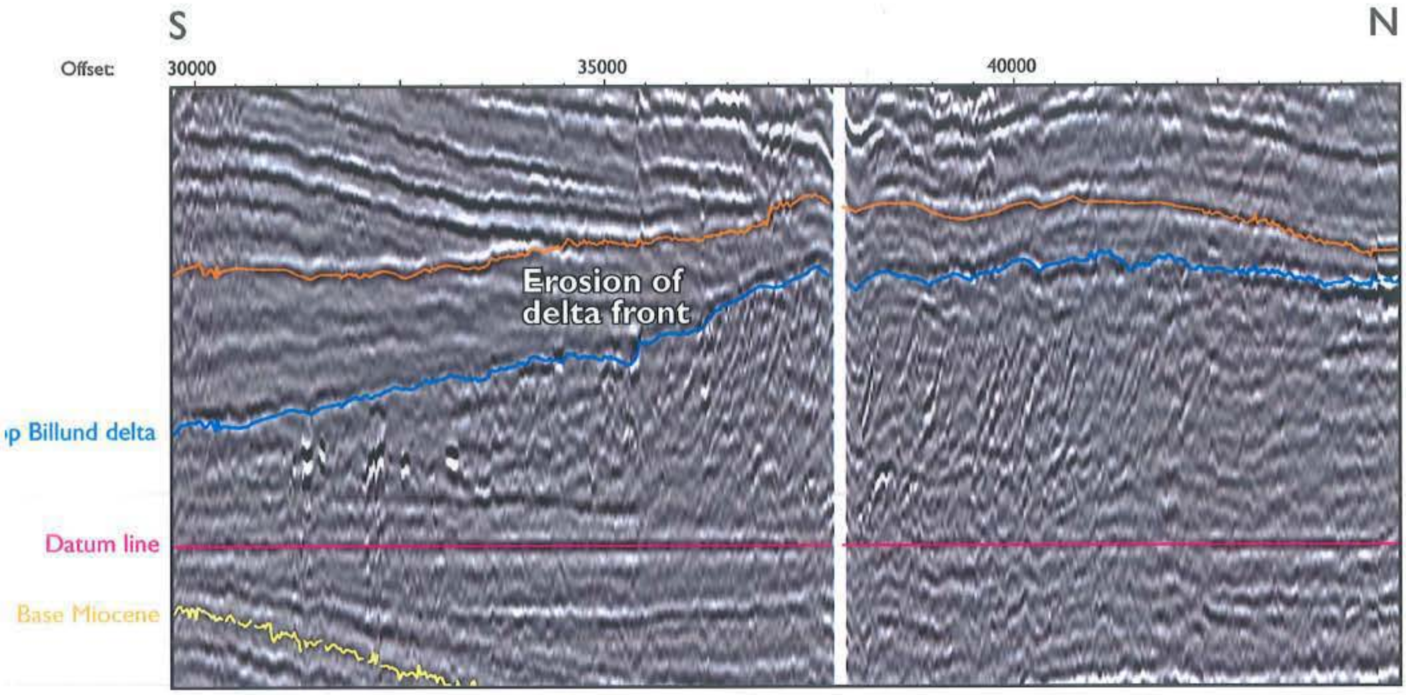

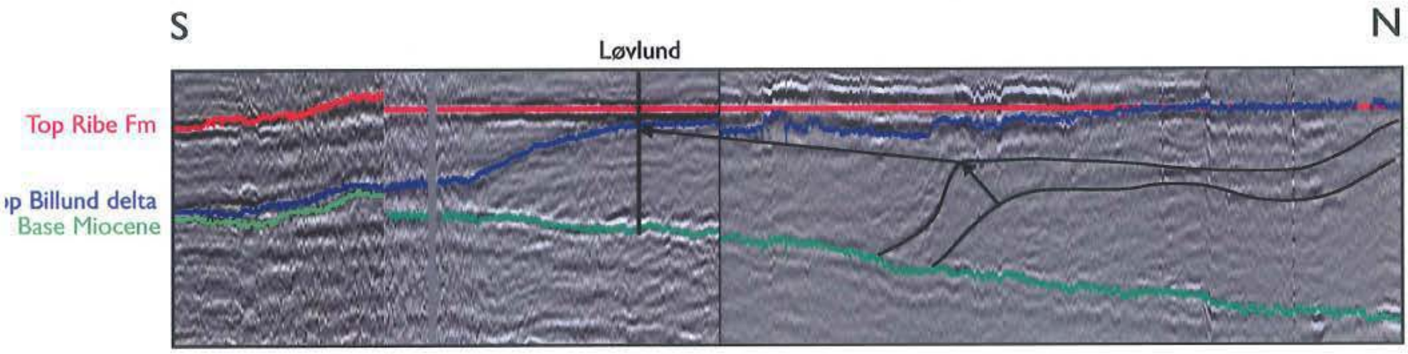

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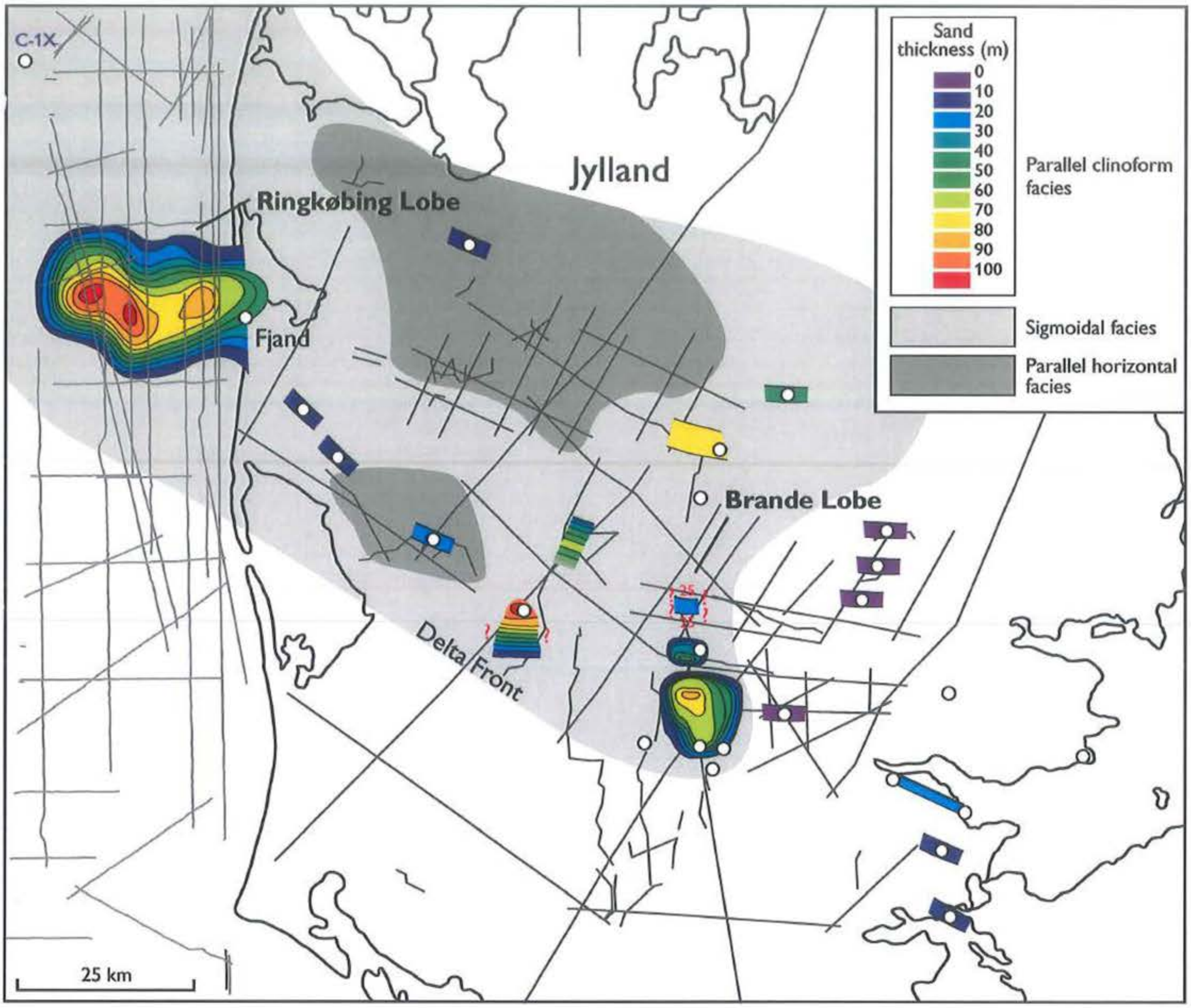

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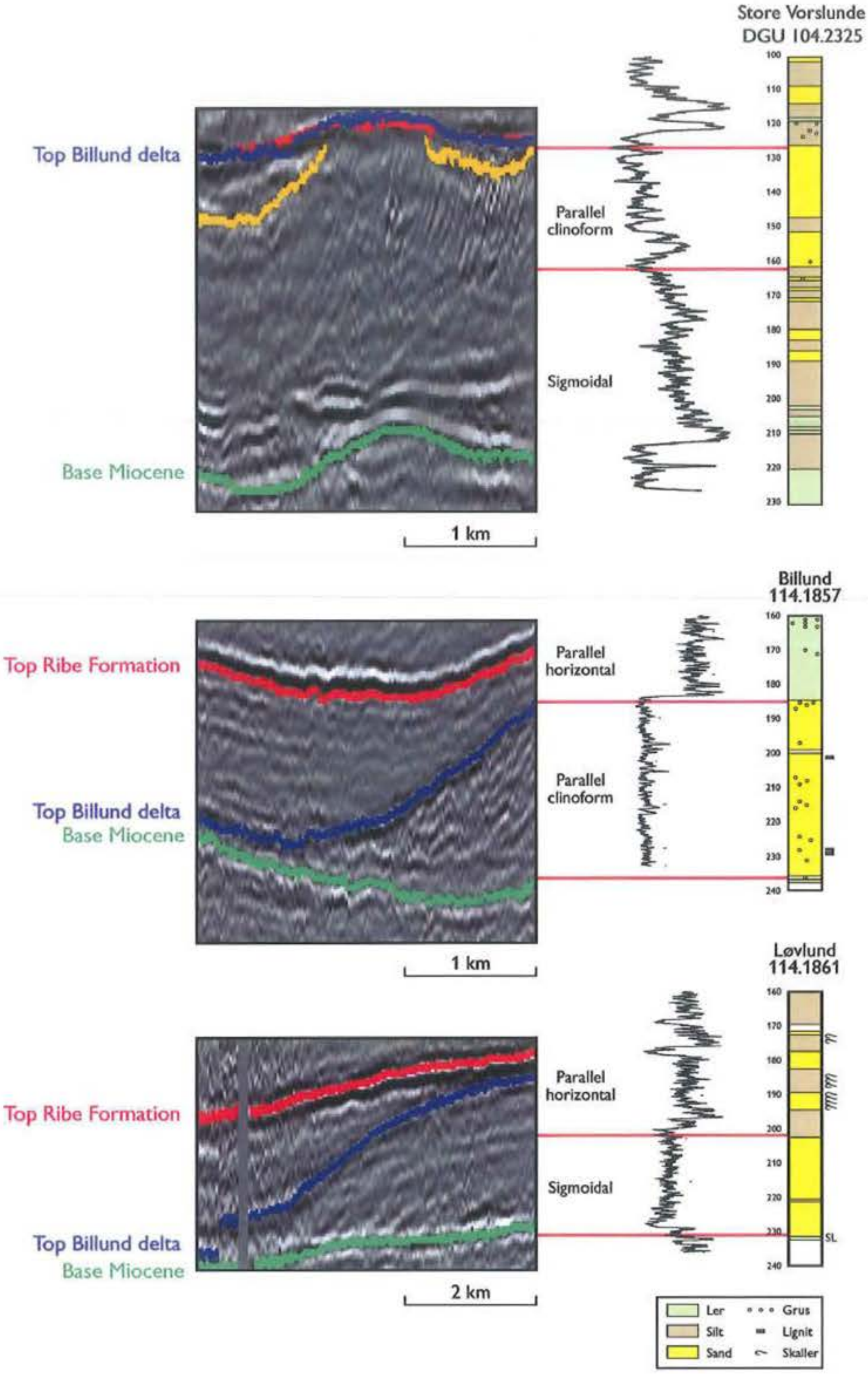

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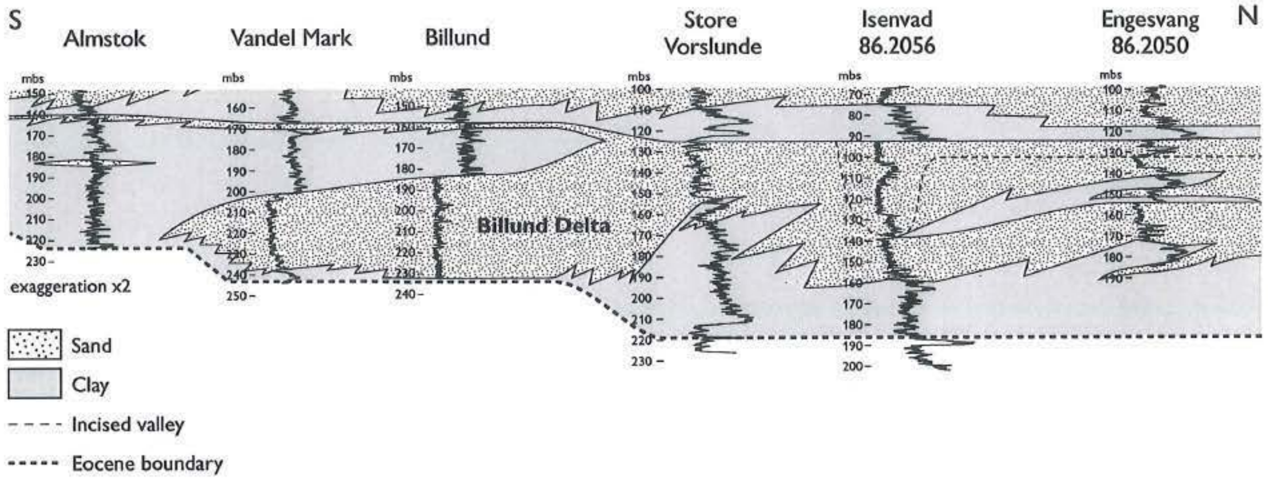

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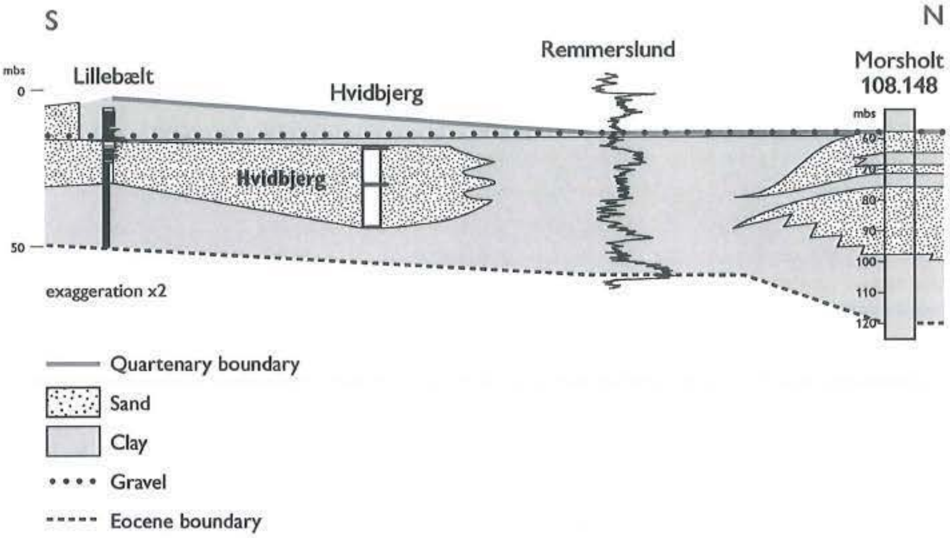

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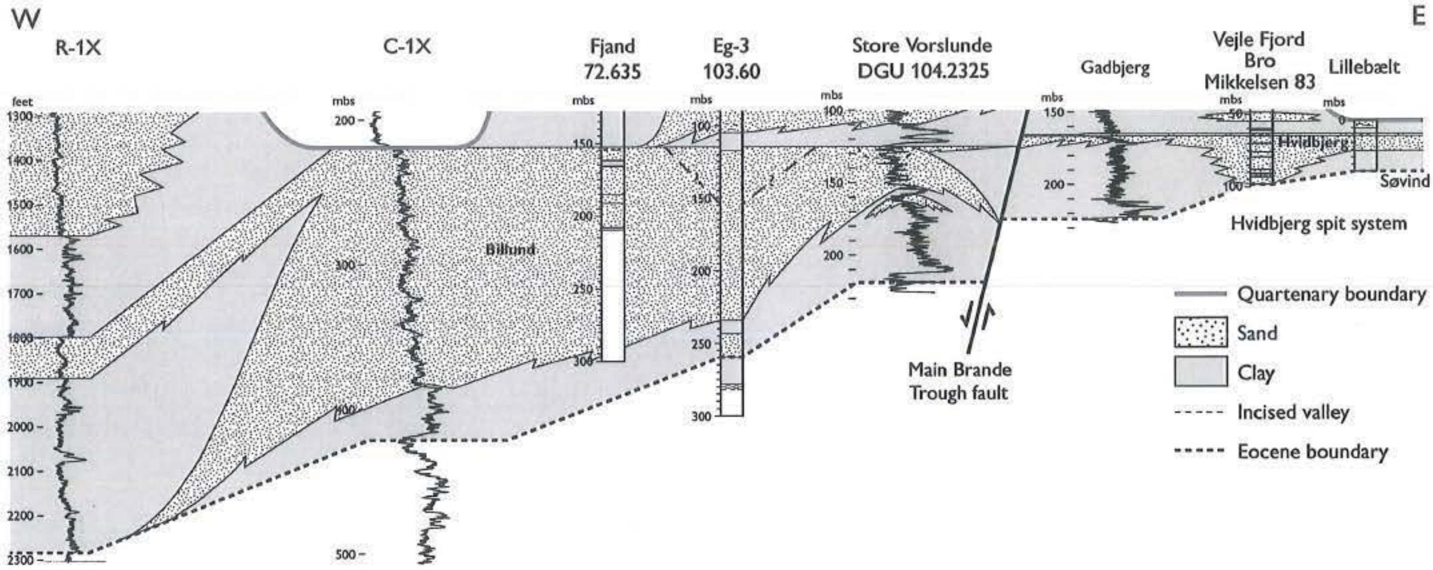

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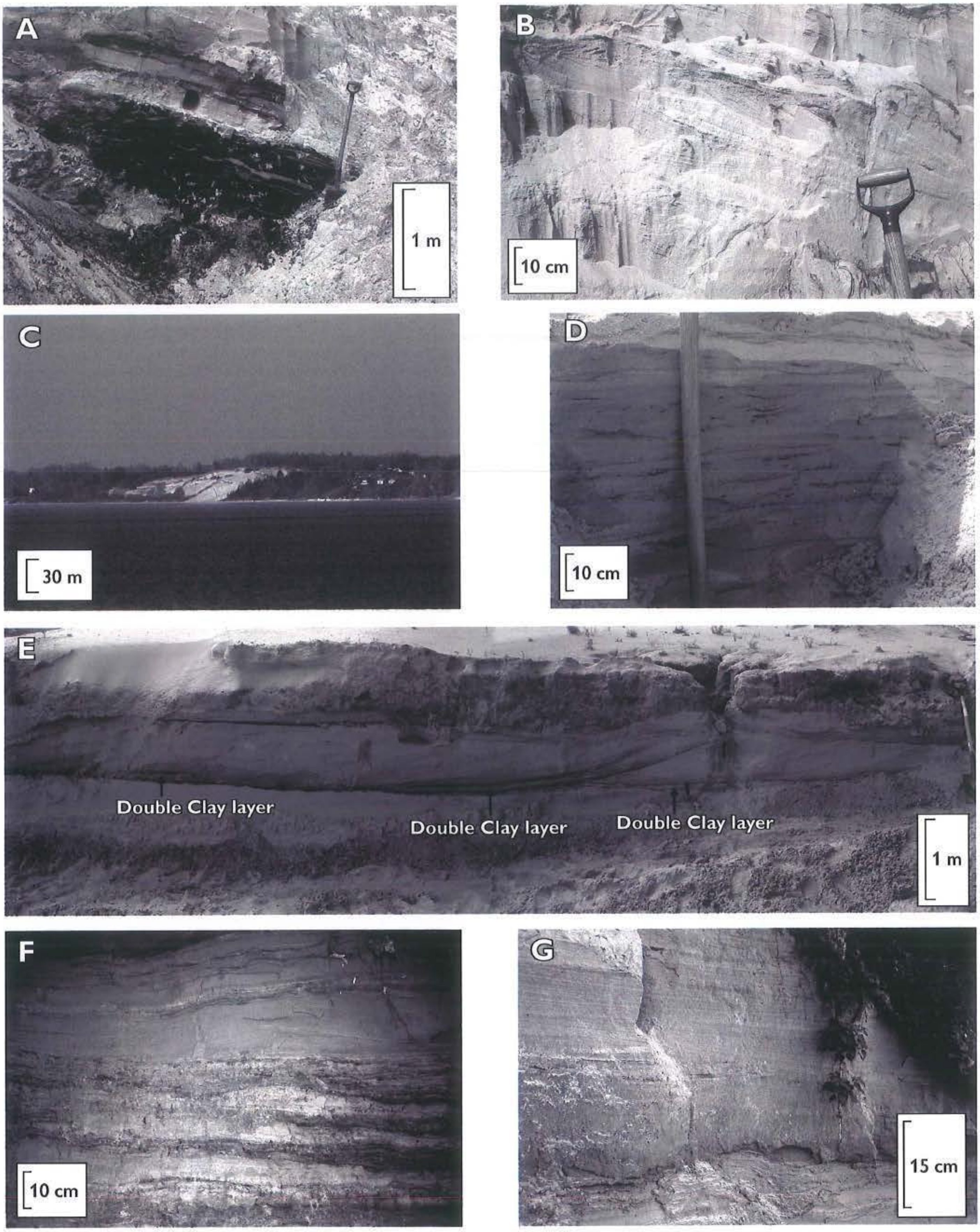

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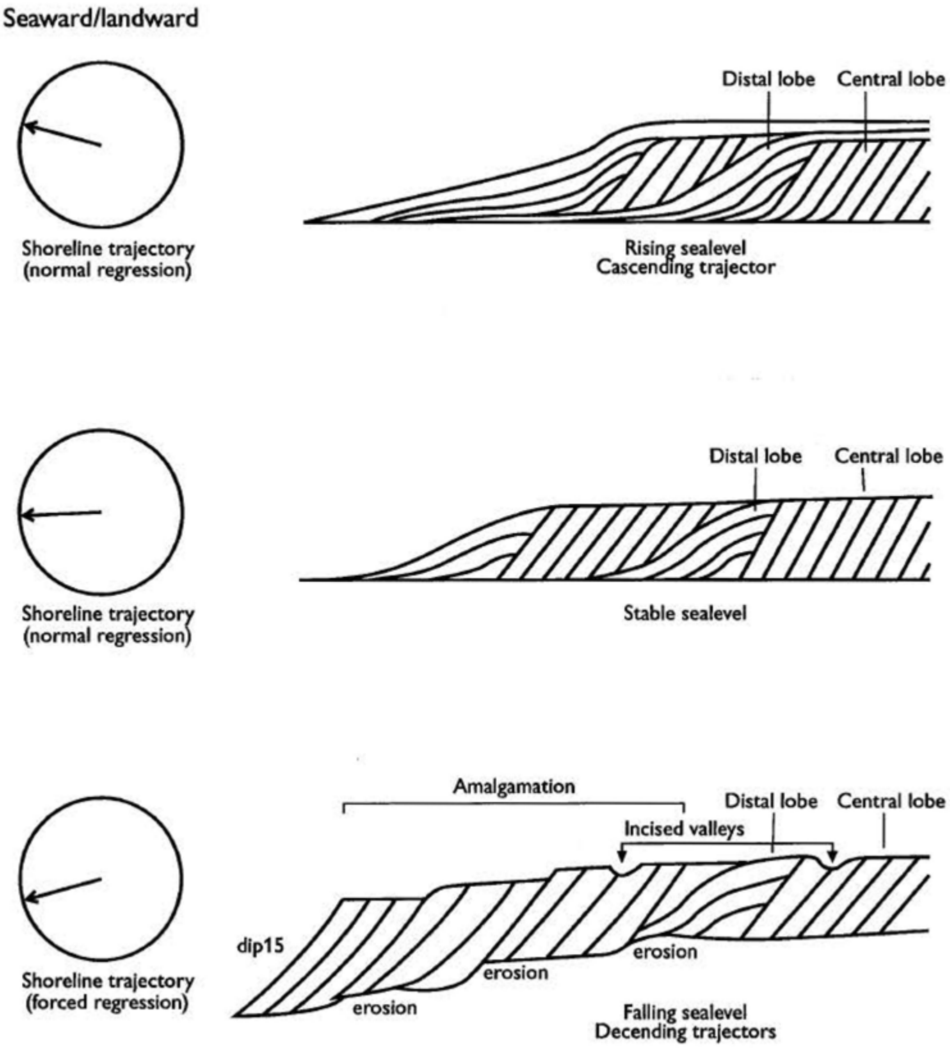

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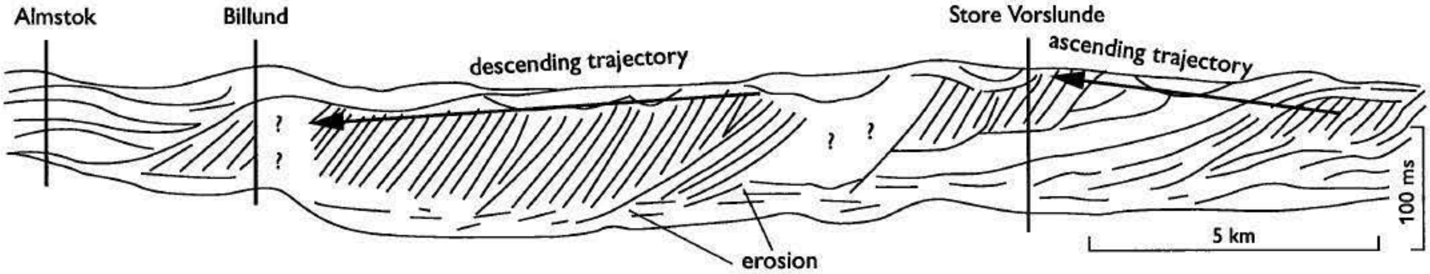

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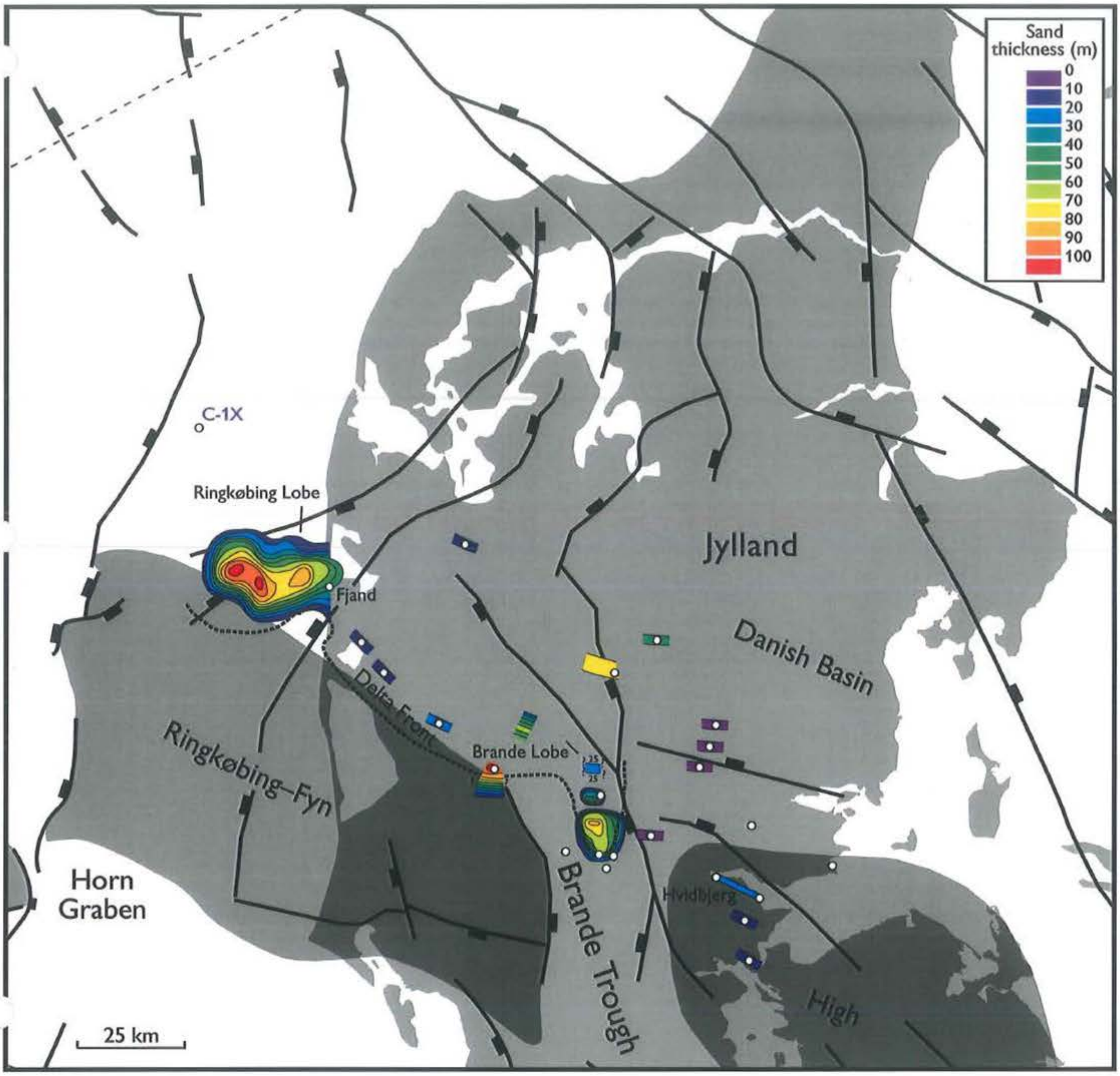

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Uppermost Oligocene – Miocene lithostratigraphy of Denmark

Forord

Denne raport er en afrapportering af det arbejde, der pågår med at definerer den Øverste Øvre Oligocæn – Miocæn litostratigrafi i Danmark. Der er nu defineret 5 formationer og 5 led. Disse enheder er markeret med fremhævet skrift i abstraktet nedenunder. Det er planen at de sidste enheder skal defineres i løbet af 2005

Preface

This part of the report is a preliminary report on the definitions of Uppermost Upper Oligocene – Miocene lithostratigraphic units in Denmark. So far 5 formations and 5 members have been defined. These units are indicated in bold in the abstract below. The work of defining lithostratigraphic units will continue in 2005.

Abstract

This paper provides an updated and revised lithostratigraphic scheme for the uppermost Upper Oligocene – Miocene succession in Denmark. The shallow marine and deltaic deposits of the Lower Miocene are subdivided into 6 formations. The Vejle Fjord Formation is revised and is subdivided into the Vejle Fjord Sand Member and Vejle Fjord Clay Member. The Brejning Clay Member is upgraded to Formation. The Klinting Hoved Formation is defined formally. The Ribe Formation is revised and includes now to new members; the Hvidbjerg Member and the Billund Member. The Arnum Formation is subdivided into three new Members the Vandel silt Member, Sdr, Vium Member and NN Member. The Odderup Formation includes the Stauning Member and the coal bearing Fasterholt Member. The fully marine Middle and Upper Miocene deposits is subdivided into the Hodde -, Gram - and Marbæk Formations. The Gram Formation also includes the Glaucony Clay Member.

Geological setting

The depositional basin of the eastern North Sea area covered by the present-day Denmark, was bounded towards the northeast by the Fennoscandian Shield (Bertelsen 1978; Vejbæk 1997)(Fig. 1). The transition to the basin was the southeast – northwest trending Sorgenfrei-Tornquist Zone. The basin was subdivided into two subbasins; the Norwegian-Danish Basin and the North German Basin with the east-southeast – west-northwest striking Ringkøbing-Fyn High separating the subbasins. The Ringkøbing-Fyn High is further segmentated into a number of north – south trending elements e.g. the Rødding Graben and Brande Trough. These structural element were formed during the Permian rift tectonics and later reactivated in the Jurassic and during the Late Cretaceous and Early Paleocene inversion tectonics (Ziegler 1991; Liboriusen et al. 1986; Mogensen and Jensen 1994). Reactivation of some of the older structures occurred in the Oligocene as well as in the Miocene (Rasmussen 2004a).

During the Paleogene fine-grained sediments of mainly deep marine origin were deposited in the basin (Heilmann-Clausen et al. 1985). A general sea-level lowstand and tectonic reorganisation during the Oligocene resulted in erosion or non-deposition in the area, especially in the central and southern part of the area. In the northern area prodeltaic wedges of the Viborg and Branden Formationens were laid down. In the latest part of the Oligocene resumed transgression resulted in the deposition of glaucony-rich clay (Fig. 2A). This was followed by deposition of deltaic and coastal-plain sand and clayey deposits in the Early Miocene (Fig. 2B – I). Three major progradation of the coastal plain occurred during the Early Miocene. The third and final progradation was characterised by extensive coal sedimentation (Fig. 2I). Upon the deposition of the dominantly terrestrial deposits of the Lower Miocene marine clayey sediments dominated the middle and Upper Miocene (Fig. 2K, L).

Late Pliocene – early Quaternary tilting of the whole eastern North Sea area (Japsen and Bidstrup 2000) combined with periodical growth of icecaps in the northern hemisphere resulted in strong erosion of the substratum

Lithostratigraphy

The former lithostratigraphic subdivision of the uppermost Oligocene – Miocene succession in Denmark was based on studies of outcrops, pits and in a few cases boreholes (Sorgenfrei 1958; Larsen and Dinesen 1959; Rasmussen 1956, 1961; Christensen and Ulleberg 1973; Koch 1989). The first overall lithostratigraphic scheme of the Miocene was constructed by Rasmussen (1961) later revisions of this scheme has been performed by Buchardt-Larsen & Heilmann-Clausen (1988) and Michelsen (1994). The new subdivision is based on the presents 25 new borehols (Fig. 3, 4, and 5), highresolution seismic data (Fig. 6) and the restudy of outcrops and pits in Jylland (Fig. 7). The correlation and dating of the succession is based on the principles of sequence stratigraphy and dinoflagelatte stratigraphy. This aloud a much more detailed and confident correlation of the succession.

Vejle Group

Brejning Formation (Fig. 9)

New Formation

History. This formation corresponds to the Brejning clay Member of the Vejle Fjord Formation of Larsen and Dinesen (1959).

Name. The formation is named the after town of Brejning at Vejle Fjord.

Type locality. The Formation is exposed at the sea bed in the eastern part of the Skansebakke Profile at Brejning. The section at Brejning was described by Larsen and Dinesen (1959). Other exposure of the formation is found at Sanatoriet, Fakkegrav, Juelsminde in the Vejle fjord area, Jensgård at the mouth of Horsens Fjord. Periodically the Formation crop out at Søvind, Sønder Vissing, and Ølst clay pit.

Thickness. The (-0,4 m - -4,65)

Lithology. The Brejning Formation consists of greenish to brown, glaucony-rich clay with scattered pebbles. In the upper part there is an increased content of organic matter and sand.

Boundaries. The Brejning Clay rest with a sharp and erosional boundary on the marly , Eocene søvind Marl Formation. The boundary is intensively bioturbated. The upper boundary is characterised by a distinct change in lithology from clay to gravel at most localities. However, the boundary may be more transitional, e.g. at the type locality, where the boundary towards the overlying Vejle Fjord Clay is recognised by the absence of glaucony.

Distribution. Same as the Vejle Group.

Geological age Late Oligocene, Chattian (Dybkjær and Rasmussen 2004).

Vejle Fjord Formation (Fig. 10)

Redefined

History. The Vejle Fjord Formation was defined by Larsen and Dinesen (1959). The formation was originally defined from the base of the Brejning Clay Member to the top of the Vejle Fjord Sand Member (Larsen and Dinesen 1959). For pratical reasons (see above) the Brejning Clay Member is excluded from the Vejle Fjord Formation.

Name. The Formation is named after Vejle Fjord in East Jylland.

Type locality. The cliff of Skansebakke at Brejning on the southern side of the Vejle Fjord

Thickness. The is 9 m at the type locality Skansebakke and 13 m a Dykjær. In boreholes up to 90 m has been penetrated e.g. at Stensig.

Lithology The formation consists of dark brown, cleyey silt with a high content of organic matter. Locally fine-grained, yellowish sand is intercalated in the formation.

Boundaries The lower boundary is often characterised by a gravel layer. It may also be marked by a marked decrease in the content of glaucony.

Distribution The formation is distributed most of central and southern Jylland.

Geological age Aquitanian (Dybkjær and Rasmussen 2000).

Subdivision The formation is subdivided into two members: The Vejle Fjord Clay Member and The Vejle Fjord Sand Member.

Vejle Fjord Clay Member (Fig. 10)
History. The Vejle Fjord Clay Member is defined by Larsen and Dinesen (1959).

Name. The named is after the two outcrops at Vejle Fjord: Skansebakke and Brejning Hoved.

Type locality. The Member is exposed at the type locality at Skansebakke, Brejning.

Thickness. The Vejle Fjord Clay is 6 m at Skansebakke, but the thickness is up to 31 m in the borehole of Remmerslund. The thickness of the Vejle Fjord Member is up to xx m in the Brande Trough.

Lithology. Brownish to black, micareous, silty clay with some fine-grained sand. Laterally it pass into a heterolitic tidal influenced sediments in the northeastern part and towards the southwest it pass into hommucky cross-stratified, fine-grained sand alternating with wave-influenced heterolithic beds.

Boundaries Same as the Vejle Fjord Formation.

Distribution The Vejle Fjord Clay Member is present in most Jylland and the north and eastern boundary follows the lower boundary of the Miocene deposits (Fig.)

Geological age. Aquitanian (Dybkjær and Rasmussen 2000; Karen Dybkjær..)

Vejle Fjord Sand Member (Fig. 10)
History. The Vejle Fjord Sand Member is defined by Larsen and Dinesen (1959).

Name. The named is after the two outcrops at Vejle Fjord: Skansebakke and Brejning Hoved.

Type locality. The Member is exposed at Skansebakke, Brejning Hoved, and Sanatoriet.

Thickness. The thickness at Skansebakke is 17 m, Brejning Hoved ca. 12 m and at Sanatoriet 7 m.

Lithology. The Vejle Fjord Sand consists of alternating layers of fine-grained, velsorted, yellowish sand and brownish clay.

Boundaries. The formation overlies the Vejle Fjord Clay Member and the boundary is placed where the first occurrence of an extensive sand layer occurs. The upper boundary is characterised by a change from yellowish sand alternating with thin silt layers to clean white sand of the Hvidbjerg member.

Distribution. The Vejle Fjord Sand Member is present along the coast of Vejle Fjord and has been penetrated by the Morsholt borehole south of Odder.

Geological age. Aquitanian (Dybkjær and Rasmussen 2000; Karen Dybkjær pers. Comm.)

Ribe Formation

Hvidbjerg Sand Member (Fig. 11)

New Member

History. The white sand at Hvidbjerg was studied by Larsen and Dinesen (1959). The Hvidbjerg Sand was not included in the Vejle Fjord Formation due to a different heavy mineral association.

Name. The Hvidbjerg Sand Member is named after the Outcrop at Hvidbjerg Strand on the south coast of Vejle Fjord.

Type locality. The Formation is exposed at Hvidbjerg on the south coast of the Vejle Fjord. Other exposures in the Vejle Fjord area are the Sanatoriet, Fakkegrav, and Dykær. At Pjedsted west of Fredericia. In the Lillebælt area at Hindsgavl, Børup and Rønshoved. The sand crops out at one locality in the Limfjord area at Søndbjerg.

Thickness. The Thickness is 24 m at Hvidbjerg. In the Lillebælt area it reaches 13 m but at most outcrops it is rarely thicker than 6 m.

Lithology. The Hvidbjerg Sand consists of white, fine- to medium grained sand with a few pebble lags. Thin light brown clay layers occur locally. Deposition took place in storm dominated shoreface environment, at Hvidbjerg as a part of a spit system.

Boundaries. The formation overlies the Vejle Fjord Clay Member and is marked by a change from black, organic-rich clayey silt to white sand. At Hvidbjerg the lower boundary is erosive. The upper boundary is erosive and normally overlain by a gravel layer

Distribution. The member is present in east Jylland and has been found at Søndbjerg in north-west Jylland. The member probably has a patchy distribution along a NW-SE trend across Jylland.

Geological age. Aquitanian (Dybkjær and Rasmussen 2000; Karen Dybkjær pers. Comm.)

Billund Member (Fig. 12)
New Member

Name. The Billund Member is named after sand-rich deposits found in boreholes in the area around the town of Billund.

Type locality. The Formation was penetrated in the borehole DGU 115.1371 at Vandel Mark where 28 m of sand were encountered from 203 m to 231 m.

Thickness. The thickness of the Billund Member is 28 m in the Vandel Mark borehole. In the borehole, DGU 114.1857 drilled at Billund, the thickness is 50 m and the maximum thickness of 70 m has been found in the Isenvad borehole DGU 86.2056.

Lithology The member composed of Fine-grained sand and medium- to coarse-grained sand. Pebbely horisons are common in the upperpart. The fine-grained sand occurs in the lower part of the member or in distal lobes. The sand was deposited in a wave-dominated delta and delta slope environment.

Boundaries The lower boundary is defined were a changes from clayey, organic-rich silt sediments of the Vejle Fjord Clay Member is superimposed by sand. Locally, e.g. at Billund the sand is overlying Eocene Søvind Marl.

Distribution The Billund Member is distributed in central Jylland and northwestwards into the North Sea just west of Ringkøbing.

Geological age The Billund Member is of Aquitanian in age (Dybkjær pers. Comm.).

Klintinghoved Formation

History. The Klintinghoved Formation was included in the stratigraphic of Rasmussen 1961. However, the formation has never been defined formally. Sorgenfrei (1940) described the molluscan fauna of the Klintinghoved Clay and breifly mentioned the Klintinghoved Formationen in the a later publication (Sorgenfrei 1958).

Arnum Group

Kolding Fjord Formation (Fig. 13)

History. Sand and organic-rich clayey sediments exposed at Lillebælt was studied by Radwanski et al. 1975, Rasmussen 1995 and Friss et al. 1998. These studies inferred that the sediments were a part of the Vejle Fjord Formation. However, a biostratigraphic study by Dybkjær and Rasmussen 2000, revealed that the sediments were significantly younger than the Velje Fjord Formation and of same age as the Arnum Formation (Rasmussen 1966; Piasecki 1980).

Name. The Kolding Fjord Formation is outcropping at a number of localities: Rønshoved, Hagenør, Børup and Galsklint in the Lillebælt and Kolding Fjord area.

Type locality. The Formation is exposed at Rønshoved on the south side of Kolding Fjord.

Thickness. The Formation is 12 m thick at Rønshoved and 8 m at Hagenør.

Lithology. The formation composed of white to yellow, fine- to medium-grained sand with a few thin, brown clay layers. The basal part of the Formation consists of a gravel layer up to 1 m thick.

Boundaries The lower boundary is erosive and characterised by a distinct changes from sand deposits of the Ribe Formation (Billund and Hvidbjerg Members).

Distribution The formation is found in east and central Jylland.

Geological age The formation is of early Burdigalian in age (Dybkjær and Rasmussen 2000).

Subdivision Hagenør member.

Vandel Member (Fig. 14)

New member
History.

Name. The member is named after the Village of Vandel east of Billund.

Type borehole. The Vandel Mark (DGU 115,1371) where it was penetrated at 111 -96 m.

Thickness. The thickness rarely exceeds 15 m as was the case at the type boring Vandel Mark.

Lithology. The member composed of grey to white silt, with a high content of heavy minerals.It might contain clasts of reworked redish Eocene clay.

Fossils. No fossils

Boundaries The lower boundary is defined by a sharp transition from grey sand to grey to white silt.

Distribution The member is distributed in central Jylland with maximum thickness around the Billund area.

Geological age Late Burdigalian is suggested as it is intercalated in the Lower Arnum Formation.

Bastrup Formation (Fig. 15)

New formation

Name. The formation is named after the village of Bastrup south of Vamdrup.

Type section. The borehole DGU 133.1298, Bastrup, 84-110 m below surface.

Thickness. The thickness is 26 m in the Bastrup borehole, but has a maximum thickness of 44 meter in St. Vorslunde borehole (104.2325).

Lithology. The Formation consists predominantly of grey, medium- to coarse-grained sand with intercalated gravel layers. Locally dark brown, organic-rich silty mud is present. Deposition took place in fluvial and deltaic environments. The intercalated mud represents floodplain deposition.

Boundaries. The lower boundary is either sharp e.g. at Bastrup or gradational as in the Almstok borehole (Fig.). In the Bastrup borehole, the lower boundary is placed where grey mud is sharply overlain by grey medium-grained sand. In boreholes where a more gradational development occurs, the boundary is marked by the change from alternating sand and mud layers to clean sand. A gravel layer is also common at the base of the Bastrup member. In the Bastrup borehole the lower boundary is characterised by a distinct decrease in gamma log response. In other boreholes the lower boundary may be represented by a minor decrease in gamma log response followed by a consistent decrease in gamma log response upwards.

Distribution. The formation is present in southern and central Jylland. Towards the north-east the formation is truncated and it pinches out towards the south-west.

Geological age Early to late Burdigalian (Dybkjær pers. Comm.)

Odderup Formation

Stauning Member

History. The Stauning Member was recognised as fine-grained sand layers with a high content of heavy minerals interbedded in the Arnum Formation in a number of boreholes in south and central Jylland (Knudsen 1998). On gamma logs the sand beds are characterised by extreme high gamma log readings. Exploitation for these sands with heavy minerals was intensive during the last part of the decay of 1990 in the Stauning area.

Name. The Stauning Member is named after village of Stauning, were the member is subcropping Quaternary deposits.

Type borehole. A complete succession of the Stauning Member is penetrated in the borehole DGU 115.1371 at Vandel Mark.

Thickness. The thickness is up to 37 m.

Lithology. The member is characterised by grey to blackish, fine-grained sand occasionally with a very high content of heavy minerals. Medium-grained to pebbly sand may occur, especially in central Jylland.

Boundaries. The lower boundary is defined at the base of the first significant fine-grained sand layer with a high content of heavy minerals.

Distribution. The Stauning Member is found in southern, central en western Jylland.

Geological age Early Miocene, Burdigalian (pers. Comm. Stefan Piasecki).

Måde Group

Hodde Formation (Fig. 16)

History. The Hodde Formation was defined by Rasmussen 1961).

Name. The formation is named after the village of Hodde where the formation was shortly exposed in connection with the construction of Karlsgårde Channel.

Type locality. The formation is exposed at Lille Spåbæk near Ørnhøj, south of Holstebro.

Thickness. The formation is 9.6 m (13.8 – 23.4 m) in the Hodde-1 borehole (DGU 113.33).

Lithology. The formation consists of darkbrown, organic-rich silty clay with thin sand linses. The basal part of the Formation composed of a thin gravel layer. In the upper part of the formation laminated silty clay are common and glaucony may occur.

Boundaries. The lower boundary is sharp and defined by a gravel layer overlying the sandy deposits of the Odderup Formation.

Distribution. The HoddeFormation is distributed in southern and western Jylland. The Formation is locally distributed as far east as Bording and Give in central Jylland in depressions associated with salt structures.

Geological age Serravalian (Piasecki 1980; 2003)

Gram Formation (Fig. 17)

redefined

History. The Gram Formation is defined by Rasmussen (1956). In the original definition of the Gram Formation the formation includes three members: The Glauconite Clay, the Gram Clay and the Gram Sand.

Name. The Gram Formation is named after the town of Gram.

Type locality. The Formation is exposed at the old pit of Gram brickwork, currently the Midtsønderjyllands Museum of Gram.

Thickness. The thickness is c. 25 m but in the borehole of Tinglev (DGU 168.1378) 119 m was penetrated (Piasecki 2001).

Lithology. The Gram Formation consists of darkbrown clay. The lower part of the Formation is greenish due to high content of Glaucony. In the upper part a few fine-grained sand layers are intercalated in the formation. Siderite concretions are common at some levels.

Boundaries. The Lower boundary is defined by the change from dark to blackish silty clay somtines laminated clay of the Hodde Formation to Greenish darkbrown clay with a high content of Glaucony.

Distribution. The Gram Formation is distributed in southern and western Jylland. The Formation is locally distributed as far east as Bording and Give in central Jylland in depressions associated with salt structures.

Geological age. The Gram Formation is of Serravallian to Tortonian in age (Piasecki 1980; Piasecki et al. 2001, 2003).

Subdivision. The Gram Formation includes the Glaucony Clay Member which forms the lower part of the Formation.

Glaucony Clay Member

Marbæk Formation (Fig. 18)

History. Sands outcropping at Marbæk Cliff and Sjælborg, north of Esbjerg and sandy sediments in the upper part of the Sæd borehole (DGU x) have with some uncertainty been referred to be of Pliocene in age (Jørgensen 1945). New studies of these sections (Piasecki 2003) however, indicate that these deposits are of Tortonian in age.

Name. The Formation is named after the coastal clliff at Marbæk, northwest of Esbjerg.

Type locality. The Formation is exposed at Marbæk Cliff.

Thickness. The Marbæk Formation is 16 m thick. At Gram Brickwork pit 1.5 m of the formation is exposed at the bank of the brook.

Lithology. The formation consists of white and reddish fine- to medium-grained sand with few intercalations of thin coarse-grained sand or gravel layers. The sand shows parallel lamination with subordinate cross-bedding and hummocky cross-stratified beds are common. Double clay layers may occur.

Boundaries. The lower boundary is defined where alternating thin clay and sand layers of the Gram Formation is overtaken by amalgamated sandbeds.

Distribution. The formation is distributed in southwestern Jylland.

Geological age. The Marbæk Formation is of Tortonian in age (Piasecki 2003)

Summary and conclusion

Based on the above a new lithostratigraphic scheme has been constructed (Fig. 19). The uppermost Upper Oligocene – Miocene succession is subdivided into 9 formations which includes both the marine and terrestrial deposits.

The shallow marine and deltaic deposits of the Lower Miocene are subdivided into 6 formations. The Vejle Fjord Formation is revised and is subdivided into the Vejle Fjord Sand Member and Vejle Fjord Clay Member. The Brejning Clay Member is upgraded to Formation. The Klinting Hoved Formation is defined formally. The Ribe Formation is revised and includes now to new members; the Hvidbjerg Member and the Billund Member. The Arnum

Formation is subdivided into three new Members the Vandel silt Member, Sdr, Vium Member and NN Member. The Odderup Formation includes the Stauning Member and the coal bearing Fasterholt Member. The fully marine Middle and Upper Miocene deposits is subdivided into the Hodde -, Gram – and Marbæk Formation. The Gram Formation also includes the Glaucony Clay Member.

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List of figures

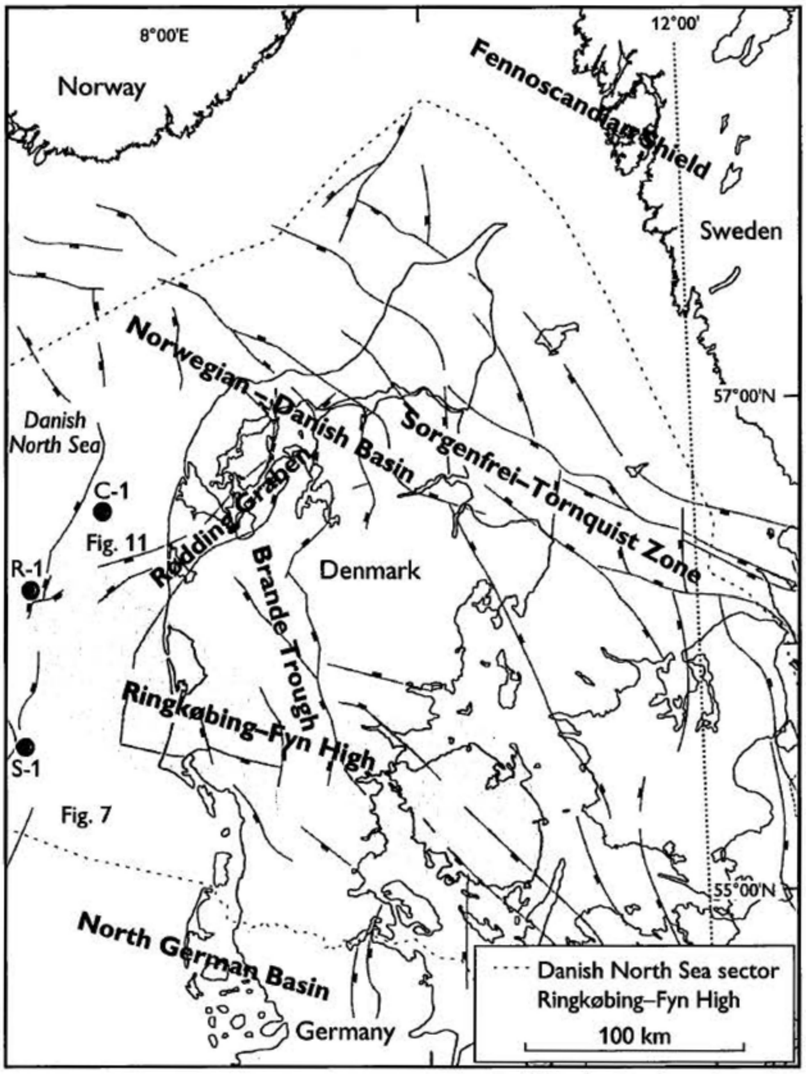

Fig. 1: Structural elements in the Danish area (Modified from Vejbæk 1997).

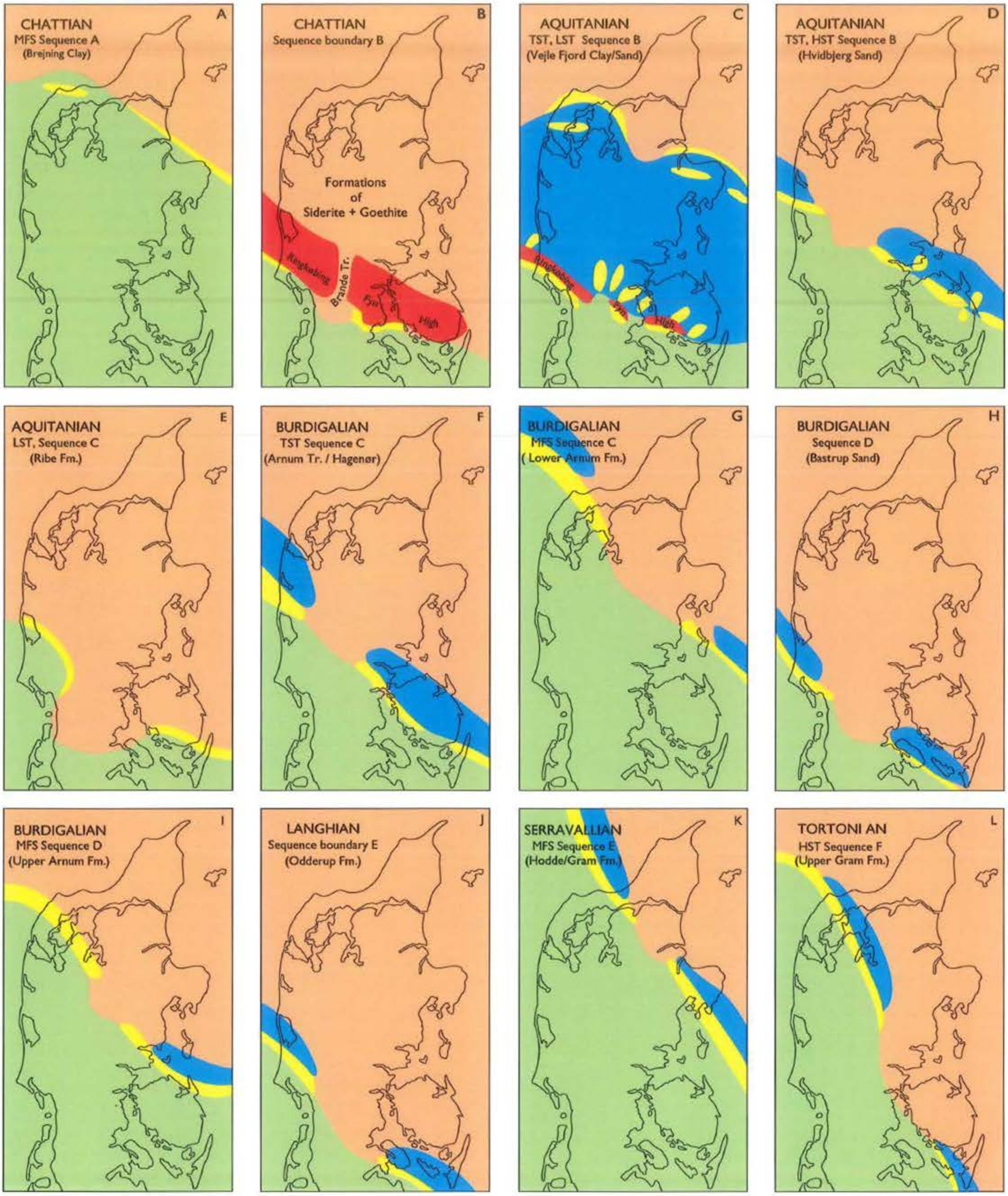

Fig. 2: Palaeogeographic reconstruction of the depositional environments during the latest Late Oligocene – Miocenen times (Modified from Rasmussen 2004).

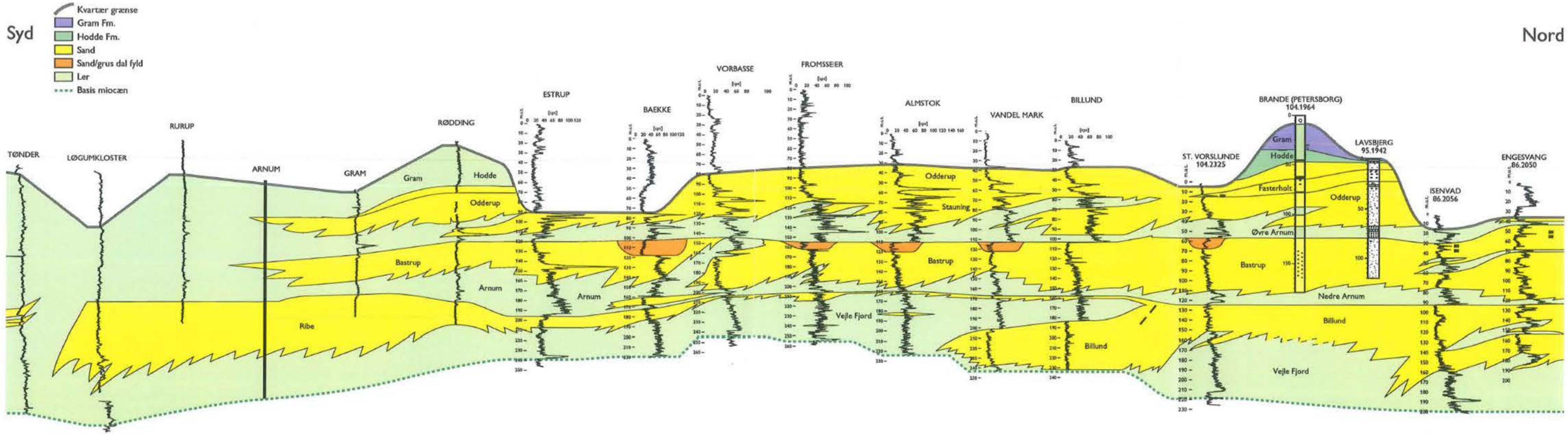

Fig. 3: North – south striking correlation panel of boreholes in central Jylland.

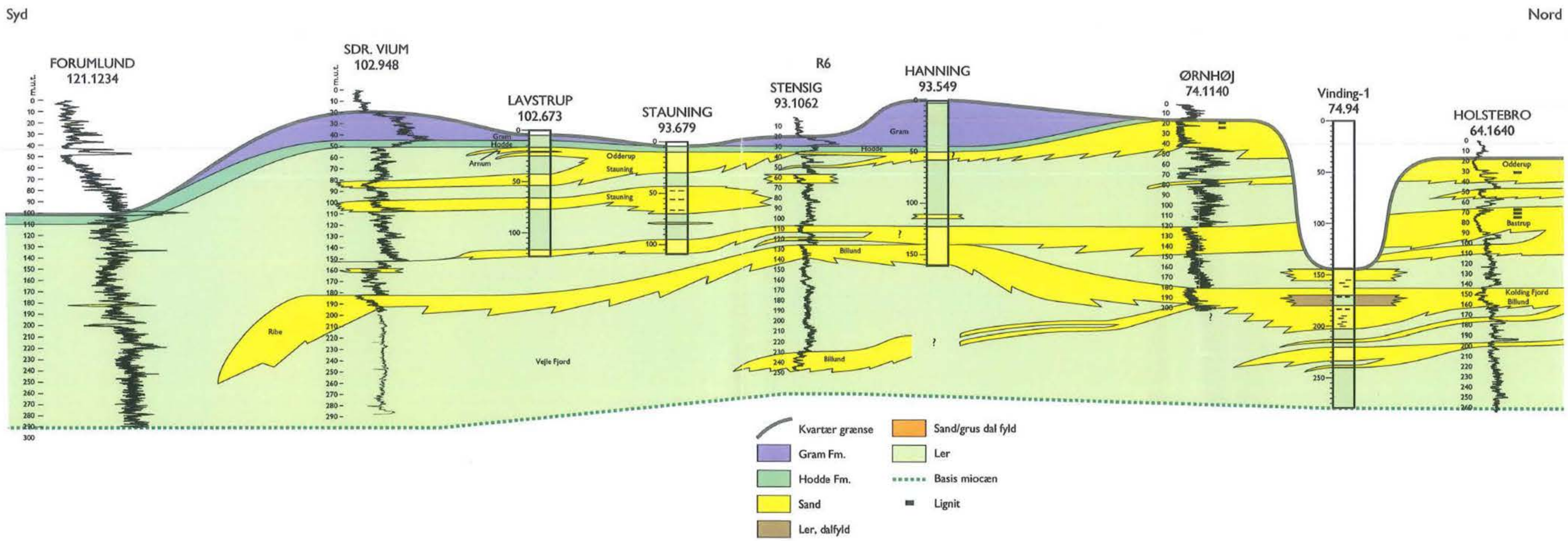

Fig 4: North – south striking correlation panel of boreholes in western Jylland.

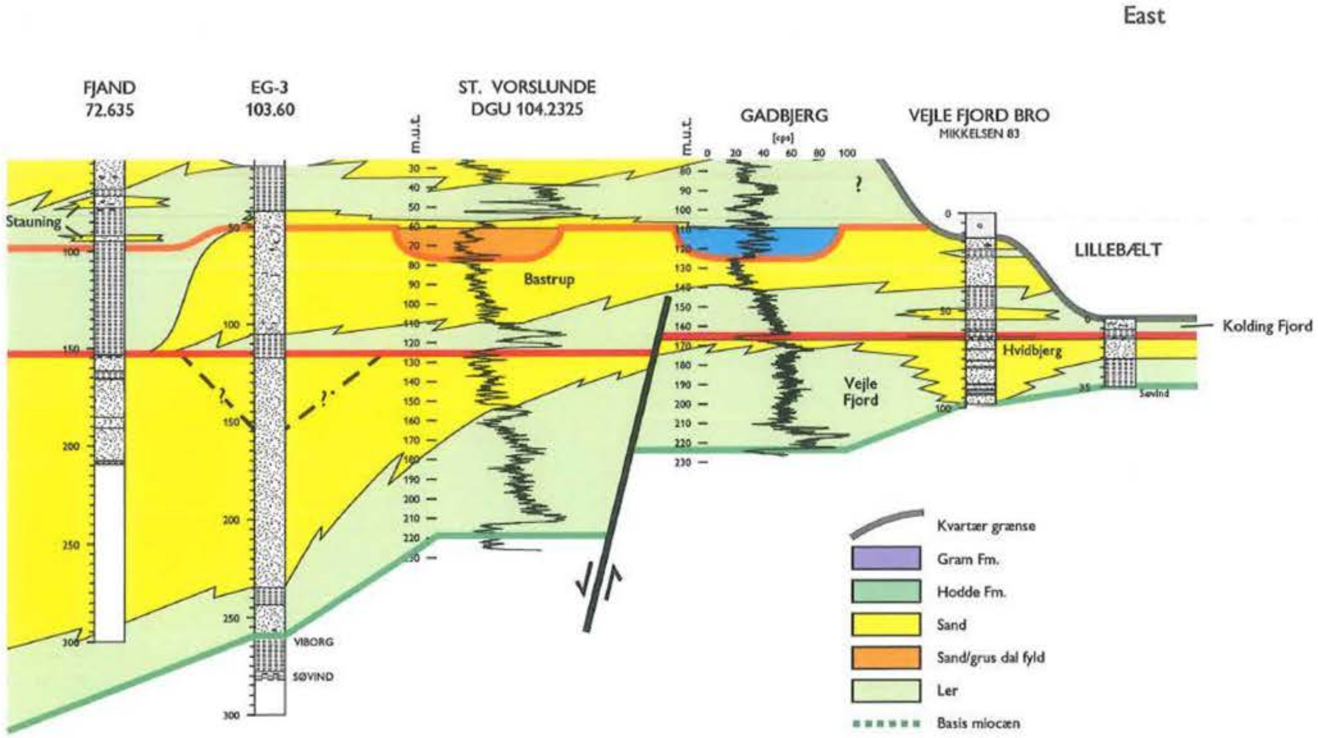

Fig. 5: East - west striking correlation panel of boreholes in central Jylland.

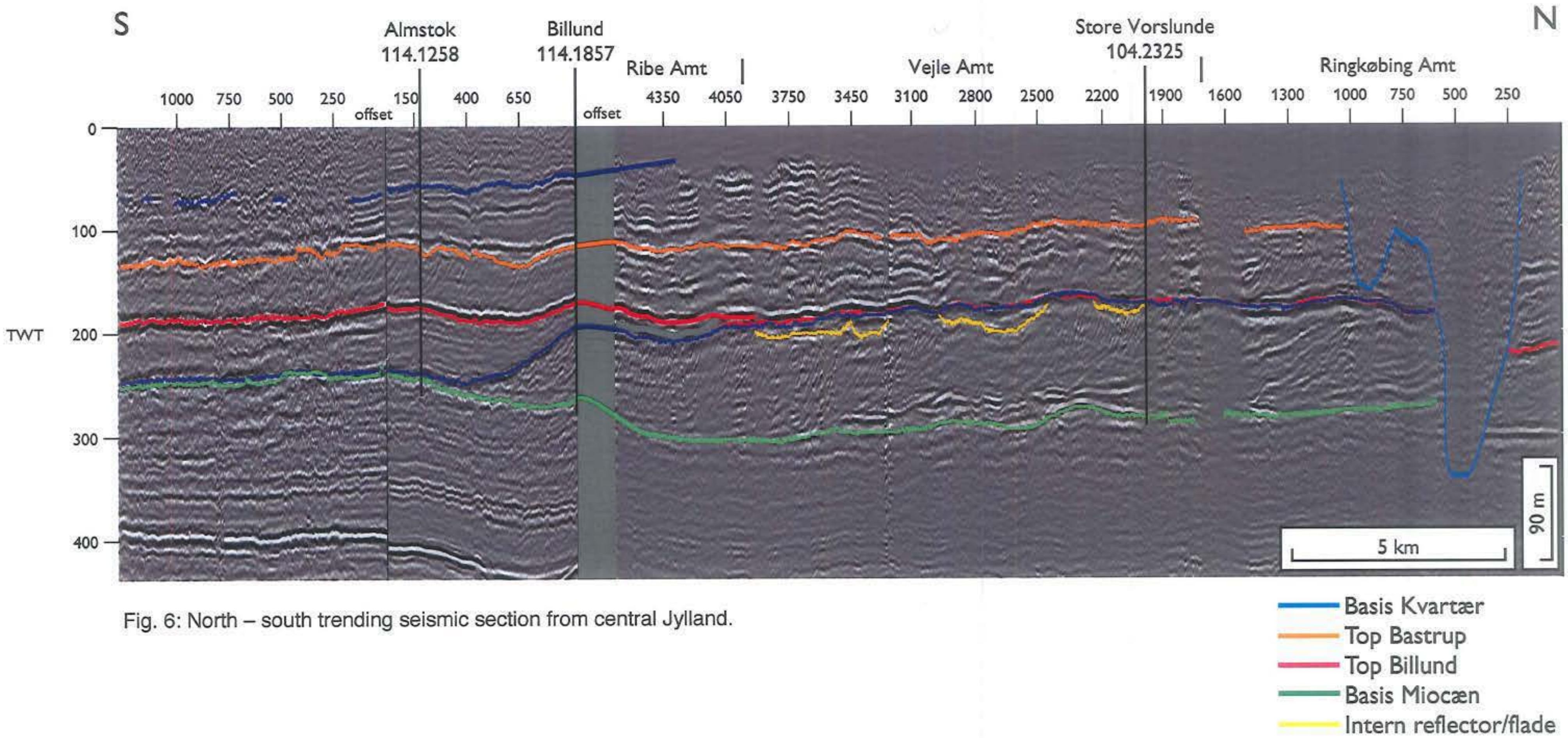

Fig. 6: North – south trending seismic section from central Jylland.

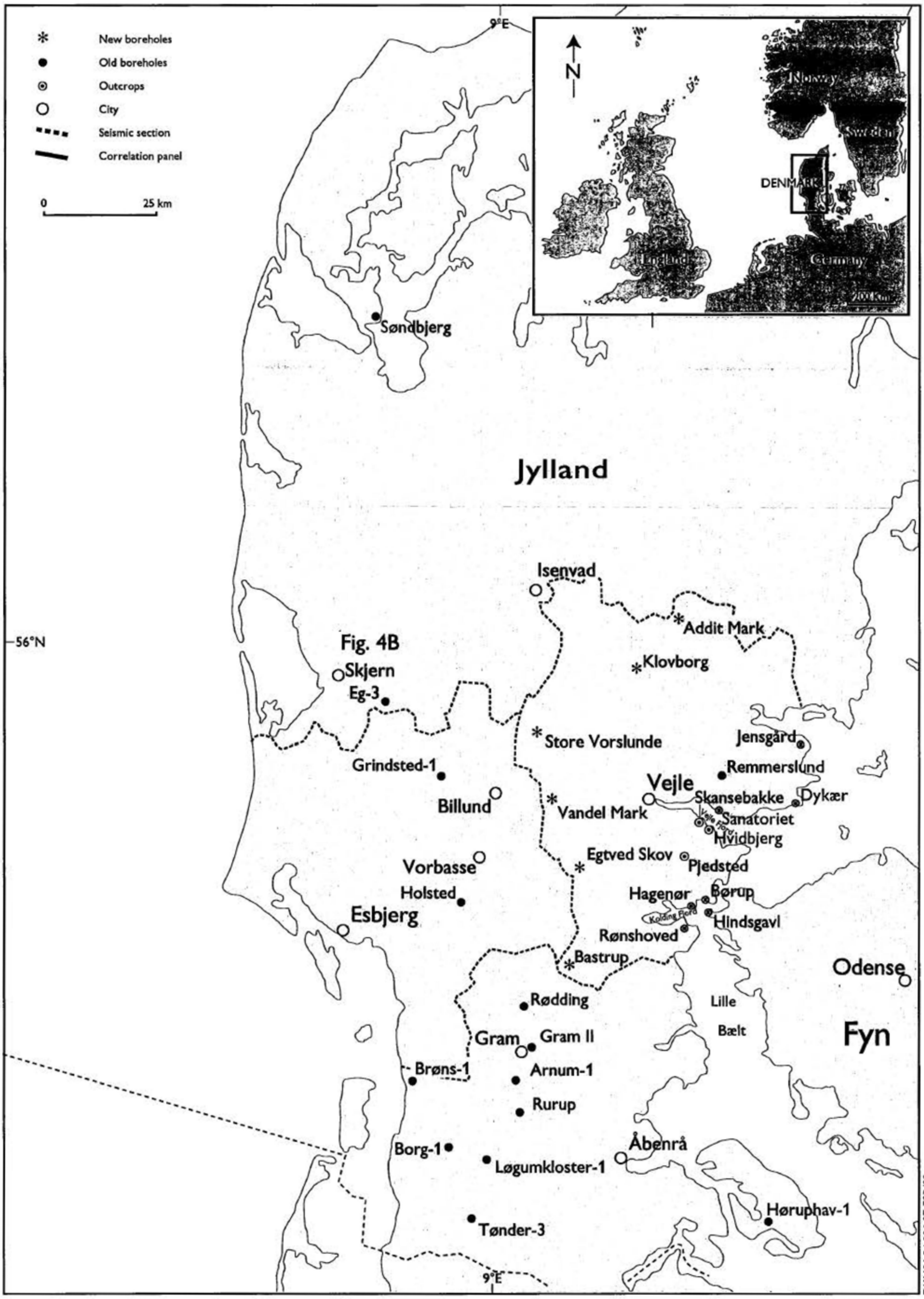

Fig. 7: Outcrops and boreholes used in the study.

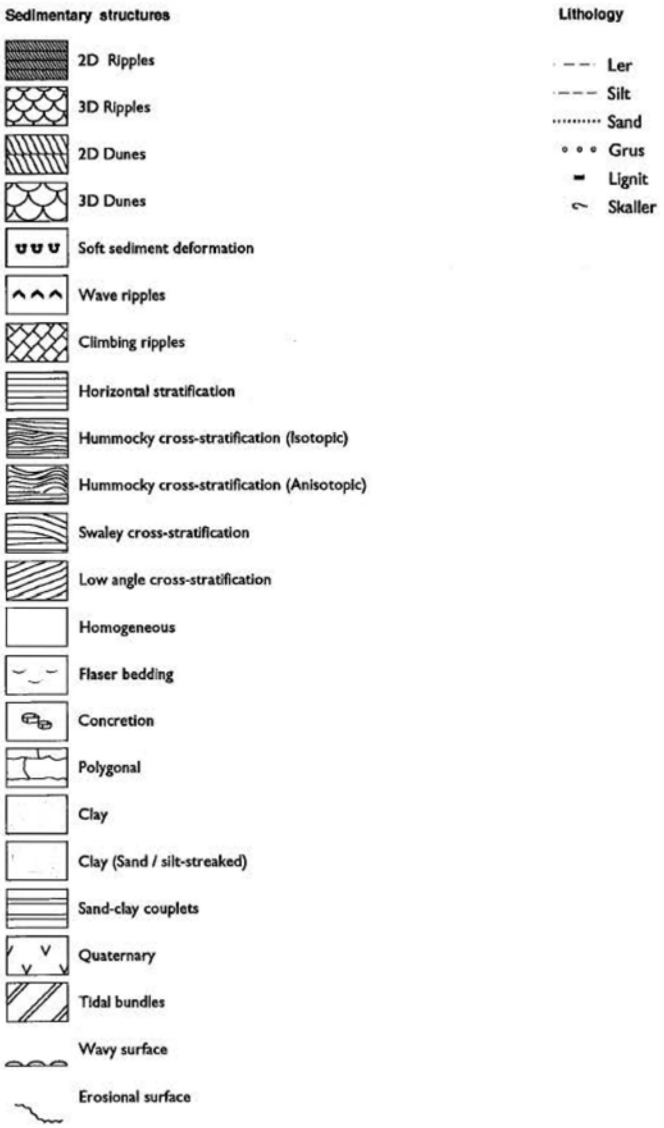

Fig. 8: Legend for the type sections shown in the report.

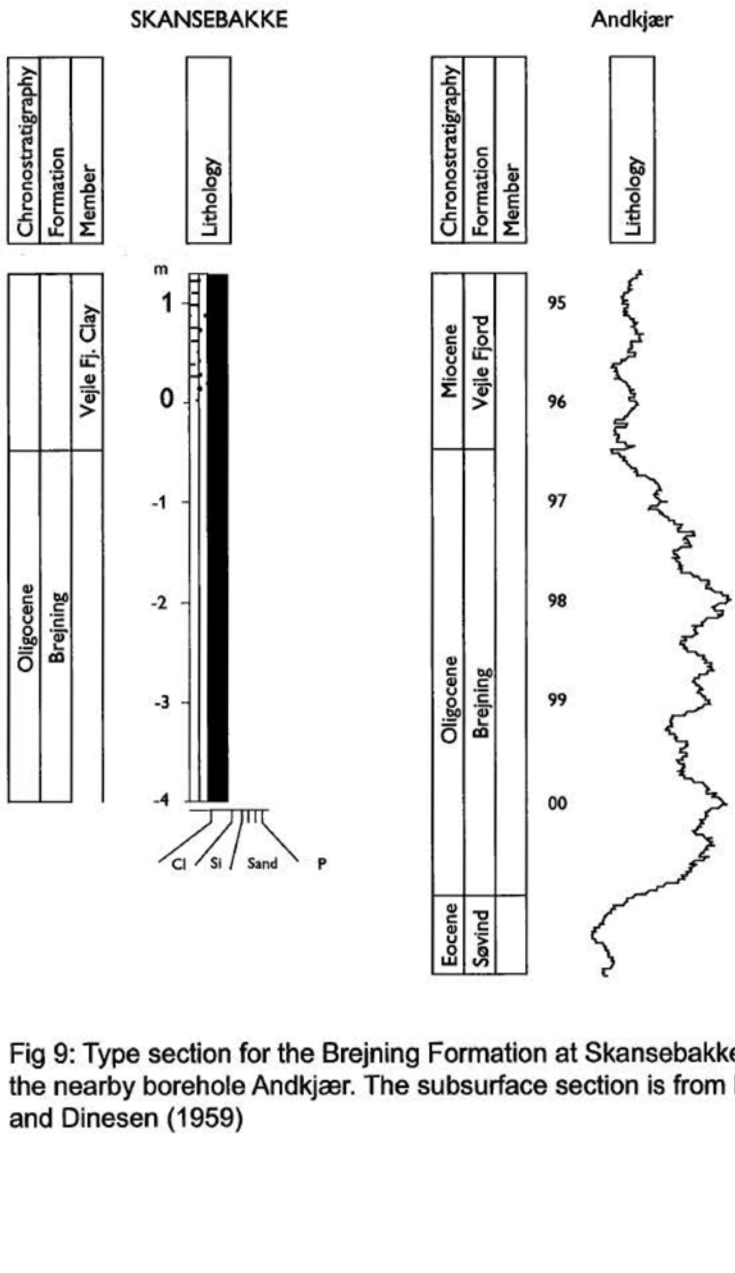

Fig 9: Type section for the Brejning Formation at Skansebakke and the nearby borehole Andkjær. The subsurface section is from Larsen and Dinesen (1959)

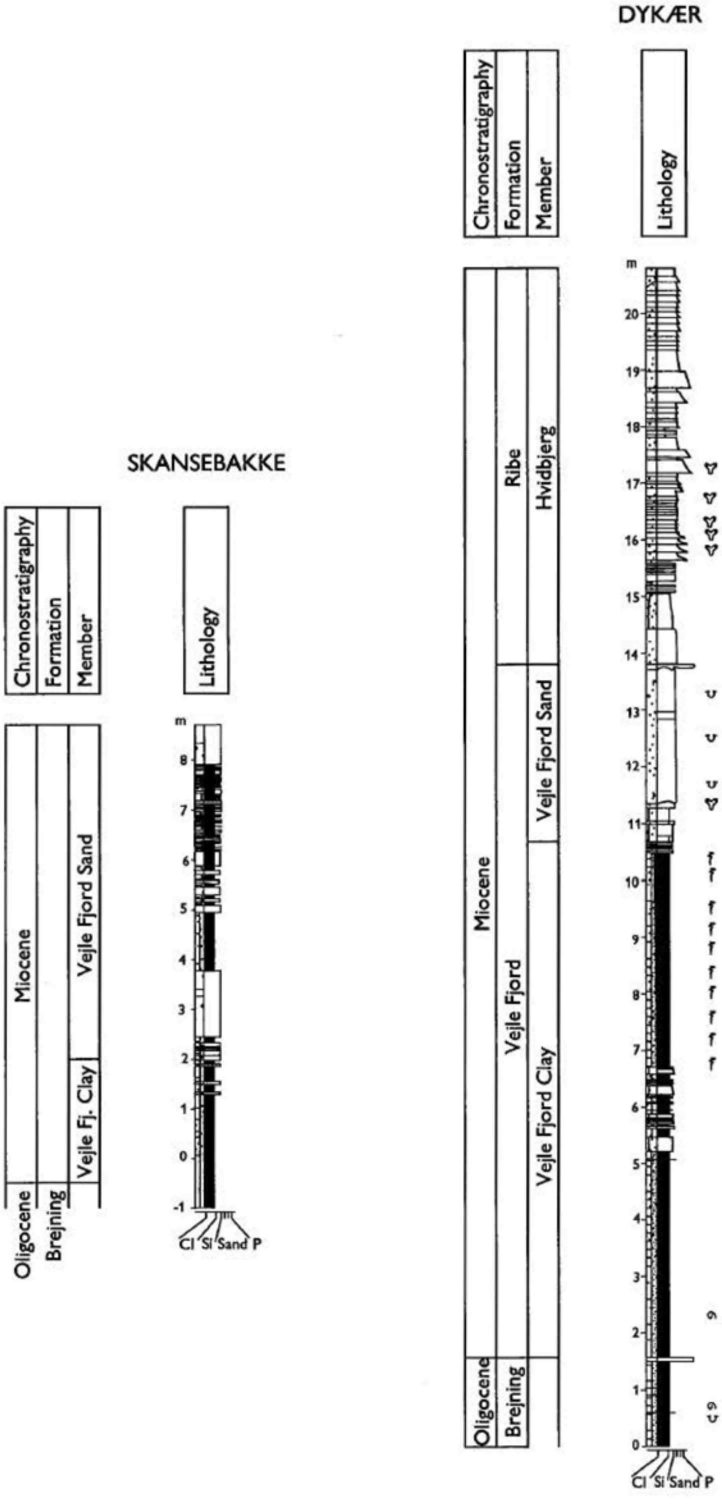

Fig. 10: Type section for the Vejle Fjord Clay Member and the Vejle Fjord Sand Member at the type lopcality of Skansebakke and Dykær.

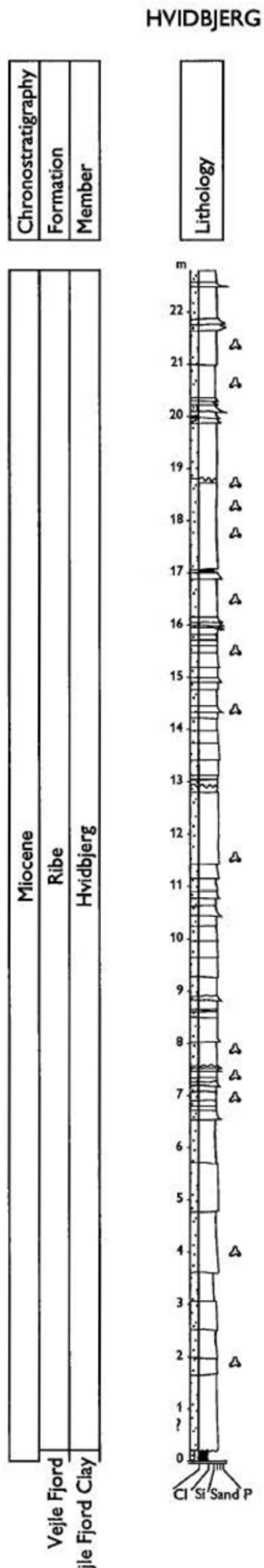

Fig. 11: Type section of the Hvidbjerg Member at Hvidbjerg.

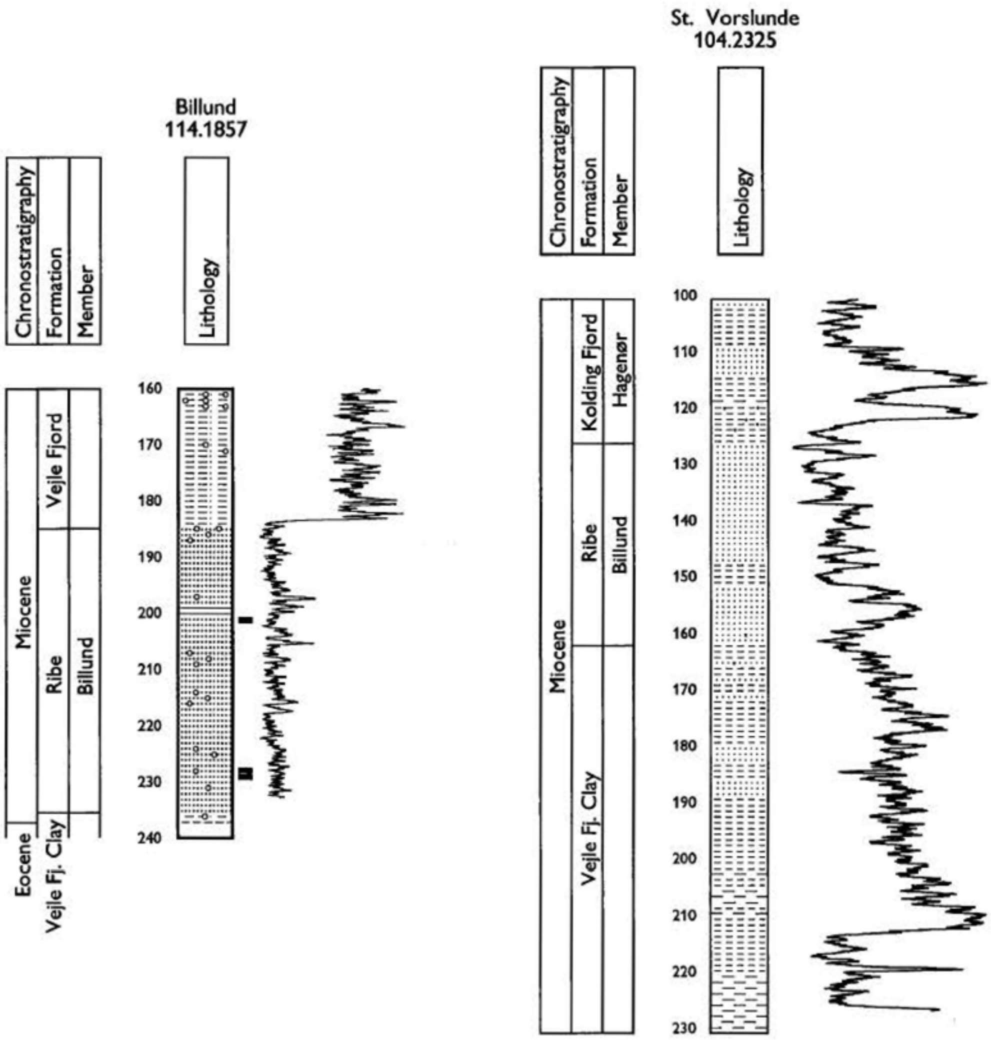

Fig. 12: Refecence section for the Billund Member in the Billund and Store Vorslunde boreholes.

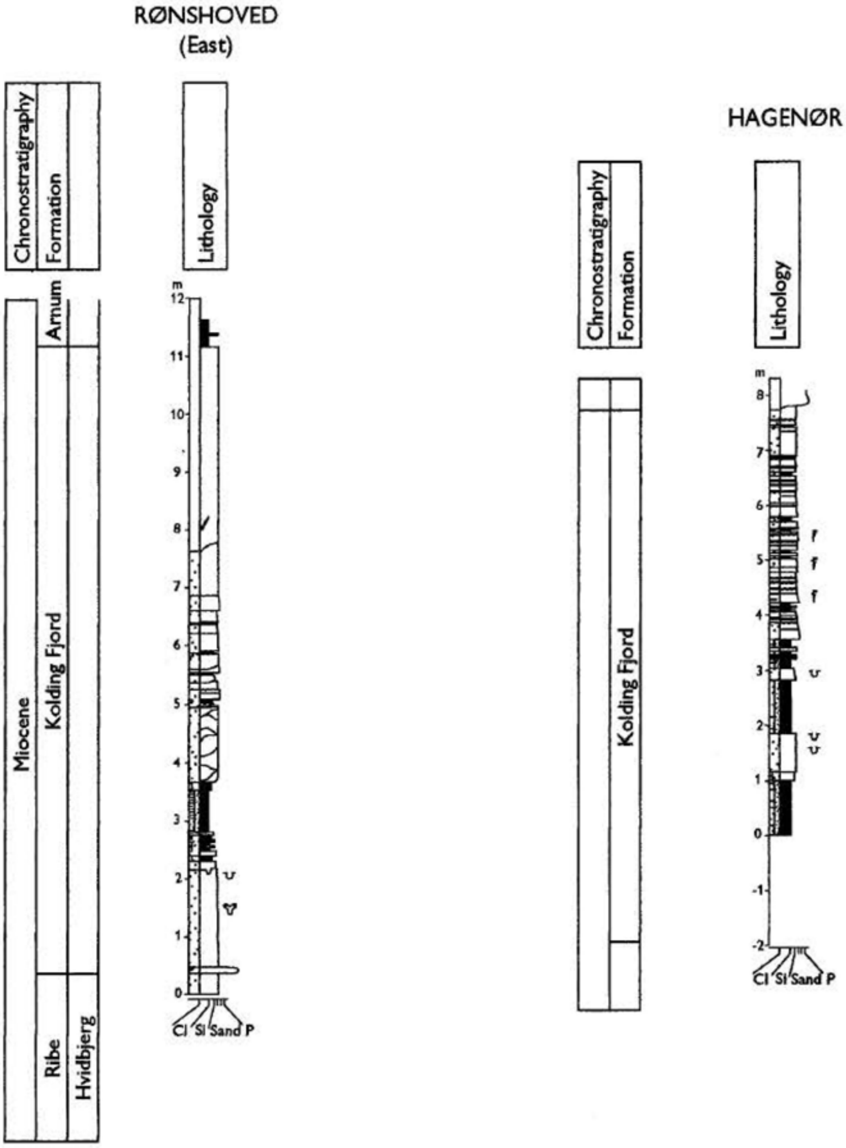

Fig. 13: Type section for the Kolding Fjord Formation at Rønshoved and Hagenør.

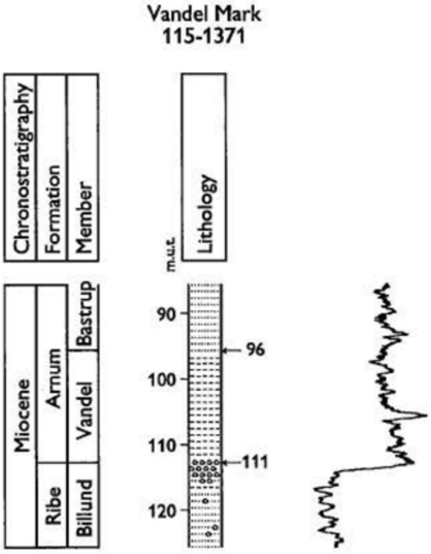

Fig. 14: Reference section for the Vandel Member in the Vandel Mark borehole.

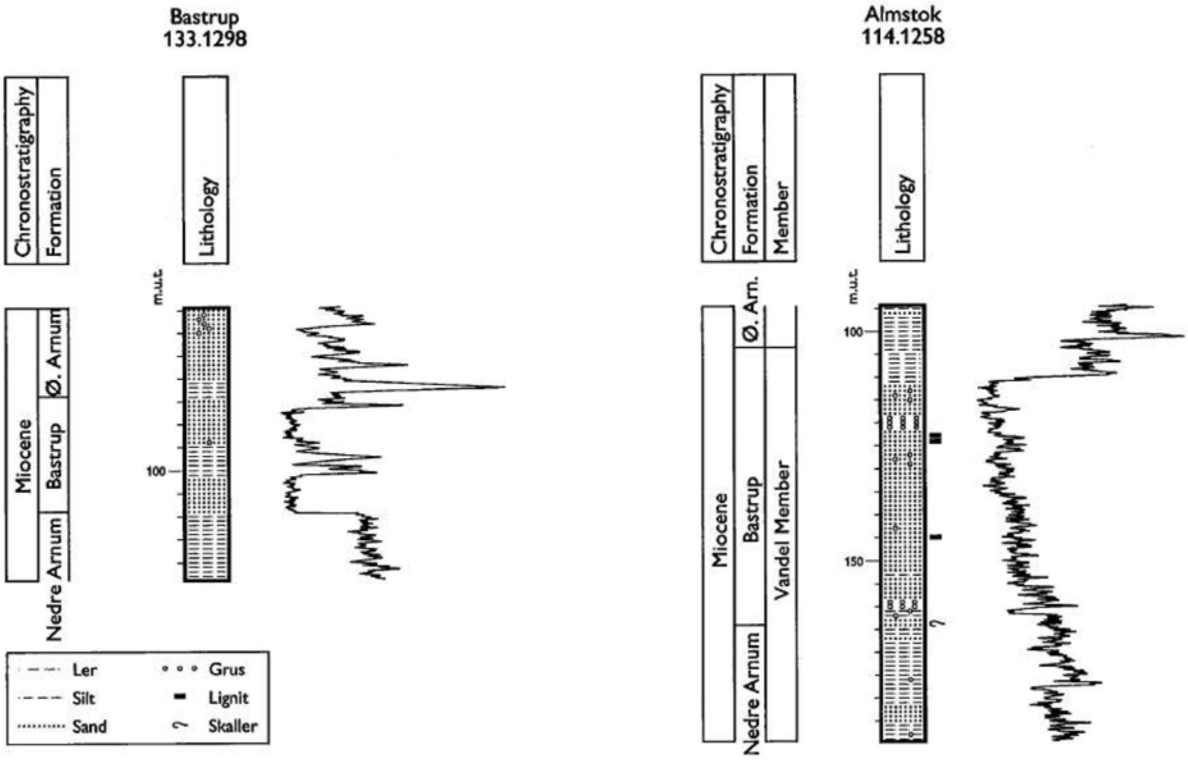

Fig. 15: Reference section for the Bastrup Formation in the Bastrup and Almstok boreholes.

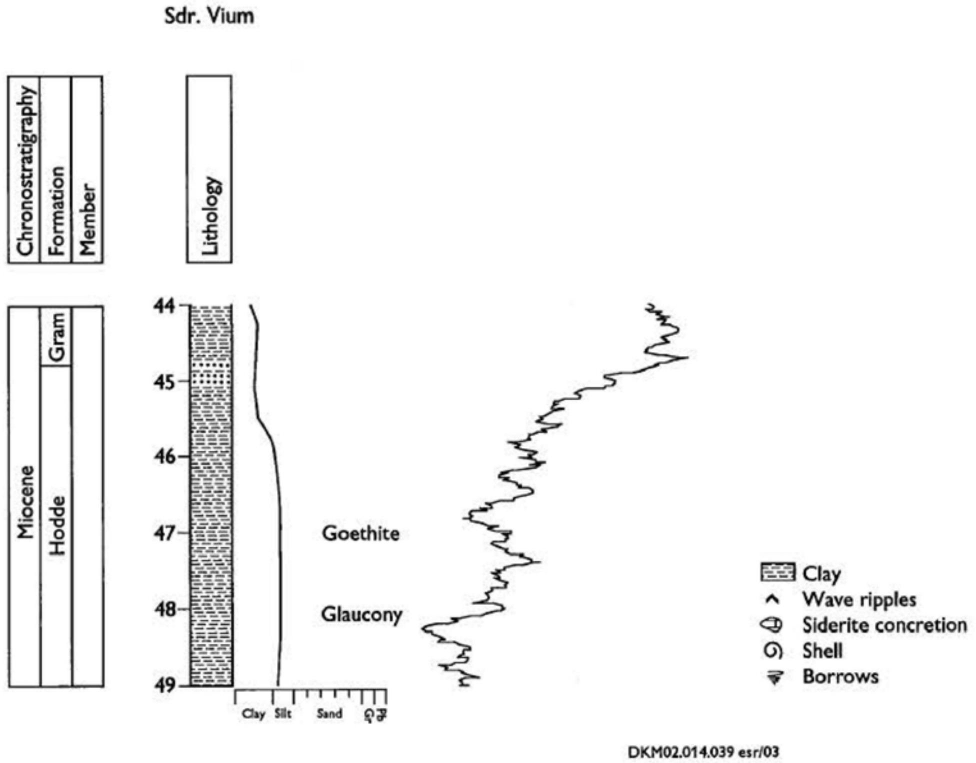

Fig. 16: Reference section for the Hodde Formation is the cored Sdr. Vium borehole.

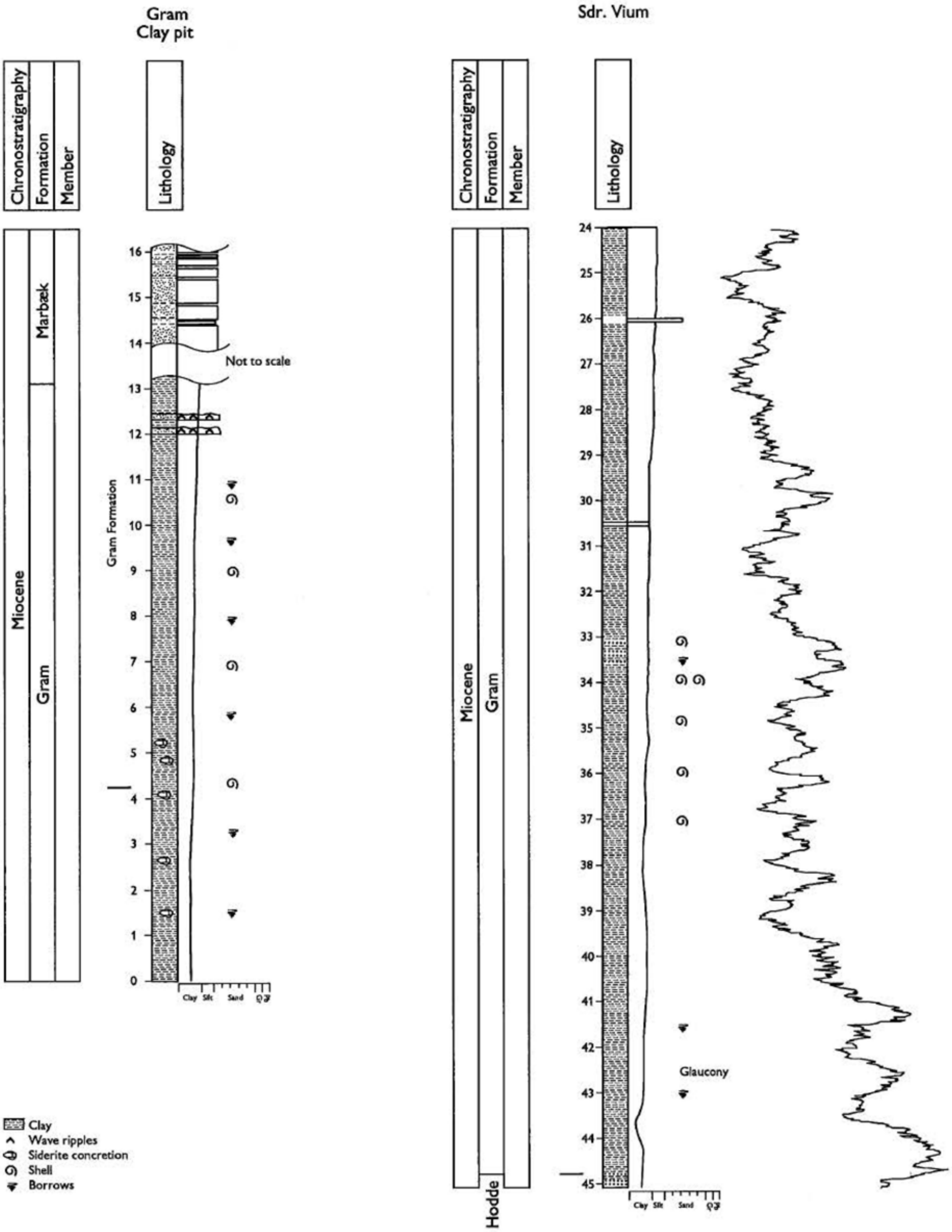

Fig. 17: The type section of the Gram Formation at Gram clay pit and the cored section from the Sdr. Vium borehole.

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MARBÆK

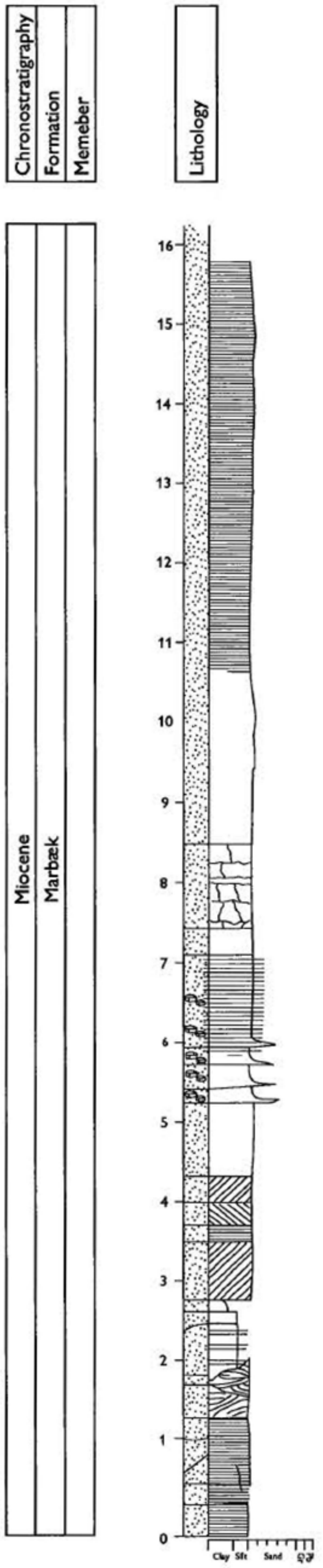

Fig. 18: The type section for the Marbæk Formation at Marbæk Cliff north of Esbjerg.

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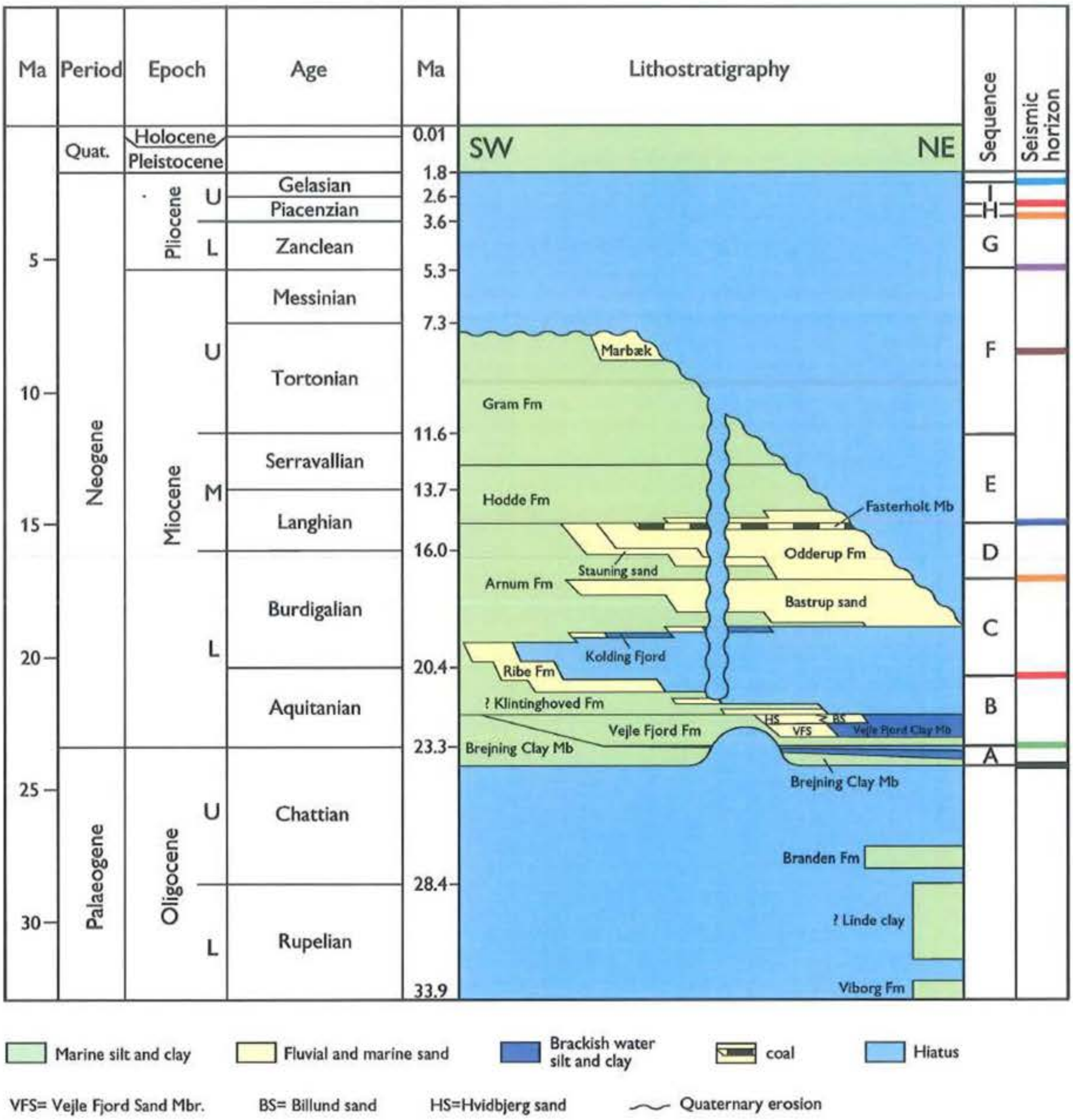

Fig. 19: The lithostratigraphy of the uppermost Upper Oligocene – Miocene in Danmark. Note that the section shows a north – south striking section.