DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/55**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 4

Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties

Gunver K. Pedersen, Bodil Lauridsen, Emma Sheldon & Helle H. Midtgaard

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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Preface

The present report is a contribution to a major geological project with the purpose to investigate whether suitable geological sites for a deep repository for the Danish radioactive waste can be identified. The Geological Survey of Denmark and Greenland (GEUS) has been given the task to identify, map, and characterize formations of low permeable rocks occurring with continuous lateral extension at 500 meters depth with thicknesses of 100 meters or more. This report is part of a series of ten reports presenting the results of the first phase of the project, which is carried out mainly as a desk study.

The geological characterisation and evaluation will provide the geological basis for the selection of two sites where, during the second phase of the geological project, detailed geological site investigations will be carried out. These two sites will be selected through a process of information sharing and dialogue between the Ministry of Higher Education and Science (MHES) and the local municipalities. The new geological data generated in the project's second phase will be used as input to a safety case when a disposal solution has been developed by the Danish Decommissioning (DD). The safety case must demonstrate that the geological properties in combination with the engineered barriers of the repository can provide the required safety for disposal on both short and long term.

In a preceding feasibility study, it was concluded that at 500 meters depth potential host rocks occur in claystones in the Jurassic and Lower Cretaceous sections, in Upper Cretaceous chalk and marl, and in Precambrian crystalline basement rocks. In this phase of the geological project, the geological properties and subsurface conditions related to these stratigraphic intervals and rock types are reviewed, and the potential host rocks' capability to retard radionuclides is investigated by conceptual 1D numerical modelling. In addition, natural processes potentially influencing short and long-term stability are identified and described.

Information gathered in the geological reports no. 2-8 forms the basis for a subdivision of Denmark into 11 areas where each area is characterized by the potential host rock type occurring at 500 meters depth, the barrier rocks in overlying sections, and the structural framework. The areas are defined to enable characterization and evaluation of the Danish subsurface at depths to 500 meters. The evaluation is based on requirements and criteria for deep geological disposal, which are defined based on international experience and recommendations. Each area is characterized and evaluated with regards to whether the geological properties and conditions are favourable for deep disposal of the Danish radioactive waste. The results of the project's first phase are presented in the following ten geological reports:

1. Requirements and criteria for initial evaluation of geological properties and conditions
2. Geological setting and structural framework of Danish onshore areas
3. Upper Cretaceous – Paleocene chalk, limestone and marl distribution and properties
4. Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties
5. Precambrian crystalline basement distribution and properties
6. Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping
7. Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes
8. Conceptual 1D modelling of nuclide transport in low permeable formations
9. Karakterisering og evaluering af geologiske egenskaber og forhold i 500 meters dybde (In Danish)
10. Characterisation and evaluation of geological properties and conditions at 500 meters depth (This report is an English translation of report no. 9, to be published late 2022)

This report is Report no. 4. It describes the subsurface distribution, stratigraphy, sedimentology, and rock properties of Jurassic and Lower Cretaceous claystones in the Danish onshore areas.

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0. Dansk sammendrag (In Danish)

I 2018 vedtog Folketinget, at en langsigtet løsning for håndtering af Danmarks radioaktive affald skal indeholde lokalisering for et muligt dybt geologisk slutdepot, som kan tages i brug senest i 2073 (Folketingets beslutning B90; Danish Parliament, 2018). Det radioaktive affald består af cirka 10.000 m^3 lavradioaktivt affald og mindre mængder af mellemradioaktivt affald, inklusiv 233 kg særligt affald, men intet højradioaktivt varmegenererende affald. De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) har af Folketinget fået tildelt opgaven med at undersøge, om der eksisterer områder i en dybde omkring 500 meter i den danske undergrund, der har de nødvendige geologiske egenskaber for etablering af et sikkert slutdepot for det radioaktive affald.

Det geologiske slutdepotprojekt omhandler de geologiske forhold, der skal tages i betragtning inden en eventuel beslutning om etablering af et dybt geologisk slutdepot for det danske radioaktive affald. De geologiske undersøgelser udføres sideløbende med aktiviteter hos Uddannelses- og Forskningsministeriet (UFM), der er overordnet ejer af slutdepotprojektet, og Dansk Dekommissionering (DD), som har ansvaret for at opbevare affaldet, indtil det skal slutdeponeres (MHES, 2021). Socio-økonomiske forhold, endeligt depotkoncept og -design, sikkerhedsforhold m.v. er ikke en del af det geologiske projekt, men varetages af UFM.

Retningslinjer for identificering af områder egnede til dyb geologisk slutdeponering
Internationale anbefalinger til de geologiske undersøgelser, der skal lede til identificering af en egnet lokalitet for dyb geologisk deponering af radioaktivt affald, er præsenteret af bl.a. det Internationale Atom Energi Agentur (IAEA, 2011) og Norris (2012) – her oversat til dansk:

"At identificere og kortlægge lav-permeable bjergarter, der udgør tilstrækkeligt tykke formationer (mere end 100 meter), og som har en kontinuert lateral udbredelse (flere kilometer i hver retning) indenfor studieområdet. Formationen skal være homogen og må ikke indeholde betydelige diskontinuiteter så som store forkastninger og sprækker. Formationen skal være så mineralogisk homogen og ensartet som muligt. De geologiske forhold skal være stabile på både kort sigt og indenfor en længere tidshorisont afhængigt af affaldets karakter."

Projektet vil følge retningslinjer fra IAEA (IAEA, 2011; IAEA, 2018a; IAEA, 2018b), Det Nukleare Agentur under OECD (NEA, 2005; NEA, 2008; NEA, 2012) og EU-direktiver indenfor området (EU, 2011).

Som bemærket af IAEA (IAEA, 2018a; IAEA, 2018b), er det ikke muligt at udpege ét enkelt område som det bedst egnede baseret på de geologiske egenskaber, idet det er umuligt at undersøge og karakterisere alle naturlige variationer af de geologiske egenskaber ned til 500 meters dybde indenfor et givent område. Opgaven er derimod at identificere et egnet område, der samlet set kan opfylde de definerede krav til sikkerhed og funktionalitet af depotet, samtidig med at etableringen af et geologisk slutdepot i området er teknisk mulig og accepteret af beslutningstagere og interessenter.

Omfanget af de geologiske undersøgelser, der er nødvendige at udføre, er defineret på basis af erfaringer fra lignende projekter i bl.a. Frankrig (ANDRA, 2005), Sverige (SKB, 2007), Schweiz (SFOE, 2008; Nagra, 2017), Holland (COVRA 2017), og Finland (POSIVA, 2017a og b). Kontakter er i løbet af projektet etableret til flere af disse organisationer med henblik på udveksling af erfaringer samt rådgivning og kvalitetssikring for det geologiske slutdepot-projekt. Som et resultat af dette internationale samarbejde, blev der i første fase af slutdepotprojektet gennemført et review af de definerede geologiske kriterier (præsenteret i Rapport nr. 1), hvor kommentarer og anbefalinger er afrapporteret i Blechschmidt et al. (2021).

På baggrund af flere årtiers undersøgelser af de lokale geologiske forhold har nogle lande besluttet at etablere et dybt slutdepot i marine lersten (ANDRA-Frankrig, COVRA-Holland, Nagra-Schweiz). I Sverige (SKB) og Finland (POSIVA) er det besluttet at etablere dybe geologiske slutdepoter i krystallinsk grundfjeld. Mange andre lande arbejder stadig med lokaliseringsprojekter, og udover krystallinsk grundfjeld og lersten er også kalksten, mergel og salt vurderet som mulige bjergarter for deponering afhængigt af de lokale geologiske forhold.

Det geologiske projekt vedrørende et muligt slutdepot i 500 meters dybde

Forud for det igangværende geologiske projekt blev en screening af den danske undergrund foretaget med henblik på at undersøge, om lavpermeable bjergarter findes i 500 meters dybde i den danske undergrund. Denne screening viste, at i 500 meters dybde findes jurassiske og kretassiske lagserier, der indeholder tætte formationer af lersten og kalksten samt prækambrisk grundfjeld bestående af granit og gnejs. Alle disse bjergartstyper kan under de rette omstændigheder have geologiske egenskaber, der gør dem egnede som værtsbjergart for et dybt geologisk slutdepot (Gravesen, 2016). Baseret på dette arbejde blev undersøgelserne i nærværende projekts første fase igangsat.

Det geologiske slutdepotprojekt blev påbegyndt i januar 2019 og forventes at forløbe over en 7-årig periode. Projektet udgør den geofaglige del af det samlede projekt om et muligt dybt geologisk slutdepot, som er defineret i Folketingets beslutning B90 (Danish Parliament, 2018). Det geologiske projekt varetages af GEUS' personale med bidrag fra eksterne forskningsinstitutioner, konsulentfirmaer og internationale eksperter, hvor det er nødvendigt. På grundlag af en karakterisering og evaluering af undergrundens geologiske egenskaber i projektets første fase, skal to lokaliteter udvælges til detaljerede geologiske undersøgelser i projektets anden fase. Uddannelses- og Forskningsstyrelsen (UFS) har ansvaret for at tilrettelægge og gennemføre en dialogproces, der inden udgangen af 2022 kan føre til afklaring af muligheden for at etablere et partnerskab mellem UFM og én eller flere kommuner om gennemførelsen af detaljerede geologiske undersøgelser.

I projektets første fase er de forskellige bjergarter kortlagt og deres egenskaber er beskrevet i det omfang, der findes data. Det skal i den sammenhæng bemærkes, at den tilgængelige information er ujævnt fordelt både geografisk og geologisk. De eksisterende data fra 500 meters dybde er hovedsageligt indsamlet fra tidligere olie- og gasefterforskningsboringer og relaterede seismiske undersøgelser og i mindre grad fra geotermiske, geotekniske og videnskabelige undersøgelser. De fleste dybe boringer i Danmark har haft som hovedformål at påvise tilstedeværelsen af sandsten og karakterisere deres reservoiregenskaber, hvorfor det er meget sparsomt med data fra de lavpermeable bjergarter som lersten og kalksten, der kan anvendes som værtsbjergarter, og som nærværende slutdepotprojekt har fokus på. Den nuværende kortlægning af undergrundens geologi er derfor behæftet med varierende grad af nøjagtighed og pålidelighed for de forskellige parametre, særligt for de lavpermeable bjergarter, som er vigtige for et geologisk sludepot. Gennemgangen af de eksisterende data har bidraget til at identificere områder med manglende geologiske data og informationer, hvor det er vigtigt at sikre indsamling af nye data i den næste fase af projektet.

I projektets anden fase skal detaljerede geologiske undersøgelser, som nævnt, foretages på to valgte lokaliteter. Undersøgelserne vil omfatte indsamling af seismiske profiler med geofysiske metoder og boring af dybe borehuller. I borehullerne udtages bl.a. borekerner og vandprøver, og der indsamles petrofysiske målinger for efterfølgende analyser med henblik på karakterisering af forseglingsegenskaberne og geotekniske egenskaber. Disse data vil indgå bl.a. i modellering af stoftransport, bestemmelse af geokemisk retardation, seismisk kortlægning og vurdering af geoteknisk stabilitet. De geologiske og geotekniske egenskaber vil også have indflydelse på hvilket depotdesign, der er teknisk muligt og sikkerhedsmæssigt forsvarligt i undergrunden. De indsamlede data og analyser vil efterfølgende indgå i en sikkerhedsvurdering, der skal afklare, om det samlede depotkoncept med de geologiske barrierer i kombination med de konstruerede barrierer kan levere den nødvendige sikkerhed for deponering på både kort og lang sigt.

Opsummering af rapport nr. 4: Udbredelse, sedimentologi og egenskaber af Jura og Nedre Kridt lersten (Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties)

Denne rapport præsenterer den eksisterende viden om de lersten, der findes i den danske undergrund med henblik på at identificere og kortlægge områder, hvor lagserier domineret af lersten er 100 meter tykke eller mere og findes i 500 meters dybde. Udbredelsen af de stratigrafiske enheder kendes fra dybe boringer og seismisk kortlægning, som viser, at lersten udgør en stor del af de marine, jurassiske og nedre kretassiske aflejringer, som i dag findes i dybder mellem 300 og 2500 meter. Sedimenterne kendes fra dybe boringer, hvor borekerner er indsamlet, beskrevet og analyseret, samt fra petrofysiske målinger (logs) i borehullerne.

Datagrundlag
De dybe boringer er geografisk set ujævnt fordelt, og de fleste er boret med det formål at teste tilstedeværelsen af sandsten og analysere deres reservoirkvalitet. Datamængden fra lersten er derimod begrænset, og analyser af bjergartsegenskaberne er kun foretaget på få prøver. Det betyder, at bestemmelse af porøsitet og permeabilitet baseret på tolkningen af petrofysiske logs fra borehuller, er behæftet med en stor usikkerhed. Det kan være vanskeligt at bestemme forholdet mellem sandlag og lerlag, især i intervaller hvor de enkelte lag er mindre end 1 meter tykke. I det følgende bliver termen lersten anvendt for intervaller, hvor lerlag udgør størstedelen af formationen, selvom der typisk også vil være et varierende indhold af silt- og sandlag, lokalt med tykkelser på flere meter. Ler anvendes om sedimenter, hvor kornstørrelsen er mindre end 2 µm.

Sedimentologi og stratigrafi
Detaljerede sedimentologiske opmålinger af eksisterende borekerner fra de jurassiske og nedre kretassiske lagserier, er udført med henblik på at karakterisere de litologiske variationer og lagtykkelser samt at tolke aflejringsmiljøerne. Nye biostratigrafiske analyser er foretaget på prøver fra Nedre Kridt lagserien for at give en mere detaljeret forståelse af den geologiske udvikling og hermed den geografiske udbredelse af de enkelte stratigrafiske enheder. Analyserne viser, at der er lange tidsintervaller, som ikke er repræsenteret i lagserien. Dette viser, at der i lange perioder kun blev aflejret meget lidt, eller slet ingen sedimenter.

Identifikation, kortlægning og forudsigelse af sandlags udbredelse i lerstensintervallerne i udergrunden er af stor betydning for, hvorvidt tykke og homogene lerstensintervaller uden sandlag, kan påvises. Sand, der er begravet på dybder ned til 500 meter, er kun i mindre omfang kompakteret og cementeret og er derfor typisk karakteriseret af høj porøsitet og permeabilitet. Sandlag i lerdominerede lagserier vil derfor muligvis kunne fokusere strømning af vand og dermed mindske barriereeffekten af en potentiel værtsbjergart for et slutdepot. Dette afhænger dog også af en række andre faktorer så som den hydrauliske gradient, udbredelsen af sandlagene og hvorvidt sandlagene er orienteret horisontalt eller er forbundet i vertikal retning.

Udbredelsen af lersten

Lagserier domineret af lersten findes i Fjerritslev Formationen (Nedre Jura), Børglum Formationen (Øvre Jura) samt Vedsted og Rødby Formationerne (Nedre Kridt). Imellem disse formationer findes i store dele af Danmark intervaller med aflejringer af marint til lavmarint, kystnært sand. Lavmarint sand fra Gassum Formationen fra Øvre Trias – Nedre Jura, forekommer direkte under de jurassiske sedimenter i hele landet.

Fjerritslev Formationen findes udbredt i den centrale del af det Danske Bassin i Nordjylland, hvor også de tykkeste ler-intervaller forekommer. Her findes toppen af formationen lokalt i 650 meters dybde, men oftest på 1000 meters dybde eller mere. Formationen har i Vedsted-1 boringen en tykkelse på mere end 500 meter. I Lolland-Falster området findes Vedsted formationens top i 450-600 meters dybde eller mere. Fjerritslev Formationen bliver generelt tyndere langs kanten af bassinet og på de omkringliggende strukturelle højderygge bl.a. nær Sorgenfrei-Tornquist zonen i Nordsjælland og langs den sydlige kant af Ringkøbing-Fyn Højderyggen i Lolland-Falster området. Samtidig stiger indholdet af marint og kystnært aflejret sand, hvilket afspejler en mere landværts position. De ældste dele af Fjerritslev Formationen, centralt i bassinet, er tidsækvivalente til de yngste dele af Gassum Formationen, der findes længere mod nord (Pedersen 1985, Nielsen 2003).

Børglum og Frederikshavn Formationerne findes ligeledes i den centrale del af det Danske Bassin i dybder på mere end 1000 meter, og særligt Frederikshavn Formationen indeholder talrige lag af kystnært aflejret sand. I de sydlige og østlige dele af Danmark er disse formationer ikke til stede.

Vedsted Formationen varierer i tykkelse fra 700 meter i Fjerritslev Truget i Nordjylland til 300-400 meter i den nordlige del af det Danske Bassin og omkring 50 meter eller mindre i de østlige og sydøstlige egne af Danmark. Baseret på tolkning af borehulslogs og enkelte kerner synes Vedsted Formationen at være domineret af vekslende ler- og silt-lag og stedvis 1-2 meter tykke sandlag. Log tolkningerne er kun kalibreret til borekerner få steder, og de eksisterende kerner viser tilstedeværelsen talrige sandlag. I Lavø-1 boringen findes sandlag med en tykkelse på op til 15 meter. Formationen har et stigende indhold af mergel og kalkstenslag i den øvre del.

Rødby Formationen er typisk 10-20 meter tyk og repræsenterer overgangen fra ler-dominerede sedimenter i Nedre Kridt til kalkdominerede aflejringer i Øvre Kridt. Lagene i formationen er ofte røde. De overliggende sedimenter i Øvre Kridt er lerholdige særligt i den nedre del, hvor lag af grå mergel forekommer ofte.

Enkeltvis er lerstensformationerne i den østlige del af Danmark generelt mindre end 100 meter tykke, men den samlede tykkelse af Fjerritslev, Vedsted og Rødby Formationerne kan lokalt være mere end 100 meter. Dette gælder i Stenlille-1, Rødby-1 og Søllested-1 boringerne, men i Stenlille-1 findes de på større dybder end 500 meter. I Rødby-1 boringen indeholder Fjerritslev Formationen 1-2 meter tykke sandlag, hvilket resulterer i en inhomogen litologi af lerstensintervallet.

Mineralogi og petrofysiske egenskaber

Lersten med et højt indhold af lermineraler (>50%) vil generelt have en lav permeabilitet, da de pladeformede lermineraler bliver orienteret parallelt med laggrænser under kompaktion. Lerindhold over 50% forekommer i visse dele af Fjerritslev Formationen, mens Øvre Jura og Nedre Kridt formationerne generelt indeholder 20 til 40% ler. Lermineraler som smectit og illit kan kompakteres meget pga. deres 3-lags struktur, hvorimod kaolinit (2-lags struktur) kompakterer i mindre grad. Et højt indhold af smectit er målt stedvis i Fjerritslev Formationen, mens formationerne fra Øvre Jura og Nedre Kridt ofte har et højt indhold kaolinit.

Målinger af porøsitet og permeabilitet findes fra flere studier af jurassiske sandsten, mens der kun findes enkelte målinger fra lersten. Borehulslogs kan anvendes til at estimere porøsitet og permeabilitet, men da de sjældent er kalibreret til målinger fra kerneprøver af lersten, er de tolkede værdier behæftet med meget stor usikkerhed. Kalkstenslag i Nedre Kridt lagserien kan være diagenetisk omdannede, hvilket vil have stor indflydelse på deres bjergartsegenskaber. Der findes ikke systematiske data fra, eller viden om, hvilke faktorer, der er styrende for udvikling af porøsitet og permeabilitet i de kalkholdige muddersten (mergel) og kalklag i Nedre Kridt sedimenterne, og tolkninger baseret på borehulslogs vil være meget usikre.

Aflejringer domineret af lersten og med stedvist højt indhold af lermineraler er påvist i Jura og Nedre Kridt formationerne, men der er pt. meget sparsomme informationer og data vedrørende porøsitet, permeabilitet og bjergarternes geotekniske egenskaber. Der er således en betydelig usikkerhed om formationernes geologiske barriereegenskaber, som bør undersøges nærmere ved målrettede geologiske detailundersøgelser i det geologiske projekts næste fase.

1. Introduction

In 2018, the Danish Parliament agreed that the long-term solution for Denmark´s radioactive waste should include a deep geological repository operating no later than 2073 (Danish Parliament, 2018). The waste is temporarily stored by the Danish Decommissioning (DD) on the Risø peninsula. It amounts to more than 10,000 m^3 and comprises mostly low-level radioactive waste (LLW), and a minor volume of medium-level waste MLW), including 233 kg special waste – but no high-level radioactive material (HLW).

The Geological Survey of Denmark and Greenland (GEUS) has been given the task by the Danish Parliament to investigate whether areas can be identified where potential host rock with suitable properties for geological disposal is present at 500 meters depth. The task is carried out in parallel with activities by the Danish Ministry of Higher Education and Science (MHES), being the project owner, and DD, being responsible for management of the radioactive waste including storage of the waste and final disposal.

The geological project was initiated in 2019 and is expected to be carried out within a period of approximately seven years. The bulk of the workload will be undertaken by staff members at GEUS, with contributions from external consultancy companies, organisations, and experts as needed. The geological siting project comprises two major phases. The current first project phase is a desk study with the purpose to map and characterize geological properties and conditions of potential host rocks in the Danish subsurface, mainly based on existing data. In the second project phase of the geological project, detailed geological investigations will be carried out at two specific sites to investigate whether the geological properties are suitable for safe disposal of radioactive waste in a deep geological repository at these specific sites. The two sites must be selected in a dialogue-based process between MHES and the local municipalities. Subjects and conditions, such as socio-economic issues, activities relating to civil participation, disposal facility design, safety cases, and other non-geological issues will be addressed and handled separately by MHES and DD with contributions from GEUS where relevant.

1.1 Guidelines for identification of deep geological repository sites

International recommendations on geological studies required to identify suitable sites for deep disposal of radioactive waste have been presented by e.g. the International Atomic Energy Agency (IAEA, 2011) and Norris (2012) as follows:

"*To identify and map layers of low-permeable rock types that are sufficiently thick (more than 100 meters) and which have a continuous lateral extension (several km*^{2}*) throughout the entire study area. The rock body should also be sufficiently homogeneous and represent no significant discontinuities like fractures and faults. Furthermore, the rocks should be as mineralogical homogeneous and uniform as possible. The geological conditions should be stable in the short term as well as in the long term.*"

These recommendations as well as experience from siting projects in other countries have been used to identify investigations that need to be performed in the Danish project. Experience from other countries include France (ANDRA, 2005), Holland (COVRA, 2018), Switzerland (SFOE, 2008; Nagra, 2017), Sweden (SKB, 2007) and Finland (POSIVA, 2017a, b).

In some countries, based on several decades of comprehensive subsurface studies, it has been concluded that marine claystones and clay rich carbonates (marl) may constitute suitable host rocks for a final geological disposal. Therefore, extensive research on clay deposits is continuously ongoing and makes available significant amounts of data and experiences that may be valuable for this project (e.g. ANDRA-Belgium, COVRA-Holland, Nagra-Switzerland). In the Czech Republic, a former limestone mine is used for disposal of institutional waste comprising radioactive material similar to the components in the Danish waste. In other countries, including Sweden, Finland, and Norway, it has been decided to establish final repositories in crystalline bedrock. When relevant, the current project in Denmark will draw on others experiences and cooperate with relevant radioactive waste disposal organisations. Furthermore, the project will follow guidelines from IAEA (IAEA 2011; IAEA 2018 a,b), the Nuclear Energy Agency (NEA (OECD), 2005; NEA 2006; NEA, 2008; NEA, 2012) and the EU directive regarding this field (EU, 2011).

As noted by the IAEA (2018 a, b), the impossibility of finding “the safest site” based on rock properties should be emphasised, because it is not possible to investigate and determine the detailed nature of every possible site. Instead, the key to find a suitable site will be to have it fulfil the required level of safety and performance, and that establishing a repository here is also acceptable to decision makers and stakeholders.

1.2 The deep geological repository project

A geological screening of the Danish subsurface layers present at 500 meters depth was carried out prior to initiation of the current geological siting project, to investigate whether low permeable rocks occur at this depth. The screening showed that the Jurassic and Cretaceous stratigraphic intervals at 500 meters depth comprise chalk, limestone, marl, and claystone, and the Precambrian basement comprises crystalline rocks in terms of gneiss and granite, which may all potentially provide a host rock for a deep geological repository (Gravesen, 2016). Based on this work, it was recommended to further analyse and characterize the geological conditions and barrier effectiveness of the geological formations at depths to 500 meters below the surface, which resulted in a decision to initiate the first phase of the present project.

The first phase of the present geological siting project comprises a geological review of all data available in the GEUS archives, the drilling-sample storage facilities, and from literature. The data have been used to map and describe relevant properties of the rock types identified at depths to around 500 meters, as well as natural processes potentially influencing the short- and long-term geological stability. The results form the basis of a subdivision into geologically different areas which are characterised and evaluated regarding the areas’ potential suitability for deep disposal as described in the project’s Report No. 9 (cf. Chapter 7.1 for reference).

The geological desk studies were carried out as separate work packages and presented in a number of reports (Reports No. 2-7; cf. Chapter 7.1 for references) addressing the following issues: overview of the onshore geological setting in Denmark; subsurface mapping based on seismic data and well data; a geological description of the three rock types chalk, claystone and crystalline basement, respectively, and issues potentially influencing long-term geological stability, such as climate conditions, possible glaciations, earthquake risks and groundwater conditions. Based on the results of the geological desk studies, conceptual 1D numerical modelling was performed to identify properties and conditions with high importance for the rocks' barrier-effectiveness for retardation of the radionuclides (Report No. 8; cf. Chapter 7.1 for reference).

Information on the subsurface geological formations onshore Denmark is quite scattered and of highly varying quality. The archives and databases comprise 2D seismic data of different vintages and quality as they are acquired for different purposes. Well data exist mainly from deep wells drilled for hydrocarbon exploration, some geothermal wells, and other technical/scientific drillings. Thus, as the data from various regions of Denmark varies in vintage, quality and level of detail, the current picture is by no means comprehensive. However, the geological desk studies combined with some new sedimentological and stratigraphic studies, and initial sensitivity studies from the conceptual 1D modelling have proven highly valuable; both in detailed mapping and identifying rock types, as well as in identifying major data gaps and critical parameters, for which it is important to obtain information during the next phase of the project.

The characterisation and evaluation carried out in this first phase of the project provide the geological basis for selection of two sites for detailed geological investigations in the second phase of the project. A dialogue-based process for the site selection is managed by MHES.

As part of the detailed investigations in the second phase of the project, new data and information will be collected at the two sites to further evaluate whether the geological properties and conditions are favourable for deep disposal. Thus, the second phase sets off with planning and preparation for the investigations, which include acquisition of seismic data and the drilling of deep boreholes (deeper than 500 meters) at each site. The extensive data sampling program will, among others, include drill-cores, well logs, and groundwater samples - thus, providing samples and measurements for laboratory analyses and various other studies. Based on the new data, a characterisation and evaluation of the geological suitability of the two sites will be made. This characterisation will also be used by DD for identification of a suitable repository design and for evaluation of the combined retention capacity of the engineered and the geological barriers as input to a safety case.

2. Geological setting

The present study is focused on identification and mapping of mudstones occurring at depths around 500 meters, and with thicknesses of 100 meters or more, and characterisation of their rock properties. The three major stratigraphic intervals comprising mudstones are the Lower Jurassic, the Upper Jurassic and the Lower Cretaceous where mudstones occur at depths from 300 to 2500 meters in the Danish onshore areas (Nielsen & Japsen 1991).

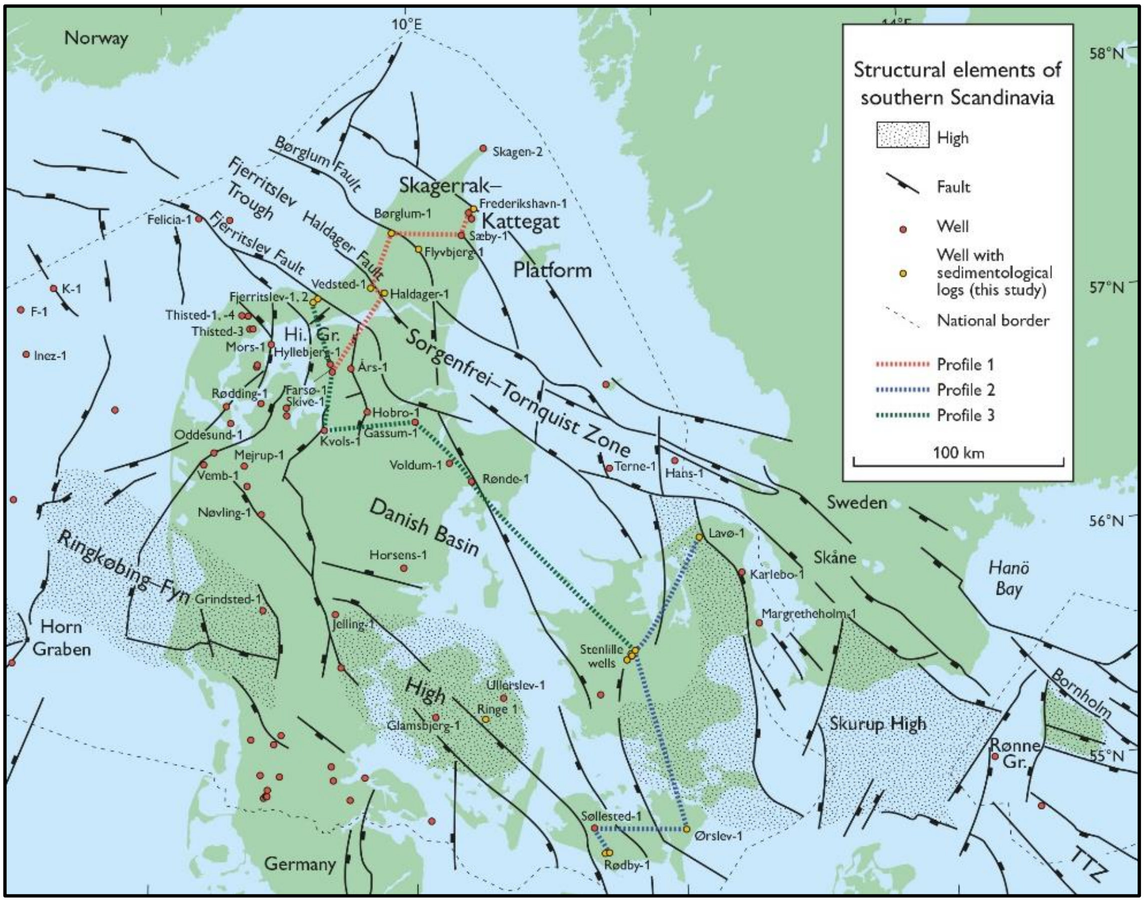


Figure 1. *Map showing the main, deep structural elements including the Danish Basin, the Skagerrak-Kattegat Platform, the Sorgenfrei–Tornquist Zone, and the Ringkøbing-Fyn High. The North German Basin is located south of the Ringkøbing-Fyn High and is known from several wells. The location of the profiles shown in Figures 6-8 is indicated. (Map based on Nielsen, 2003: Figure 1).*

Figur 1. *Kort der viser de dybe strukturelle elementer inklusivt Det Danske Bassin, Skagerrak-Kattegat Platformen, Sorgenfrei–Tornquist Zonen, og Ringkøbing-Fyn Højderyggen. Mod syd findes Det nordtyske Bassin, hvis lagserie er repræsenteret i flere boringer. Placeringen af profilerne i Figur 6-8 er vist på kortet. (Kortet er fra Nielsen, 2003: Figur 1).*

Mesozoic sedimentary deposits occur widespread in the Danish subsurface with thicknesses of several kilometres in the Danish Basin and the Fjerritslev Trough. Thinner deposits are found in the Sorgenfrei-Tornquist Zone to the North, across the Ringkøbing Fyn High and southwards (Figure 1). The Danish Basin is bounded to the NE by a regional fault zone, the Sorgenfrei–Tornquist Fault Zone, which forms the southern boundary of the Skagerrak–Kattegat Platform. To the south, the Ringkøbing–Fyn High separates the Danish Basin from the North German Basin (Vejbæk & Britze, 1994; Vejbæk, 1997) (Figure 1). The Danish Basin forms a pronounced feature on the regional top Pre-Zechstein depth map. Top Pre-Zechstein is identified at depths of 1–2 kilometres on the Skagerrak–Kattegat Platform and the Ringkøbing–Fyn High, and deeper than 7 kilometres in the central part of the Danish Basin (Vejbæk & Britze 1994).

The basin comprises a Permian to Cenozoic sedimentary succession formed during Late Carboniferous to Early Permian crustal extension with widespread volcanism followed by subsidence, which was controlled by thermal cooling and local faulting (Vejbæk & Britze 1994; Vejbæk 1997, and Nielsen 2003). The subsurface distribution of the formations has been mapped from seismic data (Japsen & Langtofte 1991, Vejbæk & Britze 1994, Vejbæk 1997, Mathiesen & Midtgaard 2021). The isochore thickness of the Jurassic–Lower Cretaceous ranges from less than 200 meters on the Ringkøbing–Fyn High to more than 2000 meters in the central part of the Danish Basin, and slightly decreasing thickness the Sorgenfrei–Tornquist Fault Zone in central and northern Jylland (Figure 2).

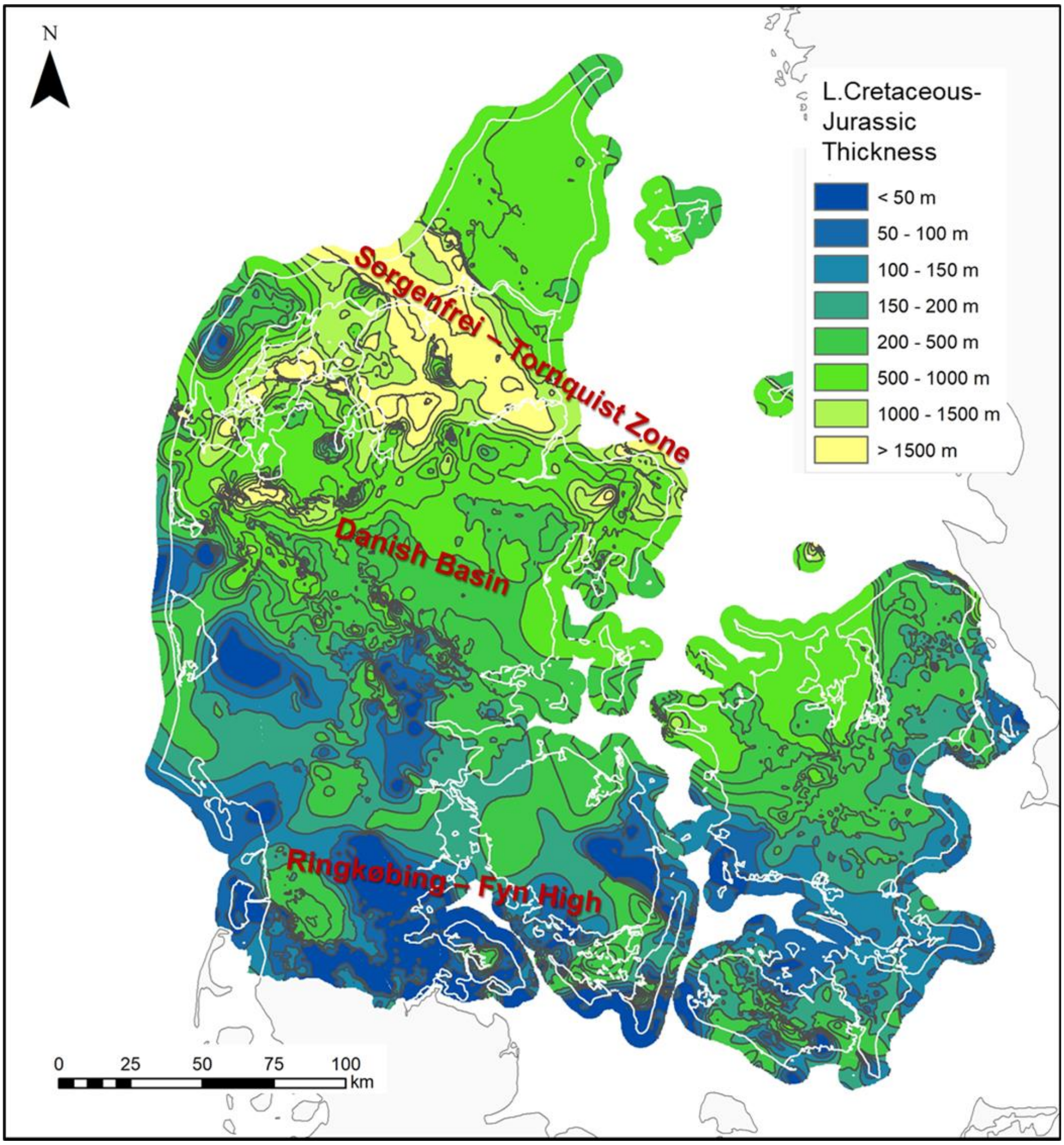


Figure 2*. Thickness map based on regional seismic interpretation. Thickest deposits exist in the Danish Basin and in the Sorgenfrei-Tornquist Zone, central and northern Jylland (yellow to green colours, for a detailed presentation see Mathiesen et al. 2021).*

Figur 2. *Tykkelseskort af Jura og Nedre Kridt intervallet baseret på seismisk tolkning. De tykkeste aflejringer findes i det Danske Bassin og i Sorgenfrei-Tornquist Zonen i midt- og Nordjylland.*

2.1 Jurassic and Lower Cretaceous stratigraphic overview

The lithologies of the Jurassic and Lower Cretaceous formations are known from deep wells (Figure 1) drilled mostly for onshore hydrocarbon and geothermal exploration where the main purpose has been identification of rocks with good reservoir properties, or deeply buried hydrocarbon source rocks. Over the last 5 decades, academic and industrial focus has therefore been directed towards the Jurassic and the Upper Cretaceous successions, which are known from offshore areas to comprise formations with reservoir properties. The intervening Lower Cretaceous succession, which is dominated by mudstones, has received little attention. The current need for identification of thick, laterally continuous, low permeable deposits at depths around 500 meters has brought the Lower Cretaceous into focus.

The Jurassic and Lower Cretaceous succession in the Danish Basin is subdivided into seven lithostratigraphic formations. The oldest is the Gassum Formation, which is Late Triassic to Early Jurassic in northern Jylland (Figure 10). The Fjerritslev Formation of uppermost Triassic and Lower Jurassic age and the youngest are the Lower Cretaceous Vedsted and Rødby Formations (Figure 3). The Lower Cretaceous section comprises the uppermost part of the Frederikshavn Formation, the Vedsted and the Rødby Formations (Figure 3).

Regional depth and thickness maps compiled by Mathiesen et al. (2021) show that the top of the Lower Jurassic mudstones occur at 500–700 meters depth in northern Jylland and in the Lolland-Falster area whereas it is more deeply buried in other parts of Denmark. The greatest thicknesses of mudstones occur in the central part of the Danish Basin in northern Jylland (Figure 2).

Recent work on the Lower Cretaceous in Denmark has shown gaps in the present knowledge of the detailed stratigraphy (both biostratigraphy and litho/sequence stratigraphy) and sedimentology – and hence the interpretation of depositional environments and palaeogeography. In some wells, the core intervals represent condensed sections of Hauterivian–Aptian pelagic marlstones and marly chalks that are time equivalent to known succession in the offshore Danish Central Graben area. The tectonic influence and structural control on the early Cretaceous palaeogeographic setting, and the lateral distribution of claystone, sand, and carbonates in the siliciclastic dominated early Cretaceous Danish Basin, remain poorly understood. This uncertainty includes the stratigraphic boundary between the Lower and the Upper Cretaceous section, which in some areas is a gradational lithological change with upwards increasing carbonate content. This gradual lithological change results in a significant uncertainty on the seismic definition and thus interpretation of the Base Upper Cretaceous (Top Lower Cretaceous).

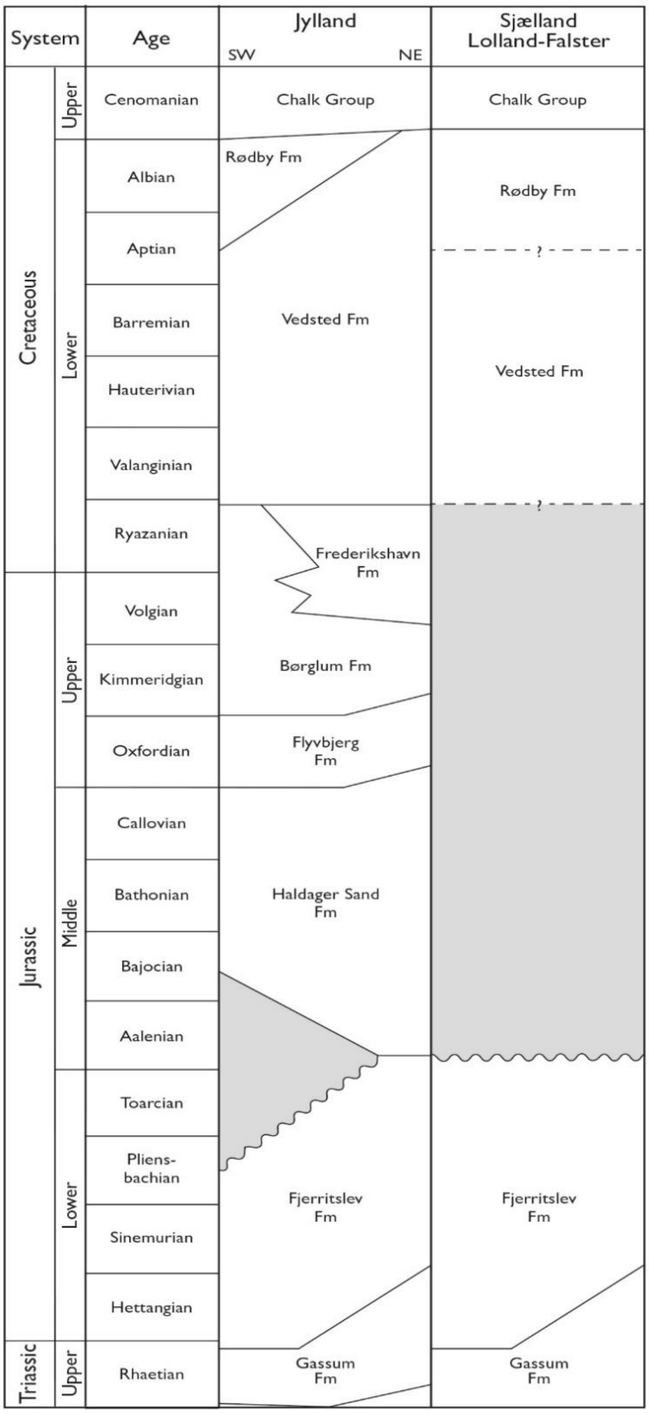


Figure 3. *The lithostratigraphy of the Jurassic and Lower Cretaceous succession in the Danish onshore area, based on Nielsen (2003: figs 4, 26) and Jensen et al. (1986: Figure 4). Claystones occur in the Fjerritslev, Flyvbjerg, Børglum, Vedsted and Rødby Formations.*

Figur 3. *Lithostratigrafisk inddeling af Jura og Nedre Kridt lagserierne (efter Nielsen,2003: Figures 4, 26) og Jensen et al. (1986: Figur 4). Lersten findes hovedsagelig i Fjerritslev, Flyvbjerg, Børglum, Vedsted og Rødby Formationerne.*

The lithostratigraphy of the uppermost Triassic, Jurassic, and Lower Cretaceous formations is summarized in Figure 3. The siliciclastic lithologies, characteristic of the Jurassic and lowermost Cretaceous, were deposited in a range of coastal, shallow marine, and deep marine environments. The sedimentary facies are referred to four depositional environments including clay dominated deep marine offshore settings, the lower–middle shoreface with deposition of interbedded sand and clay, sand dominated upper shoreface–foreshore–backshore environment, and less common shallow water lagoonal mudstones. In the present study, the focus is on the mudstone facies characteristic of the deep-water offshore complex since these lithologies may provide tight and low permeable properties needed for a repository. In contrast, high permeable sand layers are not suitable for a repository and their presence may compromise the seal capacity of repository rocks. It is therefore important to identify sand-bearing stratigraphic intervals and map geographic areas where laterally extensive sand layers are present to enable a prediction of sand presence away from data points.

In the Lower Cretaceous calcareous mudstones constituting the uppermost part of the Vedsted Formation and the Rødby Formation, a gradual change in lithology from mudstone to calcareous mudstone occurs (Ineson et al.1997). This change in lithology influences the properties of the fine-grained sediments and reflects an overall change of the depositional environment. The increasing content of carbonate has been interpreted as the result of an overall sea-level rise that resulted in increased production of carbonate and a landward retreat of coastal siliciclastic deposits.

Maps showing the paleogeographic development during the Jurassic and Early Cretaceous times are shown in Figure 4. During the Early Jurassic (Hettangian – Aalenian) the Danish area was covered by a shelf sea, and coastal deposits are known from southern Sweden, Bornholm and northern Jylland (Gravesen 1996; Gravesen et al. 1982; Lindström & Erlström 2011, Pedersen 1985, Nielsen 2003; see Figure 10). During the Middle to earliest Late Jurassic (Callovian – Oxfordian) much of the Danish onshore area was characterized by erosion, and non-marine or shallow marine depositional environments existed only to the north-east. A Late Jurassic (Kimmeridgian) transgression re-established the deep-water marine environments to the north and west. Finally, in the latest Jurassic and earliest Cretaceous (Volgian – Ryazanian), increased sediment influx from the north and east resulted in a change from mudstones to silt- and sandstones due to the southwards progradation of coastal areas (i.e., sand in the Frederikshavn Formation) (Figure 4). Maps of the early Cretaceous palaeogeographic development are not available and await further biostratigraphic and sedimentological studies to identify time equivalent deposits, their depositional environments, and geographic/lateral distribution.

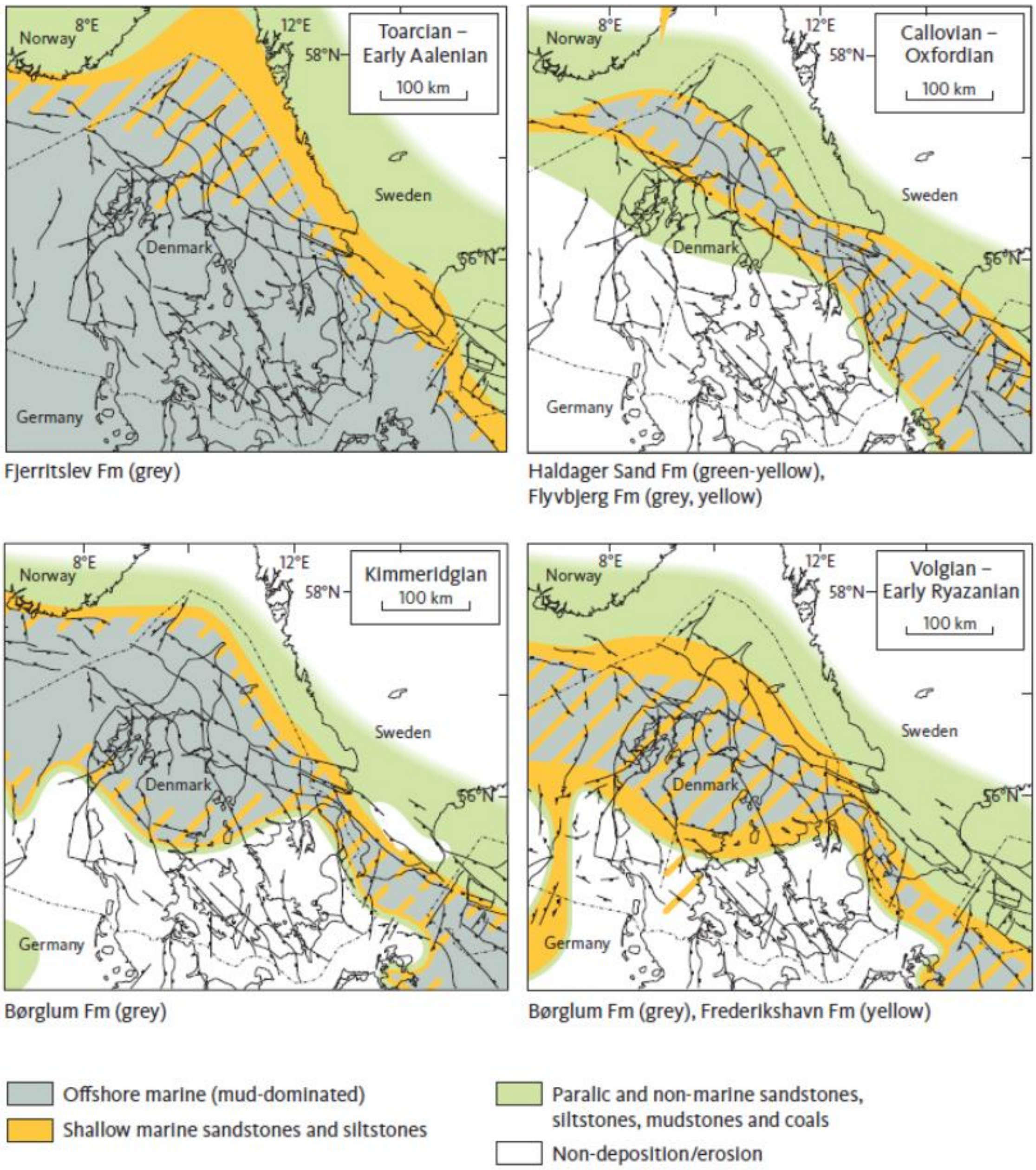


Figure 4. *Paleogeographic maps showing the distribution of depositional environments during the Jurassic and earliest Cretaceous in the Danish Basin (Michelsen et al. 2003: fig.33).*

Figur 4. *Paleogeografiske kort der viser aflejringsmiljøer i Jura og tidligste Kridt tid. (grå: marint dybt vand, domineret af leraflejringer, Orange: kystnære marine sand og silt aflejringer, Grøn: terrestriske sand, silt, ler og kul, Hvid: ingen aflejringer eller erosion (Michelsen et al. 2003: fig.33).*

2.2 Jurassic and Lower Cretaceous sedimentary basins

The present study is focused on identification, mapping, and characterisation of claystone units occurring at depths around 500 meters, and with thicknesses around 100 meters or more. The three major stratigraphic intervals comprising mudstones are the Lower Jurassic, the Upper Jurassic and the Lower Cretaceous where mudstones occur at depths from 300 to 2500 meters in the Danish onshore areas (Nielsen & Japsen 1991). Detailed data such as core and high resolution well logs is scarce and in the following the term mudstone is used as a general description, when it is not possible to distinguish precisely between the grain sizes clay and silt, and the amount of interbedded thin laminae of very fine-grained sand.

The presence and lateral continuity of sand layers is important as the sand is normally characterised by high porosity and permeability and may act as a fairway to fluid flow if they are laterally continuous. Thus, even though sand is not a potential repository rock, it is important to identify and map sand layers to enable the predict of sand presence in the stratigraphic record.

The overall thicknesses and lithology changes of the Jurassic and Lower Cretaceous succession in the Danish onshore area is illustrated in the log correlation panels in Figure 5-7, respectively perpendicular or parallel to the axis of the basin (see Figure 1 for location).

Profile 1 extends from the northern part of the Danish Basin and the Fjerritslev Trough in the northwestern part of the Sorgenfrei-Tornquist zone, and further north across the Skagerrak-Kattegat platform (Figure 5). The significant decrease in thickness from the Vedsted-1 and Farsø-1 wells in the south to the Frederikshavn wells to the north reflects the high rates of accommodation space generation in the Danish Basin and in the Fjerritslev trough, and less subsidence in the platform area to the north. In addition, the Frederikshavn and the Fjerritslev Formations, which comprise quite uniform mudstone dominated sections in the basin areas, become sandier towards the north in the Frederikshavn and Sæby wells, indicating a position closer to sand sources at the basin margin/shallow platform area, as indicated also in the paleogeographic maps in Figure 4.

A north-south oriented profile across the southeastern margin of the Danish Basin across the Ringkøbing-Fyn High is shown in Figure 6. The wells show that Vedsted Formation thickness is around 100 m in Lavø-1 and comprises several sand layers with thicknesses up to 10 meters. To the south, in Rødby-1, the Vedsted Formation thickness is only 10 meters and sand is absent. Similar variations occur in the underlying Fjerritslev Formation which is generally thicker to the north where the sand content is also higher compared to the section in Rødby-1 to the south. The sand dominated lower part of the Fjerritslev Formation is referred to the Karlebo Member. Underlying the Fjerritslev Formation is the Gassum Formation dominated by shallow marine sandstones which is present in all the wells. The presence of sand is interpreted from the GR-log showing characteristic low values, and the presence of clean quartz sand is confirmed in cores from the Rødby-1 well (see Appendix A).

Finally, the log panel in Figure 7 illustrates the thickness and lithology variations from the margin of the Danish Basin on Sjælland towards the basin centre in northern Jylland, see also Figure 2. The Lower Cretaceous Vedsted Formation is around 50 meters thick in the Stenlille-1 well and more than 700 meters in Fjerritslev-2. The thicknesses of the underlying sandy Frederikshavn Formation and the mudstone dominated Fjerritslev Formation also increase significantly towards the basin centre. In Stenlille-1, sandy layers referred to the Karlebo Formation constitute the lower part of the Fjerritslev Formation whereas sand is absent in the other, more basinwards located wells shown in the log panel (Figure7). In all wells, shallow marine sand from the Gassum Formation occur below the Fjerritslev Formation.

Figure 5. Profile 1

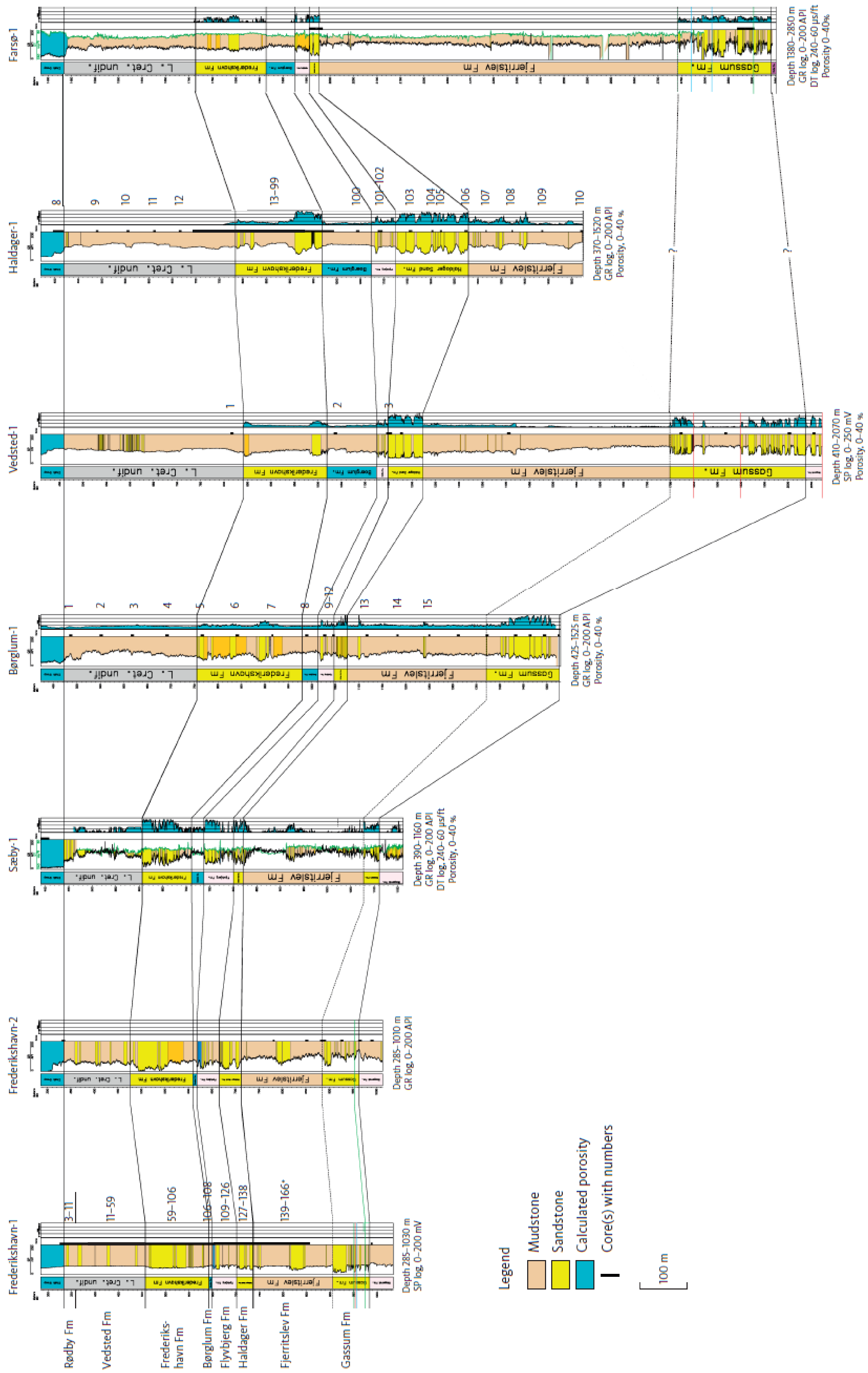


***Figure 5**. Lithostratigraphic correlation of Jurassic and Cretaceous formations based on well logs. Profile from northern Jylland, across the Sorgenfrei-Tornquist Zone, for location see Figure 1 (profile 1). Cored intervals are indicated.*

***Figur 5**. Lithostratigrafisk korrelation af Jura og Nedre Kridt formationer tolket fra borelogs. Profil fra Nordjylland, se Figur 1 for placering (profile 1).*

Figure 6. Profile 2

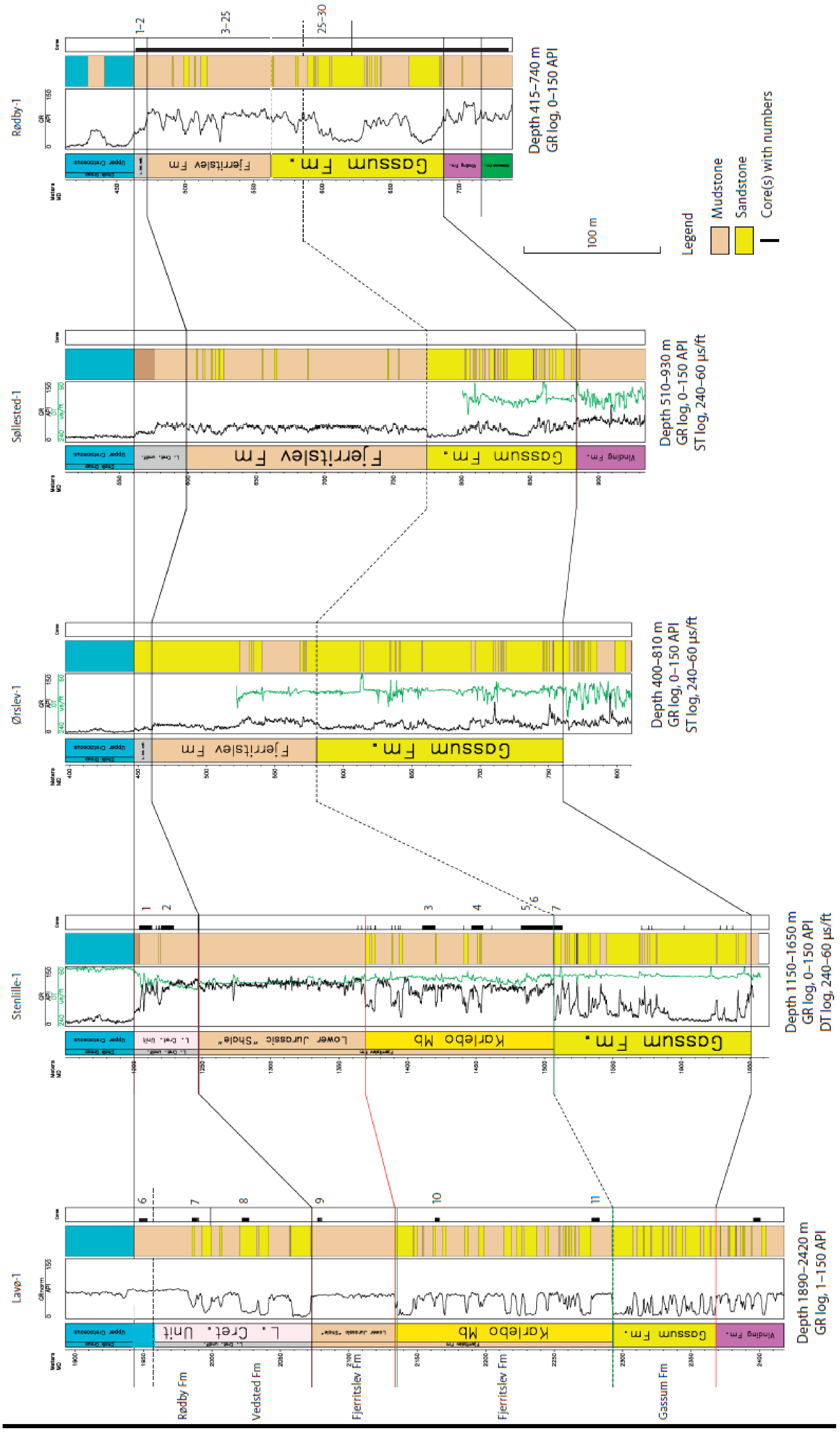


***Figure 6**. Lithostratigraphic correlation of Jurassic and Cretaceous formations based on well logs. N-S oriented profile from northern Sjælland to Falster along the eastern margin of the Danish Basin, for location see Figure 1 (profile 2).*

***Figur 6**. Lithostratigrafisk korrelation af Jura og Nedre Kridt formationer tolket fra borelogs. N-S orienteret profil langs den østlige margin af Det Danske Bassin fra Nordsjælland til Falster, se Figur 1 for placering (profile 2).*

Figure 7. Profile 3

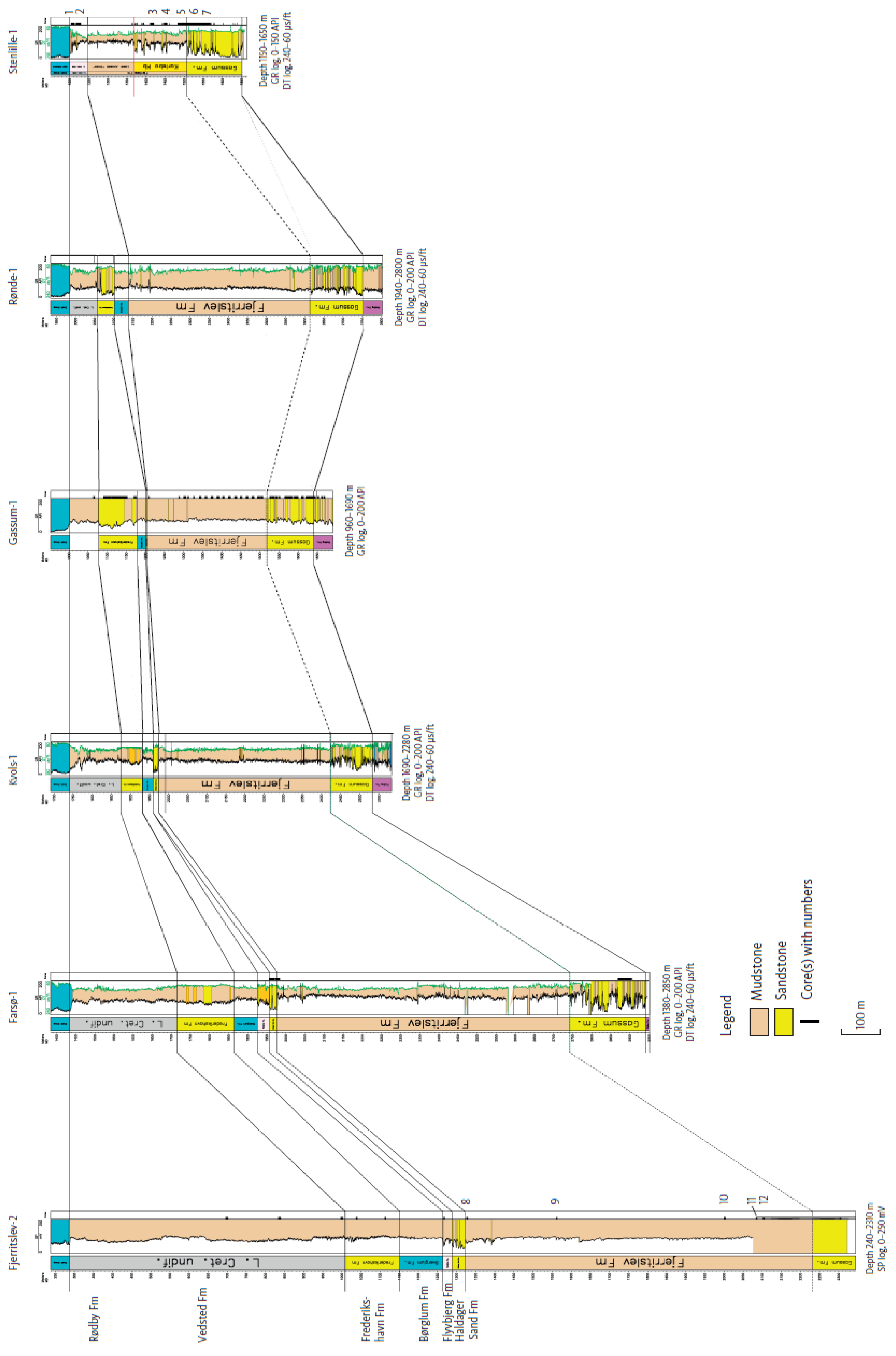


***Figure 7**. Lithostratigraphic correlation of Jurassic and Cretaceous formations based on well logs. NW-SE oriented profile across the Danish Basin from northern Jylland to Sjælland, for location see Figure 1 (profile 3).*

***Figur 7**. Lithostratigrafisk korrelation af Jura og Nedre Kridt formationer tolket fra borelogs. NV-SØ orienteret profil igennem Det Danske Bassin fra Nordjylland til Sjælland, se Figur 1 for placering (profile 3).*

Regional thickness variations in the Lower Cretaceous section based on well data are presented in Figure 8 and 9. These figures illustrate that the thickest sections of Lower Cretaceous sediments occur in the central-northern Jylland in the Danish Basin and in the Sorgenfrei-Tornquist Zone. They also explain the vey rugged thickness distribution observed in the isochore maps in Figure 2 in the northern Danish Basin.

The shallowest occurrence of the Top Lower Cretaceous section is in northern Jylland where it occurs at depths from 200 to 500 meters. In the wells drilled on top of salt diapirs (marked with green stars), or adjacent to salt diapirs, the depth to Top Lower Cretaceous varies significantly over short lateral distances. Examples are seen in Figure 8 where top of the Lower Cretaceous occurs at 400-500 meters in the Erslev-1, Erslev-2, and Uglev-1 wells. In nearby wells the top Lower Cretaceous is located 400-500 meters deeper. These depth variations are caused by local movements of salt from underlying formations which have affected overlying formations.

In the southern part of Denmark on the Ringkøbing-Fyn High and areas further south, the Lower Cretaceous sections rarely exceed thicknesses of 100 meter.

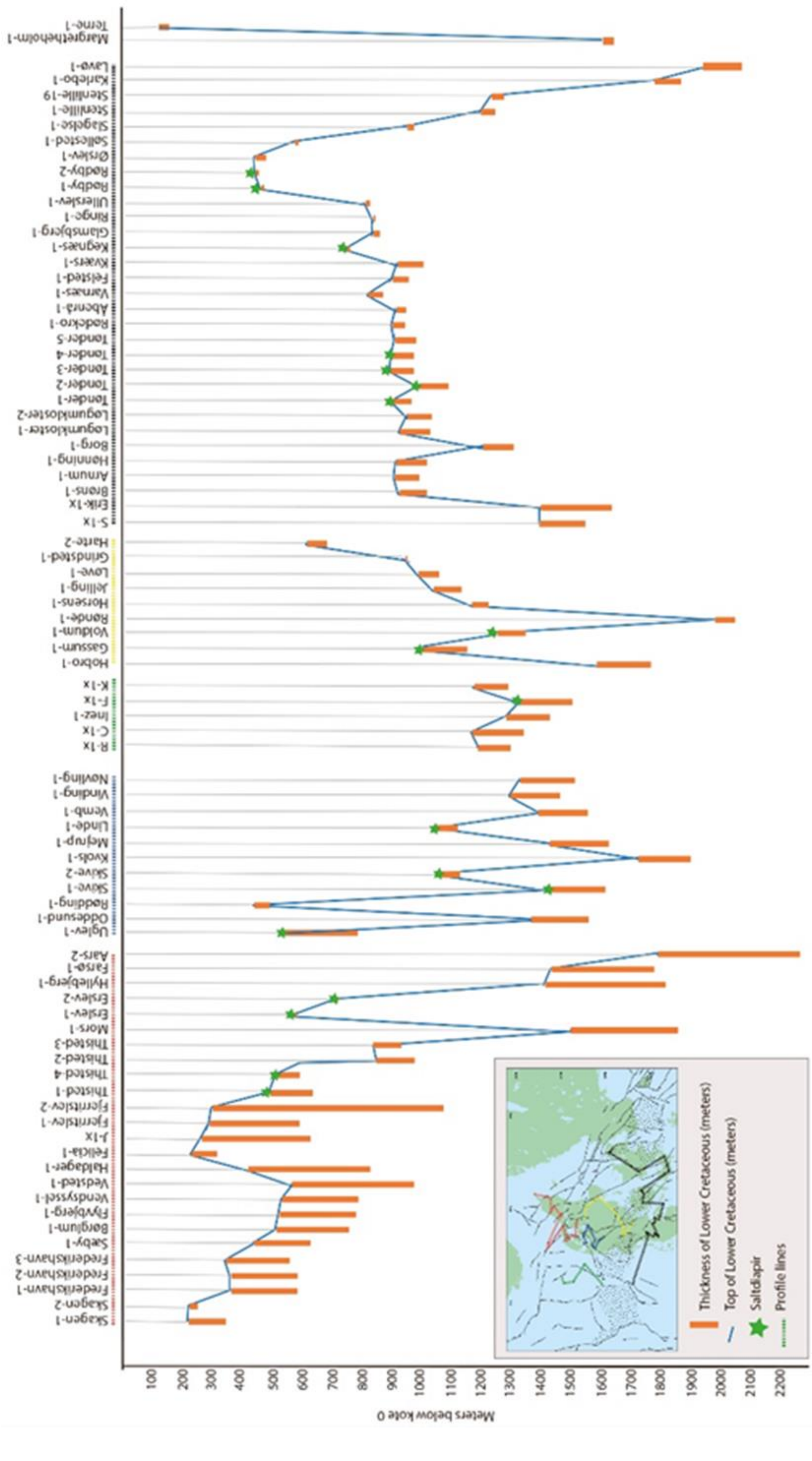

Skagen-1
Skagen-2
Frederikshavn-1
Frederikshavn-2
Frederikshavn-3
Sæby-1
Børglum-1
Flyvbjerg-1
Vendsyssel-1
Vedsted-1
Haldager-1
Felicia-1
J-1x
Fjerritslev-1
Fjerritslev-2
Thisted-1
Thisted-4
Thisted-2
Thisted-3
Mors-1
Erslev-1
Erslev-2
Hyllebjerg-1
Farsø-1
Aars-2
Uglev-1
Oddesund-1
Rødding-1
Skive-1
Skive-2
Kvols-1
Mejrup-1
Linde-1
Vemb-1
Vinding-1
Nøvling-1
R-1x
C-1x
Inez-1
F-1x
K-1x
Hobro-1
Gassum-1
Voldum-1
Rønde-1
Horsens-1
Jelling-1
Løve-1
Grindsted-1
Hørte-2
S-1x
Erik-1x
Brøns-1
Arnum-1
Henning-1
Borg-1
Løgumkloster-1
Løgumkloster-2
Tønder-1
Tønder-2
Tønder-3
Tønder-4
Tønder-5
Rødekro-1
Åbenrå-1
Varnæs-1
Felsted-1
Kværs-1
Kegnæs-1
Glamsbjerg-1
Ringe-1
Ullerslev-1
Rødby-1
Rødby-2
Ørslev-1
Søllested-1
Slagelse-1
Stenlille-1
Stenlille-19
Karlebo-1
Lavø-1
Margretheholm-1
Terne-1
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Meters below kote 0
Thickness of Lower Cretaceous (meters)
Top of Lower Cretaceous (meters)
Saltdiapir
Profile lines

Figure 8.

__Figure 8 (previous page).__ Well log panel showing depth to top of the Lower Cretaceous and thickness of the Lower Cretaceous (meters). Wells located on top of salt diapirs are marked with a green star. The map also shows the location of the profiles shown in Figs 15 and 16.

__Figur 8 (forrige side).__ Log panel der viser dybden til top Nedre Kridt samt tykkelse af Nedre Kridt lagserien. Boringer markeret med en grøn stjerne er boret på en saltdiapir. På kortet er også vist placeringen af profiler i Figur 15 og 16.

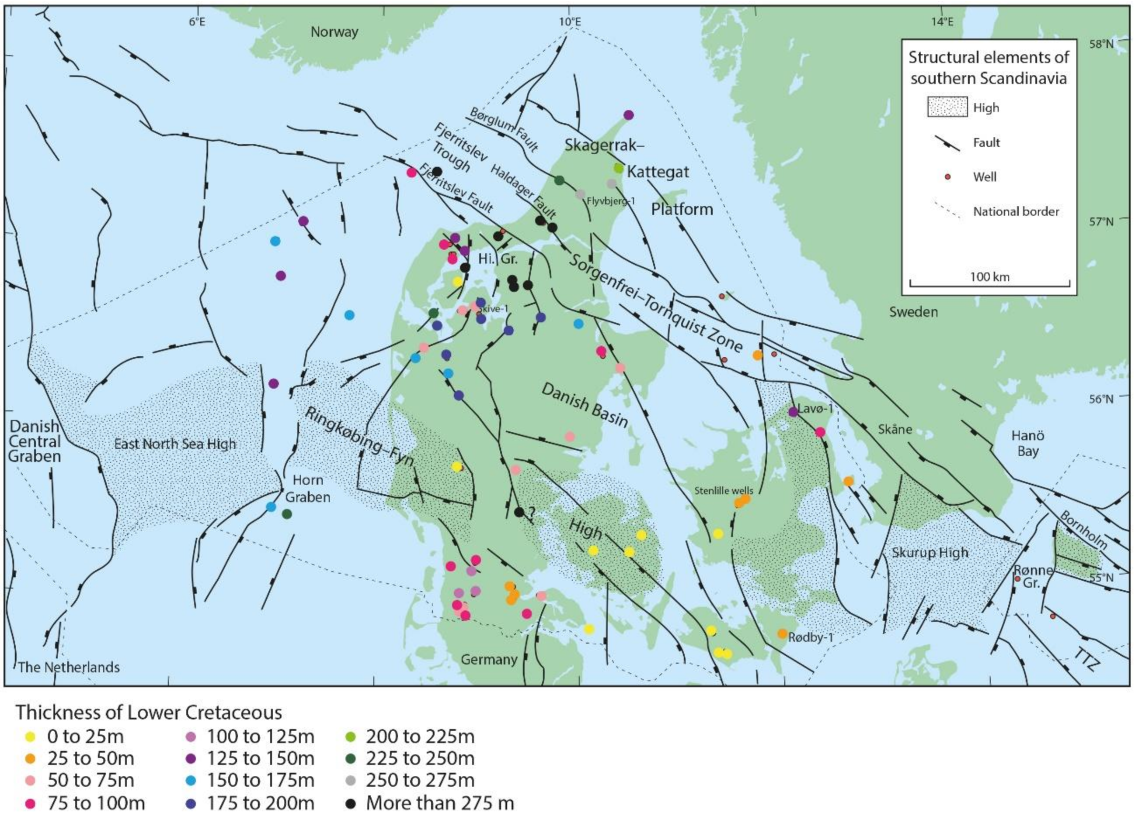


__Figure 9.__ Location of deep wells drilled into the Lower Cretaceous and colour codes showing the thickness of the Lower Cretaceous section.

__Figur 9.__ Kort der viser placeringen af boringer hvor Nedre Kridt sedimenter er gennemboret. Tykkelsen af lagserien er vist med farvekoder.

2.3 Post-depositional uplift

Tectonic uplift and erosion occurred during the latest Cretaceous and Neogene periods, most significantly in the north-eastern part of the Danish Basin. At present, the Fjerritslev Formation in northern Jylland occurs at depths of 820–980 meters in Sæby-1, and at 2500–3000 meters in Års-1. Based on the seismic interval velocity in the Neogene section, the amount of uplift of the Fjerritslev Formation is calculated to be 800 meters in Sæby-1 and 500 meters in Års-1 (Japsen 1992). Comparable values for the uplift were estimated based on vitrinite reflectance data (Jensen & Michelsen 1992, Petersen et al. 2008) and from the dissolution of garnets (Olivarius & Nielsen 2016). This uplift and subsequent erosion has resulted in mudstones, in northern Denmark, being more compacted and influenced by higher temperature diagenesis than predicted from the present burial depths. Consequently, Jurassic, and Cretaceous mudstones show slightly varying degrees of compaction and different diagenetic development depending on the amounts of local tectonic burial and subsequent uplift and erosion.

3. Lithostratigraphy of the Jurassic and Lower Cretaceous

The lithostratigraphic subdivision of the Jurassic and Lower Cretaceous sedimentary deposits in the Danish Basin is summarized in Table 1. It distinguishes between relatively homogeneous sections dominated by either sand, silt, clay or carbonate, and clay dominated sections of interbedded thin laminae of clay, silt, and fine-grained sand which is referred to as mudstone. The geological ages are determined by biostratigraphic analysis.

A complete succession of Jurassic to Cretaceous sedimentary deposits occurs in northeastern Jylland (Figure 2) i.e., in the central part of the Danish Basin (Figures 1, 3, 5 & 7). An erosional inconformity exists locally in southwest Jylland along the southern margins of the Danish Basin. In eastern Denmark deposits from Middle and Upper Jurassic and Lowermost Cretaceous are absent and the Lower Cretaceous section rests directly on the Lower Jurassic Fjerritslev Formation.

3.1 The Jurassic Formations

The base Jurassic is in some areas coinciding with the lithological boundary between the sandy Triassic Gassum Formation and the overlying mudstone dominated Fjerritslev Formation. However, the base of the Fjerritslev Formation is diachronous towards the underlying Gassum Formation ranging from latest Rhaetian (Triassic) to Sinemurian (Early Jurassic; Figs. 3 & 10). A regional unconformity separates the Fjerritslev Fm from the Middle Jurassic Haldager Sand Formation in most of the Danish onhore area (Figure 3). The Upper Jurassic comprises the Flyvbjerg, Børglum and Frederikshavn Formations. The Jurassic biostratigrahy in the Danish area was previously based on ostracods (Michelsen 1975, 1978), and is now additionally based on palynology (Dybkjær 1988, 1991; Poulsen 1996, Lindström & Erlström 2011, Lindström et al. 2012; Vosgerau et al. 2016a).

3.1.1 Fjerritslev Formation

The lower Jurassic sediments are dominated by marine mudstones of the Fjerritslev Formation (Table 1, Figures 3 & 5-7). Regional studies show that the lower boundary of the Fjerritslev Formation towards the underlying Gassum Formation sandstones varies in time across Denmark. Thus, shallow marine sands from the Gassum Formation were deposited in eastern Denmark while mainly deep marine mudstones were deposited contemporaneously in the Danish Basin to the west (Figure 10).

***Tabel 1**. Lithostratigraphy of the Jurassic and L. Cretaceous formations onshore Denmark.*

***Tabel 1.** Litostratigrafisk inddeling af Jura og Nedre Kridt aflejringer i det danske landområde*

Formation	Seismic unit	Series	Lithology	Thickness (Nielsen & Japsen 1991)	Occurrence	Wells/areas where depth to top of Fm is 500–700 m b. msl	Age	References
Rødby	C	Lower Cretaceous	Red calcareous mudstone	Max: 87 m, Års-1 Average: 15 m	Throughout Danmark	Jylland north of Limfjorden	Albian	Jensen et al. (1986) Larsen (1966)
Vedsted			Mudstone and calcareous mudstone. Locally sandstone	Max: 366 m, Haldager-1 Average: 125 m	Thick in Northern Jylland, Sjælland locally present Lolland-Falster mostly absent	Lolland and Falster	Albian to Valanginian	Nielsen & Japsen (1991) Davey (1982) Larsen (1966)
Frederikshavn	D1–D2	Upper Jurassic	Fine-grained sandstone, siltstone	Max: 243 m, Haldager-1 Average: 117 m	Northern and central Jylland	Vendsyssel	Ryazanian Volgian	Michelsen et al. 2003) Michelsen (1978, 1989a) Larsen (1966)
Børglum			Mudstone	Max: 123 m, Mors-1 Average: 37 m		Skagen-2 Frederikshavn-1, -2 Sæby-1, Fjerritslev-1 Thisted-1, -4	Ryazanian to Kimmeridgian	Michelsen et al. 2003) Michelsen (1978, 1989a) Larsen (1966)
Flyvbjerg			Mudstone with thin sandstone beds	Max: 64 m, Sæby-1 Average: 29 m	Northern Jylland		Kimmeridgian to Oxfordian	Michelsen et al. 2003) Michelsen (1978, 1989a)
Haldager Sand	D3	Middle Jurassic	Sandstone, siltstone, thin coal beds	Max: 173 m, Terne-1 Average: 40 m		Skagen-2 Frederikshavn-1, -2 Fjerritslev-1 Thisted-1, -4	Callovian to Aalenian	Michelsen et al. 2003) Michelsen (1978, 1989a) Larsen (1966)
Fjerritslev Formation	E1	Lower Jurassic, top Triassic	Mudstone	Max: 911 m Fjerritslev-2 Average: 303 m	Throughout Danmark, except Ringkøbing-Fyn High	Skagen-2 Frederikshavn-2 Thisted-1, -4 Rødby-1, -2 Søllested-1 Ørslev-1	Aalenian to latest Rhaetian	Lindström et al. (2017) Lindström & Erlström (2011) Nielsen (2003) Dybkjær (1988, 1991) Michelsen et al. 2003) Michelsen (1978, 1989a) Michelsen (1975, 1978) Larsen (1966)
Subdivision, members: F-IV Mb			Mudstone	Max:113 m, Års-1				
F-III Mb			Mudstone	Max: 279 m, Fjerritslev-2				
F-II Mb			Silty mudstone, sandstone	Max. 179 m, Fjerritslev-2				
F-Ib Mb			Mudstone	Max: 163 m, Fjerritslev-2				
F-Ia Mb			Heterolithic mudstone	Max: 203 m, Fjerritslev-2	Not at the Skagerrak–Kattegat Platform			
Karlebo Mb			Mudstone and sandstone	Max: 186 m, Karlebo-1A	Eastern Sjælland			Vosgerau et al. (2016a)

The youngest part of the Fjerritslev Formation is Aalenian (Vosgerau et al. 2016a). In the Sorgenfrei–Tornquist Zone, the regional Mid-Jurassic unconformity is overlain by the Haldager Sand Formation (Figures 3 & 10, Table 1). In the Vedsted-1 well, the Fjerritslev Formation is dominated by mudstone, which is erosively overlain by sandstones of the Haldager Sand Formation (Figure 11). In the Haldager-1 well, less than 10 kilometres away, several sandstone beds occur in the uppermost part of the Fjerritslev Formation and the transition to the Haldager Sand Formation is less abrupt (Figure 12). The Fjerritslev Formation becomes thicker and mudstone-dominated towards the south, indicating a more basinward position. Coastal progradation supplying sand to basin was from the north towards the south (Figure 6). The fine-grained, mudstone dominated sediments dominate in the central part of the Danish Basin, where they occur at depths of more than 1000 meters (Figure 4). The biostratigraphic zonation is based on ostracods and dinoflagellate cysts (Michelsen 1975, 1978, 1989b; Dybkjær 1988, 1991; Lindström & Erlstrom 2011; Lindström et al. 2012, 2017; Vosgerau et al. 2016a).

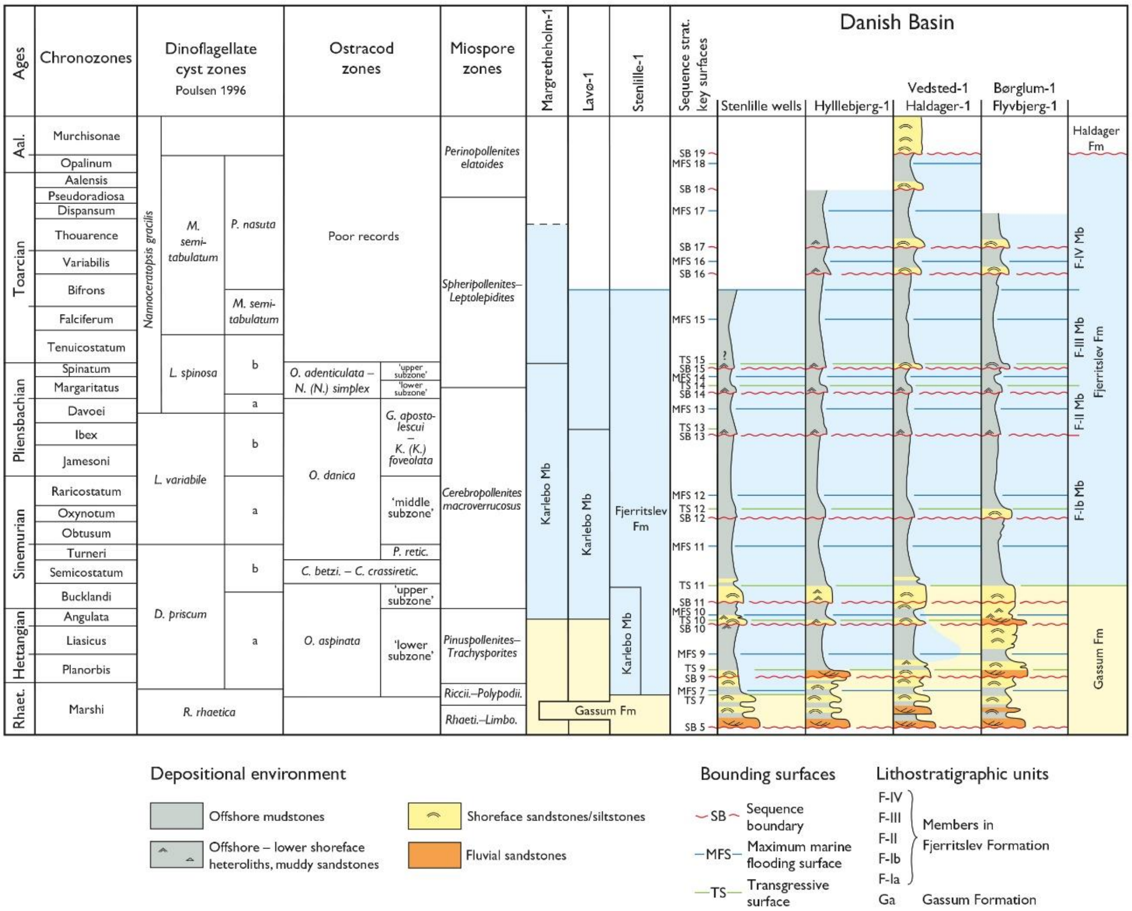


Figure 10. *Biostratigraphy and lithostratigraphy of the Fjerritslev Formation. The Top Fjerritslev Formation is in most of Denmark erosively overlain by the Haldager Sand Formation. The figure is drawn from Nielsen (2003: Figure 31), and Vosgerau et al., (in prep.).*

Figur 10. *Bio- og litostratigrafisk inddeling af Fjerritslev Formationen. Formationens øvre grænse er over store områder en erosionsflade hvor Fjerritslev Formationen overlejres erosivt af Haldager Sand Formation. (Se også Figur 13 & 14).*

3.1.2 Haldager Sand Formation

The Middle Jurassic Haldager Sand Formation comprises mainly fluvial to shallow marine sandstone (Figures 11 & 12). It contributes to the total thickness of the Middle Jurassic to Lower Cretaceous sections as mapped from seismic data. However, since the average thickness is around 40 meters, top and base of the Haldager Sand Formation has not been mapped on seismic data but is identified based on well data only.

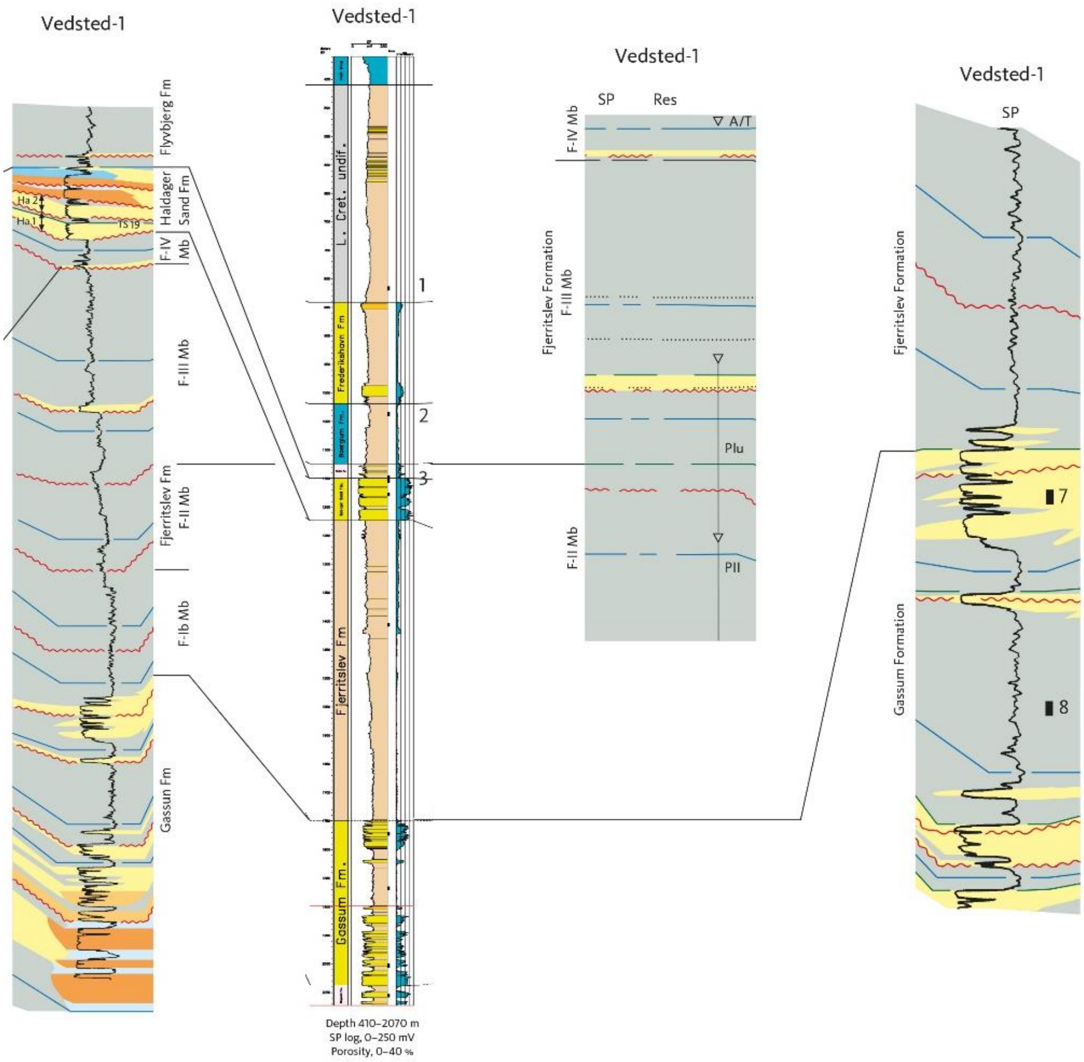


Figure 11. *Well log expressions and interpretations of the Gassum, Fjerritslev, Haldager Sand and Flyvbjerg Formations and their boundaries in the Vedsted-1 well (Based on Nielsen 2003).*

Figur 11. *Borelog data der viser karakteristika for Gassum, Fjerritslev, Haldager Sand og Flyvbjerg Formationerne og deres grænseflader i Vedsted-1.*

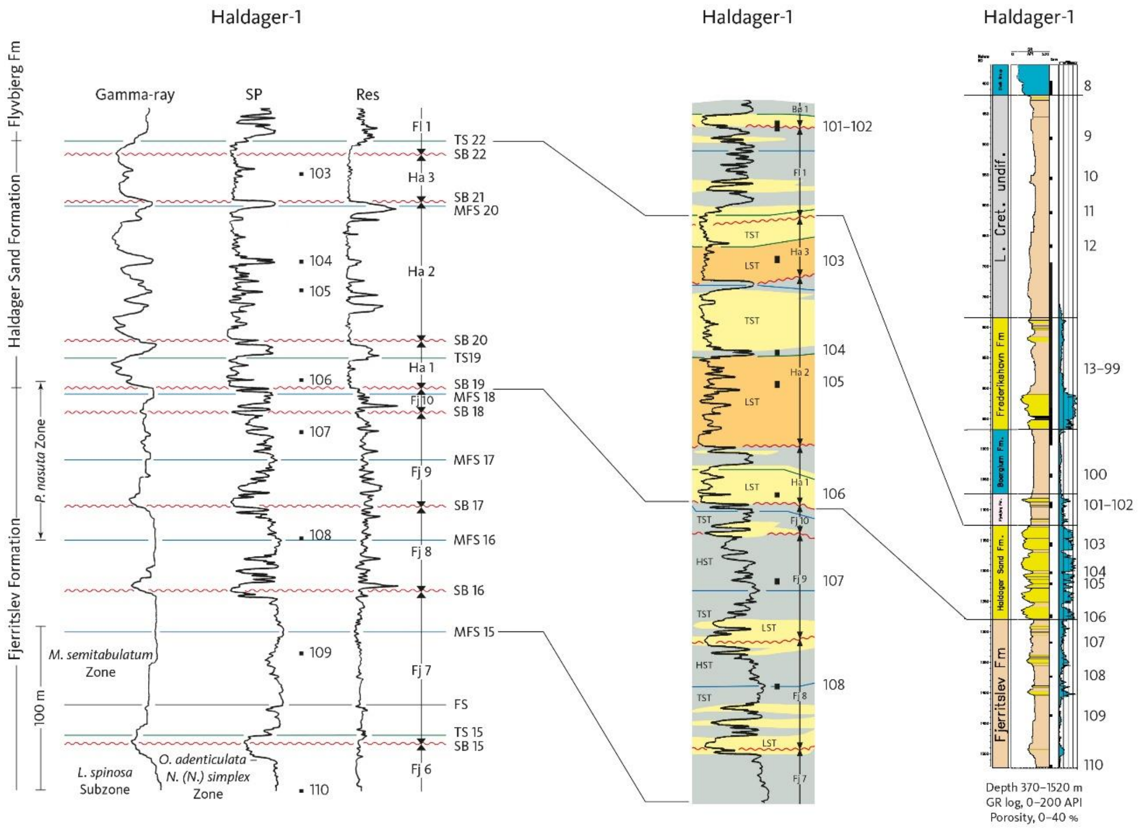


Figure 12. *Well logs showing the characteristics of the Haldager Sand Formation in Haldager-1 well. Three marine sandstones (yellow) occur in the upper part of the Fjerritslev Formation. The left side of the figure shows the correlation between litho-, bio-, and sequence stratigraphic subdivisions (Based on Nielsen 2003, see also Figs 4, 5).*

Figur 12. *Haldager Sand Formation i Haldager-1 boringen. Tre marine sandstenslag ses i toppen af Fjerritslev Formationen. Figurens venstre side viser korrelationen mellem lito-, bio- og sekvensstratigrafiske inddelinger.*

3.1.3 Flyvbjerg Formation

The Upper Jurassic Flyvbjerg Formation is c. 30 meters thick and late Early or early Middle Oxfordian to Kimmeridgian in age (Table 1, Figure 3). The Flyvbjerg Formation is present in northern Jylland, and offshore areas, and the depth to the top of the formation ranges from 550 meters to 1800 meters (Nielsen & Japsen 1991). The formation comprises silty mudstones and siltstones, passing gradually up into sandstone (Michelsen et al. 2003). Due to the average thickness around 30 meters, it has not been possible to map the Flyvbjerg Formation based on seismic data and the formation is identified and mapped based on well data.

3.1.4 Børglum Formation

The Børglum Formation is known from northern and central Jylland, where it is generally less than 50 meters thick (Figure 5 and 7; Table 1). The Børglum Formation was defined by Larsen (1966), revised by (Michelsen 1978, 1989a), and described by Michelsen et al. (2003). The age of the formation is Kimmeridgian to earliest Cretaceous (Ryazanian) and the younger parts represents a deep-water time equivalent to the Frederikshavn Formation (Figure 3). Palaeogeographical maps of the Kimmeridgian and Volgian–Early Ryazanian provide a generalised regional model for the depositional setting for the Børglum and Frederikshavn Formations (Figure 4). The lower boundary of the Børglum Formation was formed during a regional Kimmeridgian transgression. In central to northern Jylland, the Børglum Formation is characterized by grey, fossiliferous mudstones, and organic-rich, black mudstones. The mudstones of the upper part of the Børglum Formation interfinger with marine silt- and sandstones of the Frederikshavn Formation (Figure 3).

3.1.5 Frederikshavn Formation

The Frederikshavn Formation is known from northern and central Jylland and is 50–250 meters thick (Nielsen & Japsen 1991). The Frederikshavn Formation comprises one to three upwards coarsening successions, two of these are well developed in the Sæby-1 well (Figure 5). The marine sediments include bioturbated silt- and fine-grained sandstones, locally fossiliferous (Birkelund & Pedersen 1980). The Frederikshavn Formation was defined by Larsen (1966), later included in the Bream Formation by Michelsen (1978), and then re-established as the Frederikshavn Formation (Michelsen 1989a, Michelsen et al. 2003). The macrofossils and foraminifera were described and interpreted as Portlandian by Sorgenfrei & Buch (1964). Two ammonites from the Aars-1a well indicate a Middle Volgian age for the lower part of the Frederikshavn Formation (Birkelund & Pedersen 1980). The boundary between the Frederikshavn- and Børglum Formations and the overlying Vedsted Formation is probably of late Ryazanian age (Jensen et al. 1986) thus the formation extends across the Jurassic–Cretaceous boundary (Michelsen et al. 2003: see Figure 3).

3.2 Lower Cretaceous Vedsted and Rødby Formations

The Lower Cretaceous marine mudstones overlying the Ryazanian Frederikshavn Formation are referred to the Vedsted and Rødby Formations (Figure 3, Tabel 1). The Vedsted Formation occurs widespread in Danish onshore area, and thicknesses >100 meters are found in northern Jylland (Nielsen & Japsen 1991; Table 1, Figures 5-7). On Sjælland and Lolland–Falster, the Vedsted, or locally the Rødby Formation, directly overlies the Lower Jurassic Fjerritslev Formation (Figures 3, 6, 7). The top of the Lower Cretaceous Vedsted and Rødby Formations are located at depths around 200–550 meters in northern Jylland.

The Rødby Formation is thin and occur at depths of c. 450 meters at Lolland and Falster. The distribution and thickness variation of the Lower Cretaceous is shown in more detail in Figures 8 and 9. The biostratigraphy of the Lower Cretaceous was previously based on foraminifera, while the revised ages are based also on nannofossils (see Section 4, Figures. 15-16). The Vedsted Formation comprises pale grey or greenish-grey mudstones, calcareous mudstones, and locally glauconitic fine-grained sandstones. The uppermost part of the formation in addition also comprises calcareous mudstones and limestone beds. The Rødby Formation is characterized by red mudstones and calcareous mudstones and has a transitional boundary towards the Vedsted Formation (Figure 3) (Larsen 1966).

4. Biostratigraphic analysis of the Lower Cretaceous

Selected representative samples were dated to fill some of the gaps in the Lower Cretaceous section. Nannofossils were used for analysis and sampling from core material was preferred where available, otherwise cuttings were used. Smear slides were prepared for nannofossil biostratigraphy and palaeoecology using the preparation techniques described in Bown & Young (1998). The simple relative abundance counting technique was applied where possible. Nannofossil biostratigraphy was carried out using the Martini (1971) and the Boreal Palaeogene scheme of Varol (1998).

4.1 Previous biostratigraphic studies

The biostratigraphy of the Jurassic and Lower Cretaceous of the Danish onshore area has been based on foraminifera, ostracods, and dinoflagellate cysts (Michelsen 1975, 1978, 1989b; Lund 1977; Davey 1982; Heilmann-Clausen 1987, Dybkjær 1988, 1991; Poulsen 1996, Poulsen & Riding 2003; Lindström et al. 2017, Lindström & Erlström 2006, 2007, 2011). Nannofossils have become increasingly important as the technology has developed. Macrofossils such as ammonites and bivalves are rare in the core material from the Danish onshore areas and therefore seldom used for biostratigraphy (see Sorgenfrei & Buch 1964). The bivalve fauna in the Fjerritslev Formation indicates palaeoenvironmental changes, interpreted as caused by changes from normal marine to dysoxic conditions (Pedersen 1986). New data on the Jurassic biostratigraphy have not been added in this project as the Jurassic sections are generally much better dated.

4.2 Revised Lower Cretaceous biostratigraphy

The overview of the Lower Cretaceous in Denmark and neighbouring countries, Figure 13, shows large hiati in several areas, including the Danish onshore area. In addition, the Lower Cretaceous includes a wide range of lithologies and depositional environments. Consequently, biostratigraphical data are necessary for correlation between different areas. Samples listed in Appendix C have been dated or re-dated by nannofossils (Figures 14-16). All the Early Cretaceous nannofossil biozones appear to be present except biozone BC5 (Late Valanginian; Figure 14: green columns). Some biozones, however, appear in condensed sections e.g., biozones BC21–23 in Ringe-1 (Figure 14). Biozones BC15 to 18 are only confirmed to be present as reworked material (e.g., Haldager-1 and Vinding-1). In the Frederikshavn-1 core several intervals are barren of nannofossils, marine conditions are only demonstrated in beds of Late Hauterivian to Early Aptian age.

The new biostratigraphic data on nannofossils and the former foraminiferal data are not always in agreement. The few ostracod data available are often comparable to the nannofossil data. A combination of all biostratigraphic suggests that a complete Lower Cretaceous section is present in the available core material (Figure 14). The new biostratigraphical data on cutting samples from Vedsted-1 (Figure 14, Appendix C) demonstrates that the Lower Cretaceous is much thinner than previously thought. The top of the Lower Cretaceous was previously stated to be at 460 meters, but revised dating by nannofossils suggests this level to be Cenomanian (UC3c to UC1a). The top of the Lower Cretaceous is demonstrated at 579 meters, which reduces the thickness of the Lower Cretaceous section by at least 100 meters. The Vedsted Formation has its type section in Vedsted-1, which originally was selected due to its completeness and thickness (Larsen, 1966). However, this study has shown that the Vedsted Formation in Vedsted-1 needs a revision based on a correlation to the other wells in the Danish onshore area (Figure 14).

***Figure 13 (next page)**. Lithostratigraphy of the Lower Cretaceous strata in Northwest Europe. The Lower Cretaceous section on Bornholm, comprises non-marine to marine shoreface deposits (Noe-Nygaard et al. 1987, Noe-Nygaard & Surlyk 1988, Surlyk et al. 2008) overlain by glauconitic sandstone and Upper Cretaceous limestone (Ravn 1925, Kennedy et al. 1981).*

***Figur 13 (næste side)**. Lithostratigrafisk inddeling af Nedre Kridt i nordvest Europa. Bemærk, at lagserierne rummer flere hiati, dette ses også på Bornholm, hvor der er en markant kontrast mellem ældre de kystnære aflejringer (Noe-Nygaard et al. 1987, Noe-Nygaard & Surlyk 1988, Surlyk et al. 2008) og de yngre aflejringer af grønsand og kalksten (Øvre Kridt) (Ravn 1925, Kennedy et al. 1981).*

	Series	Stage	Formations	Denmark (outcrops)	NW Germany (outcrops)	Helgoland, Dünen Island (partly outcropping)	NE England (outcrops)	S England (outcrops)
Lower Cretaceous	Albian	Late	Rødby				Poorly lithified mudstones and calcareous mudstones. Greensand common around the Aptian/Albian boundary	
		Early		*Ammonites of Early Albian age in the Lower Cenomanien Arnager Greensand conglomerate indicate previous deposits of Early Albian at Bornholm*	Condensed section			
	Aptian	Late	Vedsted		300m of dark laminated clays			
		Early				Laminated dark clays (Fishschiefer) and pale clays		Sandstone and grey clay
	Barremian	Late			200m of finely laminated clay	Dark grey clays and marly clays	Clay and marl beds, mid-Barremian Cementstone	Dark grey to black laminated clays and marls beds, mid-Bareremian cementstone
		Early						
	Hauterivian	Late			400m of clay		Clay	
		Early						
	Valanginian	Late			Clay with sandstone horisons and sideritic nodules		Phosphatic nodule bed	
		Early		Non-marine and coastal depositis, Rabekke, Robbedale and Jydegård Fm.			Clay, ironstone, nodular beds	
	Ryazanian	Late	ederikshavn/ Børglu		Non-marine Wealden deposits			
		Early						

Figure 13

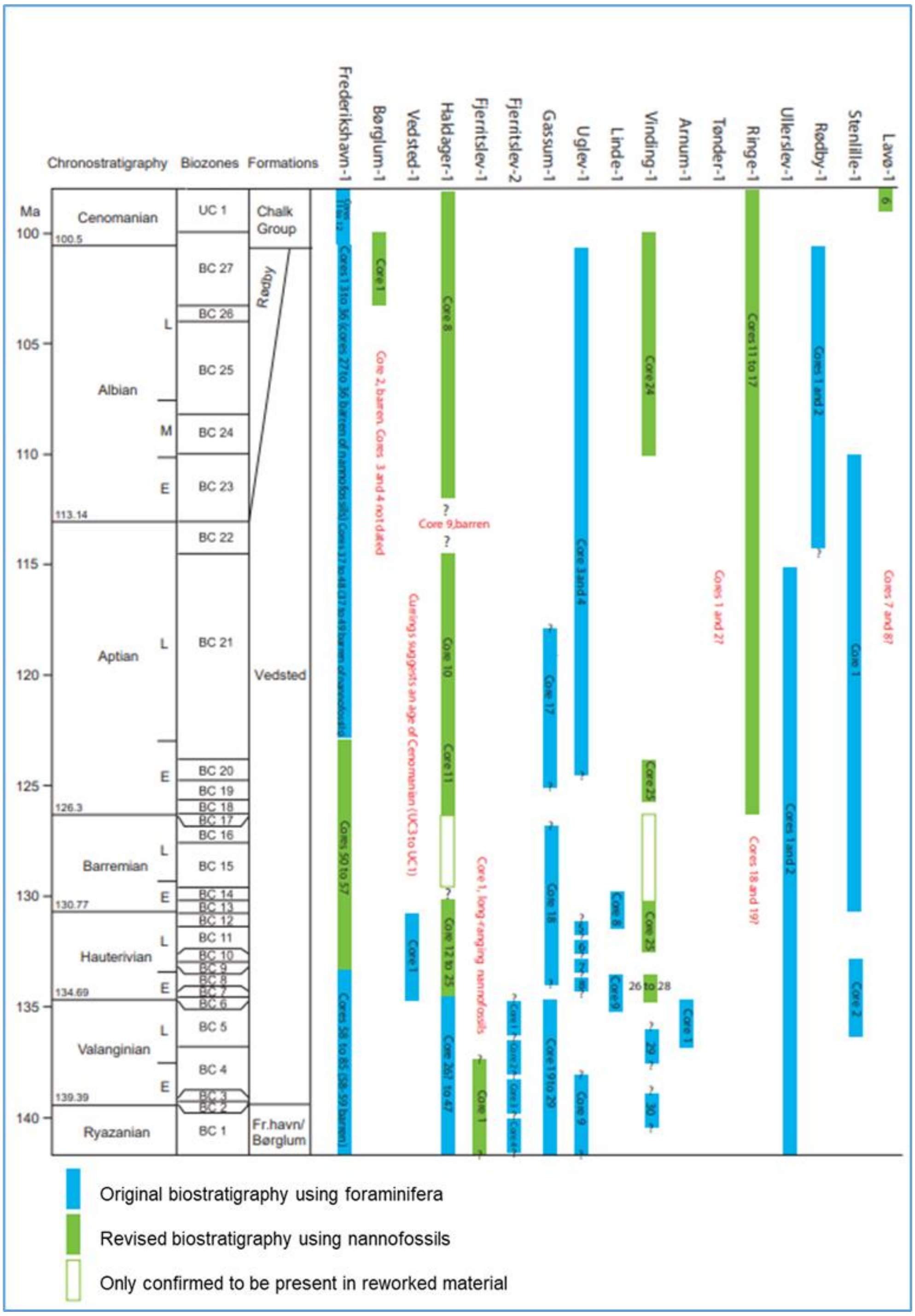
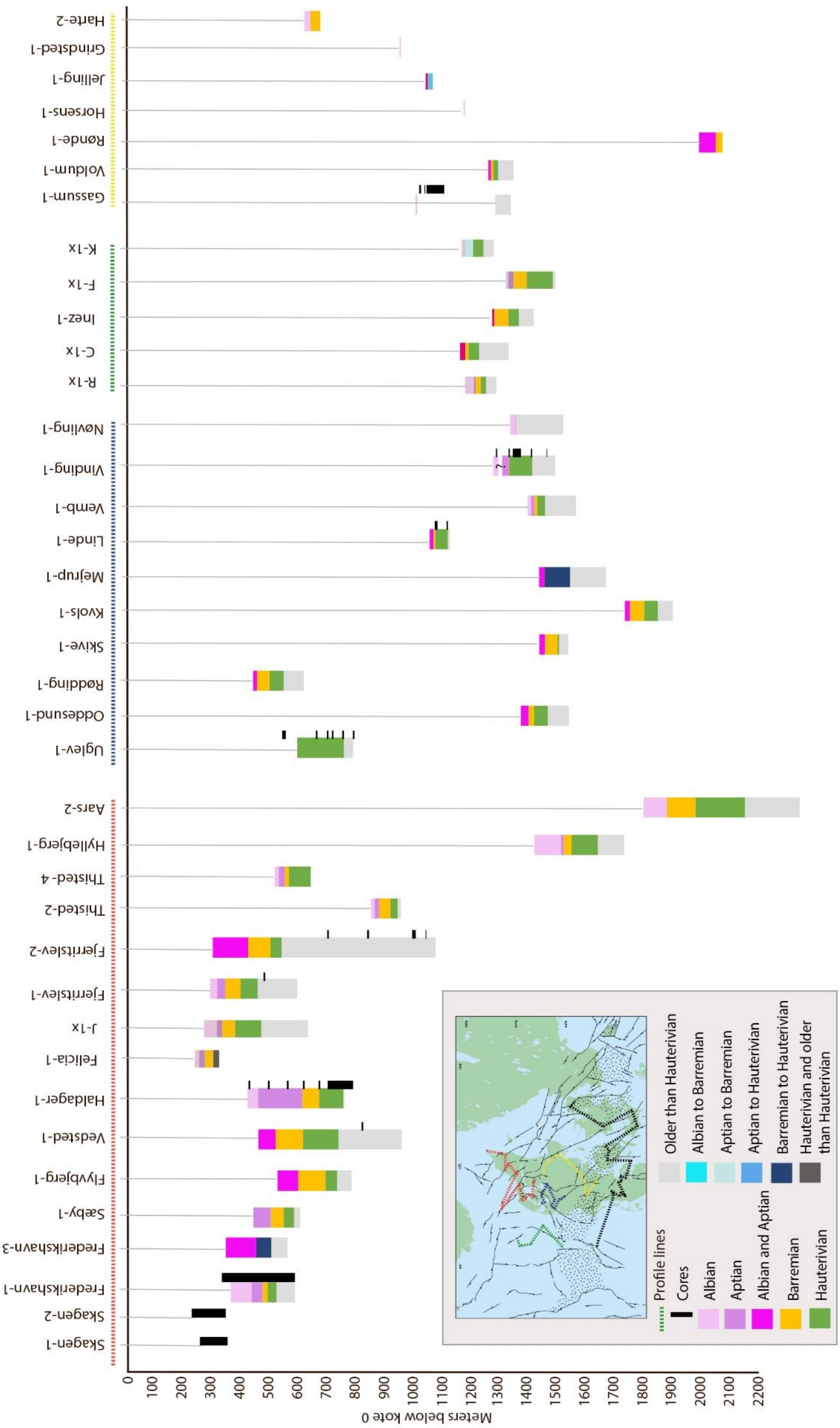


Figure 14. *Stratigraphic distribution of fully cored wells through the Lower Cretaceous in the Danish onshore area. Many of the cored successions were originally dated on basis of foraminifera and macro fossils (Sorgenfrei & Buch 1964, Appendix c). New biostratigraphic data (this study, Table 13) has revised the ages in some wells, and has, importantly, demonstrated inconformities in the Lower Cretaceous succession. The wells Harte-2, Skagen-1 and -2 are not on the figure because of lack of continuous core data. Note that the biozonation only refer to the revised dating of nannofossils, not to foraminiferal biozones which have another terminology.*

Figur 14 (forrige side)*. Biostratigrafisk zonering af Nedre Kridt i boringer, hvor hele successionen er repræsenteret ved borekerner. De nye data er baseret på nannofossiler, medens de tidligere dateringer væsentligst var baseret på foraminiferer og makrofossiler (Sorgenfrei & Buch 1964). Boringerne Harte-2, Skagen-1 of -2 er ikke på figuren da data ikke er tilstrækkelig præcise. Spørgsmålstegn refererer til usikre definitioner af de forskellige zoner. Bemærk at biozonerne refererer til de reviderede dateringer med nannofossiler og ikke til foraminifer-biozoner, der har en anden terminologi.*

Figure 15 (next page)*. Ages of the Lower Cretaceous in different wells in Jylland north of the Ringkøbing-Fyn High and offshore in the North Sea close to the coast. The ages are based on revised biostratigraphic data from nannofossils and include original data from completion reports and geophysical logs. The question mark between the Albian and Aptian units in Vinding-1 indicates that the boundary between the two stages has not been identified. Some wells are lacking compared to the overview at Figure 8. The reason is that wells with inadequate biostratigraphic information are omitted. The inserted map shows the positions of the different profiles.*

Figur 15 (næste side)*. Aldre af lagserien fra nedre Kridt i Jylland. De viste aldre er baseret på nye reviderede biostratigrafiske bestemmelser ud fra nannofossiler og ældre data. Boringer med utilstrækkelig biostratigrafisk kontrol er udeladt og derfor er der ikke fuld overensstemmelse mellem de boringer, der er nævnt på Figur 8 og dem, som ses på denne figur. Det indsatte kort viser beliggenheden af de forskellige profiler.*



Harte-2
Grindsted-1
Jelling-1
Horsens-1
Rønde-1
Voldum-1
Gassum-1
K-1x
F-1x
Inez-1
C-1x
R-1x
Nøvling-1
Vinding-1
Vemb-1
Linde-1
Mejrup-1
Kvols-1
Skive-1
Rødding-1
Oddesund-1
Uglev-1
Aars-2
Hyllebjerg-1
Thisted-4
Thisted-2
Fjerritslev-2
Fjerritslev-1
J-1x
Felicia-1
Haldager-1
Vedsted-1
Flyvbjerg-1
Sæby-1
Frederikshavn-3
Frederikshavn-1
Skagen-2
Skagen-1
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
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1400
1500
1600
1700
1800
1900
2000
2100
2200
Meters below kote 0
Profile lines
Cores
Albian
Aptian
Albian and Aptian
Barremian
Hauterivian
Older than Hauterivian
Albian to Barremian
Aptian to Barremian
Aptian to Hauterivian
Barremian to Hauterivian
Hauterivian and older than Hauterivian

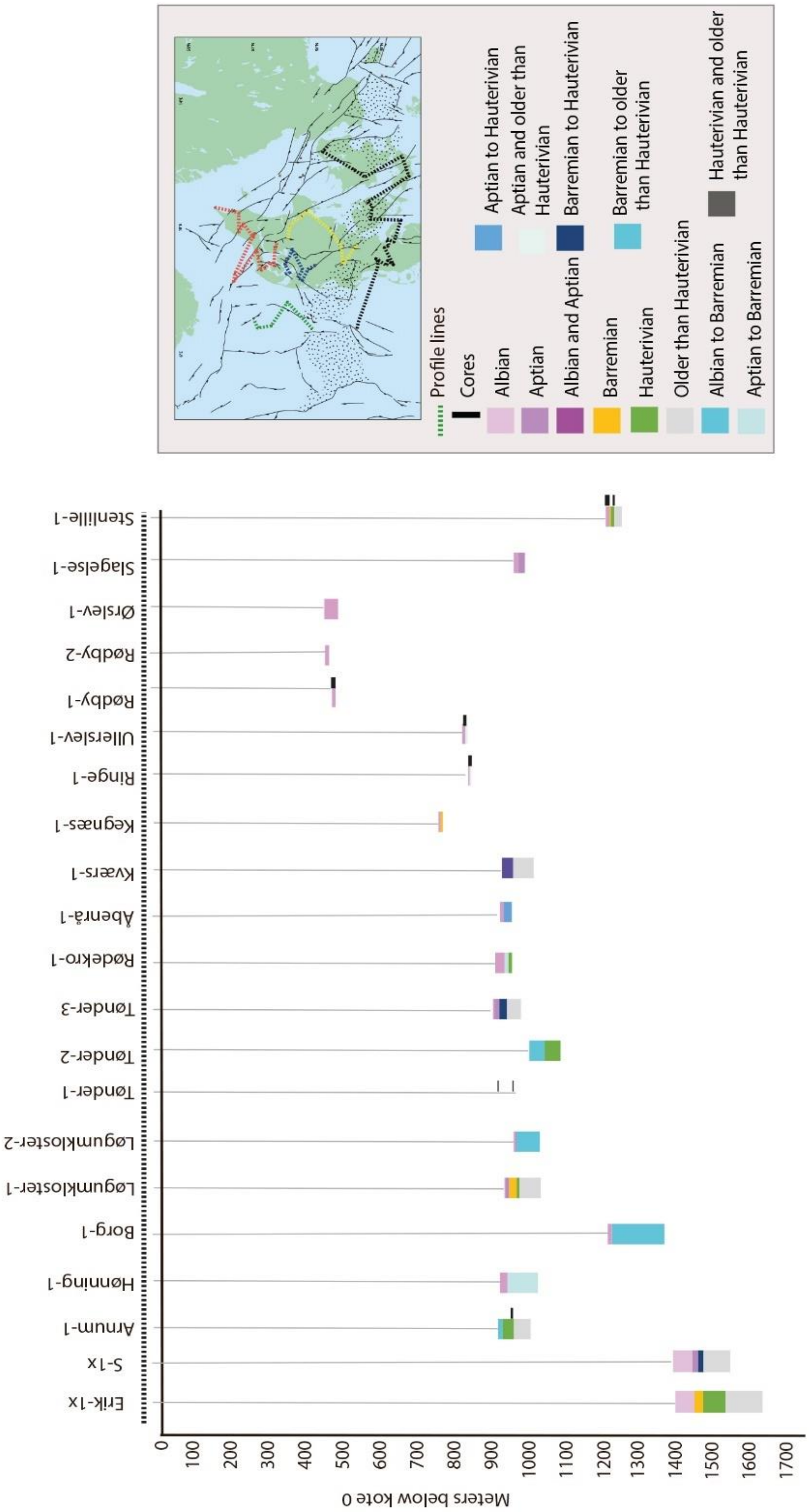


Figure 16. *Ages of the Lower Cretaceous succession in different wells south of the Ringkøbing-Fyn High in Jylland, offshore in the North Sea, at Fyn, Lolland, Falster and Sjælland. The ages are based on revised biostratigraphic data from nannofossils and include original data from completion reports and geophysical logs. Some wells are lacking compared to the overview in Figure 8. The reason is that wells with inadequate biostratigraphic information are omitted. The inserted map shows the positions of the different profiles.*

Figur 16 (forrige side). *Aldre af lagserien fra nedre Kridt i Danmark syd for Ringkøbing−Fyn Højderyggen, på Fyn, Sjælland og Lolland-Falster. De viste aldre er baseret på nye reviderede biostratigrafiske bestemmelser ud fra nannofossiler og ældre data. Boringer med utilstrækkelig biostratigrafisk kontrol er udeladt og derfor er der ikke fuld overensstemmelse mellem de boringer, der er nævnt på Figur 8 og dem, som ses på denne figur. Det indsatte kort viser beliggenheden af de forskellige profiler.*

4.3 Distribution of the Lower Cretaceous in wells

Lower Cretaceous strata are recorded in 70 wells onshore Denmark and 11 wells offshore in the eastern part of the North Sea, Skagerrak, and Kattegat (Figure 9). Data from five coloured profiles (Figs 9, 15 & 16) onshore Denmark show the thickness and the depth to the top of the Lower Cretaceous (Figure 9). This figure combines revised data from this study, data from the original well completion reports and petrophysical logs.

The red profile from Skagen-1 to Aars-2 includes the two offshore wells (Felicia-1 and J-1x) and shows the shallowest depth to the top of Lower Cretaceous (around 300 m) and also the thickest Lower Cretaceous succession, generally up to 400 meters thick, apart from in Fjerritslev-2 (Figures 9 and 15). The wells in this profile also represent the most complete Lower Cretaceous stratigraphy. Albian, Aptian, Barremian, Hauterivian and older strata are present in most of the wells, but unfortunately very little core material is present, so a revision of the biostratigraphy is difficult (Figure 15).

In some cases, the new biostratigraphy has significantly revised previous chronostratigraphic interpretations. The top Lower Cretaceous in the Vendsyssel-1 well was picked using petrophysical logs. New biostratigraphic data from presumed Lower Cretaceous deposits based on cuttings samples gave an Early to Mid Campanian (UC18- 15b-d) age (Appendix C).

The dating of the Albian and Aptian is uncertain, and, in some wells (Frederikshavn-3, Flyvbjerg-1, Vedsted-1, and Fjerritslev-2), the strata are therefore compiled as an Albian/Aptian group. Albian deposits are absent in the Sæby-1 well and Aptian strata are not found in Aars-2. The thickest Albian succession, 91 meters, is found in Hyllebjerg-1, the thickest Aptian section, 212 meters, is found in Haldager-1 and the thickest Barremian section, 100 meters is found in Aars-2. The thickest section of Hauterivian deposits, 170 meters, is found in the Aars-2 well, and deposits older than Hauterivian are 533 meters thick in Fjerrislev-2 (Figure 15). However, these thicknesses are uncertain because many of them are based on petrophysical logs and cuttings. Variations in the depth to the top of Lower Cretaceous, and the thickness of the Lower Cretaceous successions along this profile are related to repeated re-activated faulting in the Sorgenfrei–Tornquist Zone and continuous subsidence in the area during the Late Jurassic to Early Cretaceous (see Figure 4). Some of the shallower wells are affected by uplift due to halokinetic movement (Thisted-1, -4 and Erslev-1, -2) (Figure 8).

Wells along the blue profile from Uglev-1 to Nøvling-1 are all located in the Danish Basin in western Jylland (Figs 8, 15). The top of Lower Cretaceous is generally deeper (from 440 meters to 1700 m) compared with the red profile which is located across the Fjerritslev Trough and the Sorgenfrei-Tornquist Zone, and the Lower Cretaceous succession is also generally thinner (on average 200 meters). In the Uglev-1 well, the top of the Lower Cretaceous section is found at a shallow depth due to an underlying salt diapir and the Rødding-1 well was drilled into the footwall of a normal fault. In general, all the chronostratigraphic stages are thinner. Most of the Albian and Aptian deposits are not defined as discrete units, Barremian beds are thin and only the Hauterivian beds have a thickness equivalent to those in more northern areas.

The green profile represents a transect of offshore wells in the North Sea from the Ringkøbing–Fyn High to the northern boundary of the Danish offshore area (Figs 9, 15). The top of the Lower Cretaceous is located at depths around 1200 to 1400 meters, the average thickness is around 150 meters. Barremian and Hauterivian deposits are well- developed whereas those older than Hauterivian are not preserved with their original depositional thickness.

Wells along the yellow profile from Gassum-1 to Harte-2 represent data from Eastern Jylland, along the present coast, to wells along the margin of the Ringkøbing–Fyn High (Figs 8, 15). The top of the Lower Cretaceous in theGassum-1 and Voldum-1 wells occurs at relatively shallow depths due to halokinetic movement. The top of Lower Cretaceous in Horsens-1, Jelling-1, and Grindsted-1 wells occur at shallow depths and are incomplete due to deposition along the southern basin margin which was structurally controlled by the Ringkøbing–Fyn High. The Gassum-1 well is inadequately dated, and more work is needed to revise cores 17 to 29 (Figure 15). The Voldum-1 well has a thin, but relatively complete Albian to pre- Hauterivian succession.

Along the black profile, in almost all wells to the south of the Ringkøbing Fyn High in Jylland (offshore and onshore) across Fyn, Lolland, Falster and Sjælland, the Lower Cretaceous sections are condensed and very limited biostratigraphic data is available (Figures 8 & 16). The wells from Fyn and Sjælland, e.g., Ringe-1, Ullerslev-1, and Stenlille-1, have very condensed Lower Cretaceous sections (Figure 16). It is only possible to subdivide the successions of two offshore wells (Erik-1x and S-1x) into discrete stratigraphic units. The top of the Lower Cretaceous in the wells in Jylland is found at c. 1000 meters, whereas it occurs at slightly shallower depths in the wells on Fyn. The top of Lower Cretaceous in the Rødby-1 and -2 wells and in Ørslev-1 is found at depths of around 500 meters. In Stenlille-1 much of the Lower Cretaceous is cored, allowing for a detailed sedimentological description (See Appendix A, Stenlille-1).

4.3.1 Summary of the Lower Cretaceous biostratigraphy

The Lower Cretaceous succession is thickest in the Danish Basin in northern Jylland, with thicknesses of 200–400 meters in the Børglum-1, Farsø-1, Fjerritslev-2, Flyvbjerg-1, Frederikshavn-3, Haldager-1, Hyllebjerg-1, Mejrup-1, Mors-1, Vedsted-1 and Aars-1 wells (Figs 1 & 9). In these wells the total thicknesses of the Middle Jurassic to Lower Cretaceous also reach maximum values l (Figures 2, 8 & 9). In comparison, the Lower Cretaceous successions in the Stenlille-1, Ringe-1, and Vinding-1 wells located along the southern margin of the Danish Basin are thin and condensed.

The upwards change in lithology from mudstone to calcareous mudstone is important. Table 2 shows the carbonate content measured from selected Lower Cretaceous cores. The oldest part of the Vedsted Formation (pre-Hauterivian) generally has low carbonate content (Vinding-1, core 29–306; Haldager-1, cores 26–47; Frederikshavn-1, cores 58–85), while the carbonate content is higher in the Hauterivian–Albian parts of the Vedsted Formation (Table 3). The calcareous mudstones and sandstones accumulated at a much lower rate during the same period (Figure 16). It may be speculated that a marine transgression drowned areas on Sjælland and Lolland and thereby reduced the siliciclastic input, where the Vedsted or Rødby Formations directly overlie the Lower Jurassic Fjerritslev Formation (Stenlille-1, Rødby-1). In the Lavø-1 well, the undated Fjerritslev Formation and glauconitic sandstones (cores 7−8) occur below Upper Cretaceous (Cenomanian) sandstone (core 6) (see Appendix A). It is tentatively suggested that the glauconitic sandstones in Lavø-1 may correlate with glauconitic sandstones found near the boundary between the Vedsted and Rødby Formations in the Fredeirkshavn-1well.

***Table 2**. Carbonate content in Lower Cretaceous deposits in the Danish Basin (data from completion reports and Larsen, 1966).*

***Tabel 2**. Kalkindholdet i sedimenter fra Nedre Kridt i Det danske Bassin (data fra completion rapporter og Larsen, 1966).*

Core	**Depths**	**CaCO3 (listed from top to base of measured core)**	**Formation**	**Age**
Børglum-1	2018 to 2038'	20 - 50%	Vedsted	L. Cretaceous
Frederiks-havn-1	All core	less than 20%	Vedsted?	L. Cretaceous
Rødby-1	459 to 469m	62 - 80%	Rødby	L. Cretaceous
Lavø-1	all core	around 20%	?	Cenomanian
Skagen-2	802' to 820'	around 20%	?	L. Cretaceous
Ullerslev-1	800 to 826m	40 to 85%	Rødby and Vedsted	L. Cretaceous
Vedsted-1	814 to 820m	60%	Vedsted	L. Cretaceous
Haldager-1	1815 to 1830'	40%	Rødby?	L. Cretaceous
Haldager-1	2000 to 2015'	less than 10%	Rødby/Vedsted?	L. Cretaceous
Haldager-1	2180 to 2195'	around 40%	Vedsted	L. Cretaceous
Vinding-1	4262 to 4278'	80%	Rødby and Vedsted	L. Cretaceous
Vinding-1	4399 to 4016	20 to 30%	Vedsted	L. Cretaceous
Vinding-1	4461 to 4477'	less than 20%	Vedsted	L. Cretaceous

5. Sedimentological description and analysis

Detailed sedimentological descriptions are made of the available core material from the Jurassic and Lower Cretaceous sections (Table 3). The descriptions are made to enable a detailed characterisation of the lithological variations, the corresponding rock properties, and the scale of homogeneity/inhomogeneity. Further, the facies descriptions are used for interpretation of depositional processes and environments. Knowledge about depositional environments and paleogeography can be used for prediction of the lateral extent of specific lithologies, as well as lithological changes in certain directions, e.g., from offshore mudstone to shoreface sandstone as presented in the depositional models. The predictions are normally made as a range of outcomes, alternatively, different scenarios are identified.

All the sedimentological logs are presented in appendix A, the corresponding facies descriptions and interpretations are presented in Appendix B and listed in tables as presented in Appendix C. The identified facies, the log signatures and their interpreted depositional environment are illustrated in Figure 17A and B, and 18.

The sedimentological descriptions of the various formations are based on available core material varying in vintage and quality with diameters ranging from 8–10 cm to c. 3 cm. The depths were originally measured either in feet or in meters below reference level, which is usually related to the drill rig (Rotary table, Drill floor, or Kelly Bushing). The original depths are shown on the sedimentological logs to retain the correlation to the original data and to previous studies.

Jurassic sections	**Lower Cretaceous sections**
Frederikshavn-1	Frederikshavn-1
Børglum-1	Børglum-1
Flyvbjerg-1	Haldager-1
Fjerritslev-1	Lavø-1
Fjerritslev-2	Fjerritslev-2
Haldager-1	Haldager-1
Lavø-1	Lavø-1
Rødby-1	Ringe-1
Stenlille-1	Rødby-1
Stenlille-4	Stenlille-1
Vedsted-1	

Table 3*. List of wells where existing core material from Jurassic and L. Cretaceous sections has been logged for sedimentological analysis (Logs are found in Appendix A).*

Tabel 3*. Liste over boringer hvorfra kerner er beskrevet i dette studie (sedimentologiske logs findes i Appendix A)*

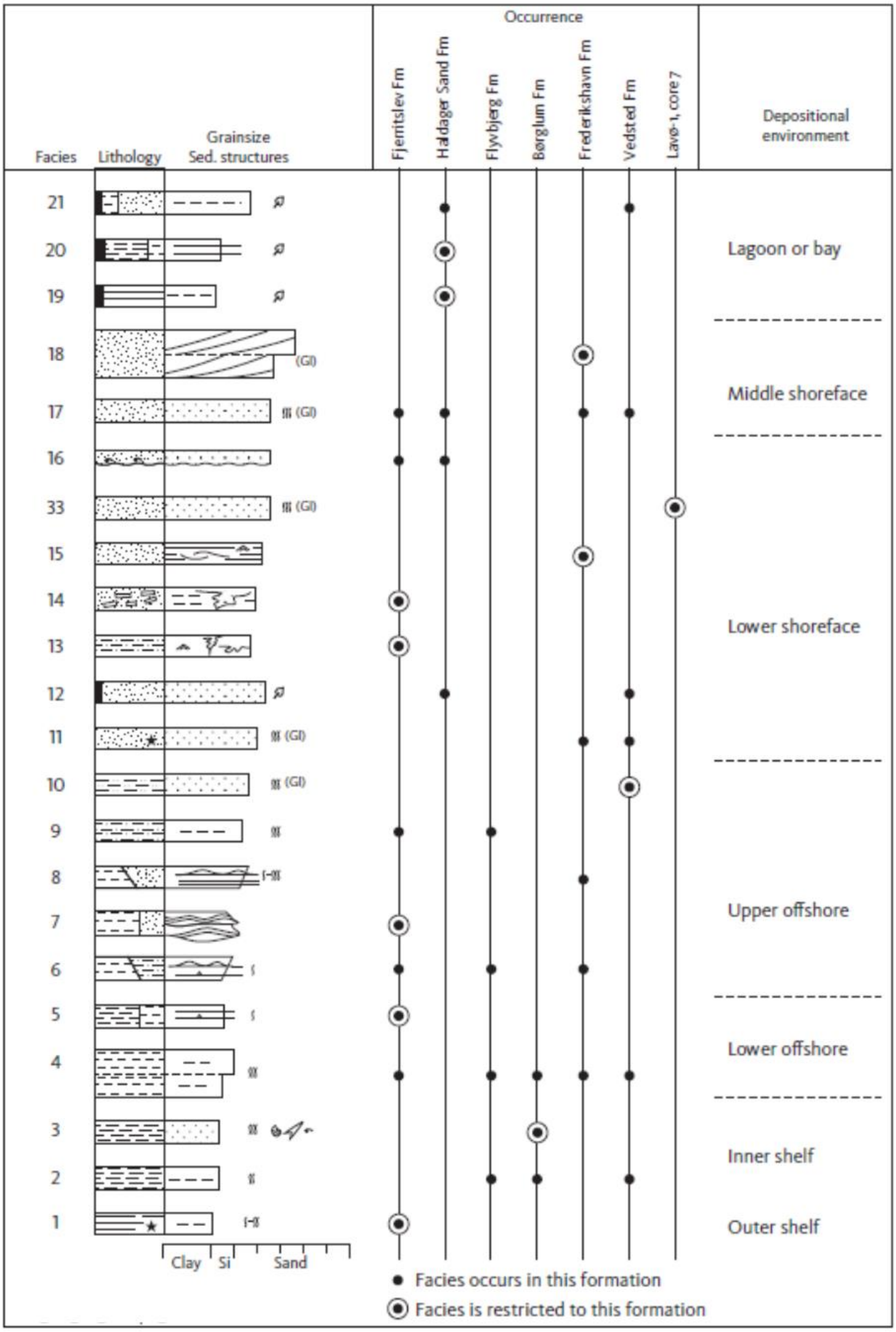


***Figure 17A**. Facies identified and described in cores form the Jurassic and Lower Cretaceous sections.*

***Figur 17A.** Facies der er identificeret og beskrevet i kerner fra Jura og Nedre Kridt.*

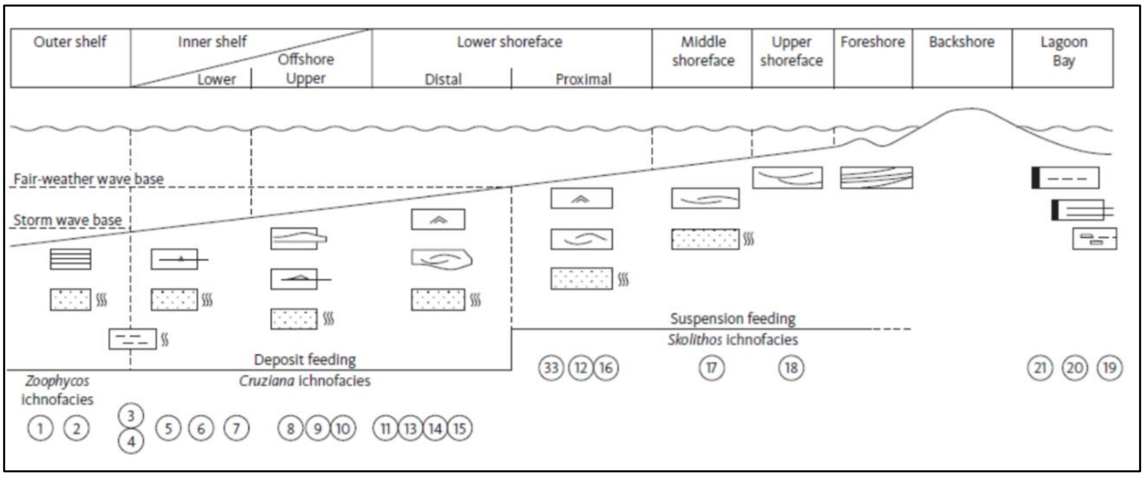


Figure 17B. *Facies model showing interpreted depositional environments for the defined facies (after Pemberton et al., 2012).*

Figur 17B. *Faciesmodel der viser tolkede aflejringsmiljøer for de definerede facies (efter Pemberton et al., 2012).*

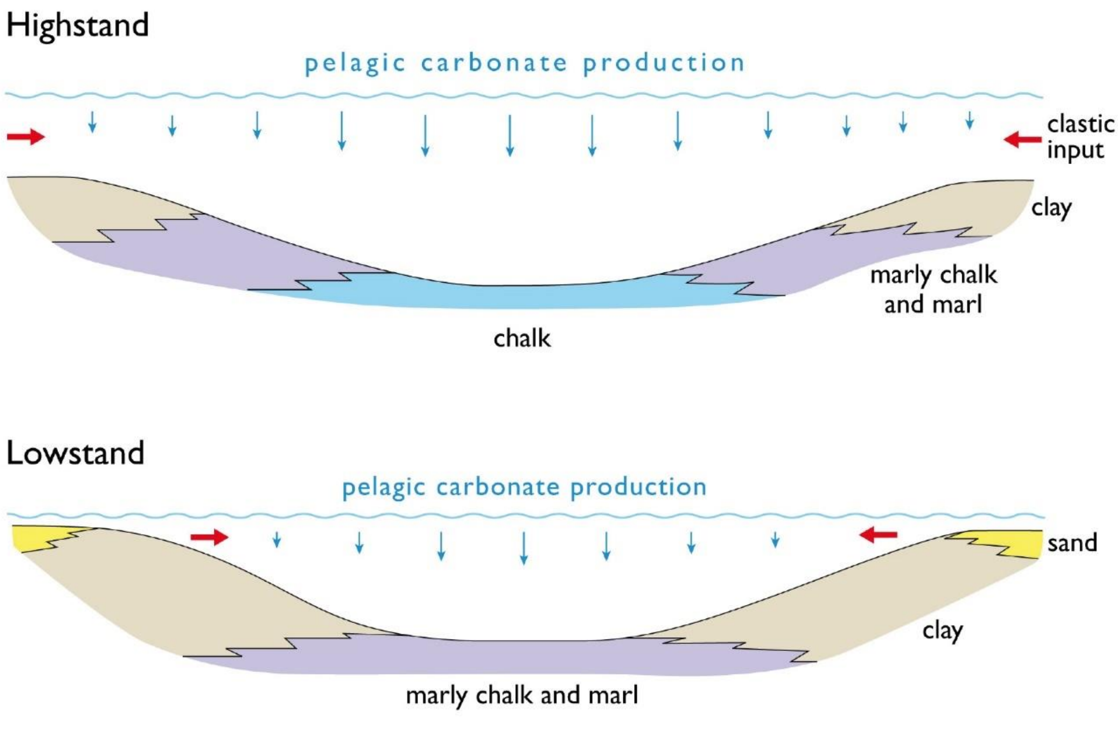


***Figure 18**. Model for the deposition of mixed siliciclastic-carbonate facies, based on Ineson (1993) and Ineson et al. (1997).*

***Figur 18.** Model for aflejring af vekslende siliciklastiske og karbonatrige sedimenter baseret på Ineson (1993) og Ineson et al. (1997).*

The sedimentological logs record the lithology and grain-size, the sedimentary structures and trace fossils (where possible), and additional observations on macro fossils (invertebrates), coal debris, diagenetic minerals (such as pyrite or jarosite), and concretions. The colours of the dry sediments are mentioned in the facies descriptions (Appendix B). The average grain-sizes are estimated macroscopically, with some uncertainties especially where sediments comprise heterolithic interbedded laminae of various grain sizes (i.e., clay, silt, fine grained sand, and carbonate). Representative core photos of the sedimentary facies are presented later in this section.

The length of cored sections, as well as their stratigraphic position, is highly variable from well to well. On average, less than 10 % of the drilled sections are cored. Thus, the available cores may not be representative of the dominant lithologies in a specific formation, but rather they present examples of the sedimentological features. Even small sections of core are very important as they are used for calibration of interpreted lithologies from well logs, and for the rock properties, when core analysis has been performed.

This study has focussed on the sections dominated by mudstone, which may potentially be suitable for a geological repository for radioactive waste. However, sand beds of varying thicknesses occur interbedded with the mudstones. It is therefore also important to characterise the sand, to enable mapping and prediction of its presence, which may compromise the barrier effectiveness of the claystones and mudstones.

5.1 Sedimentary facies and depositional environments

Sediments in the Jurassic and Lower Cretaceous sections were deposited in environments representing a range from marine, deep water offshore areas, where sedimentation was dominated by suspension fall-out of clay size particles, to the offshore and lower shoreface environments where deposition of clay was occasionally interrupted by deposition of sand supplied by density, or storm driven traction currents, to shallow water wave influenced shorefaces, and more rarely back barrier lagoonal environments (Figure 17A & B).

Figure 17A illustrates the lithology, grainsize and sedimentary structures characterising the facies found in the cores, and their interpreted depositional environments. Pictures of the various facies are presented in the following sections. The vertical succession shows an upwards grain size increase reflecting a change towards a higher energy level during sediment deposition which is generally related to a gradual shift towards a more proximal position relative to the sediment source. The lagoonal facies in the uppermost part of the diagram are rather fine gained, due to deposition in sheltered lagoons and back shore environments where sand was supplied only during major storm events (Figure 18).

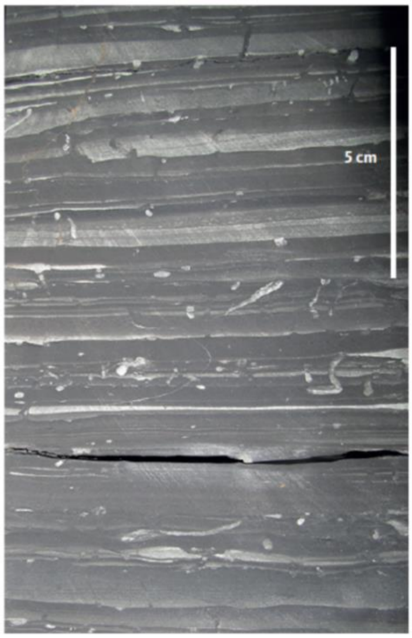
In the upper part of the Lower Cretaceous Vedsted and Rødby Formations carbonate rich sediments, such as marl and limestones, occur interbedded with mudstones and represent deposition in a mixed carbonate-siliciclastic system, as illustrated in the model in Figure 18.

5.2 Sedimentology of the Jurassic formations

In the Jurassic sections, the marine mudstones have been divided into a range of facies from black to grey or brownish clayey mudstone (Figure 19) to silt-streaked mudstone (Figure 20). The heterolithic mudstone (Figure 21) contain a higher proportion of silt and very fine-grained sand, and the small-scale sedimentary structures indicate a higher energy depositional environment with occasional deposition from traction currents.

Deep marine, offshore to shelf mudstones (facies 1-6) occur in the Fjerritslev, Flyvbjerg, Børglum, Frederikshavn, and Vedsted Formations. Heterolithic sandstone of thinly laminated fine-grained sand and clay occurs in the Frederikshavn and Vedsted Formations and locally in the Fjerritslev Formation. Lower shoreface sediments include a greenish, sandy siltstone (facies 10) occurring in the Frederikshavn and Vedsted Formations. A grey siltstone unit (facies 13 and 14) has been found only in the basal part of Fjerritslev Formation in the Stenlille wells 1 to 5, and in Rødby-1.

Rødby-1, 535-541 m.



Laminated inner shelf mudstone (facies 2), burrows 1-2 millimeters cut the lamination. Stenlille-1, core 2, box 10

Figure 19. *Laminated inner shelf mudstones (facies 2), Fjerritslev Formation*

Figur 19*. Lamineret muddersten der er aflejret på den indre shelf (facies 2), Fjerritslev Fm.*

Figure 20. *Lower offshore laminated silty mudstone (Facies 5), Fjerritslev Fm.*

Figur 20*. Muddersten aflejret på dybt vand nær stormbølgebasis, eksempler fra Fjerritslev Fm (Facies 5).*

Stenlille-4, core 2, box 8.

Børglum-1, core 1, box 3, 1587'-1607'

Figure 21. *Various appearances of heterolithic, upper off-shore mudstone composed of interbedded silty clay and very fine-grained sand occasionally with wave generated ripple lamination as observed in Stenlille-4 (Fjerritslev Fm). Burrows are few.*

Figur 21. *Vekslende lag af ler og finsand med bølgegenererede ribber aflejret i et marint offshore miljø. Lille grad af bioturbation er observeret. De to billeder illustrerer den varierende kvalitet af det tilgængelige kernemateriale.*

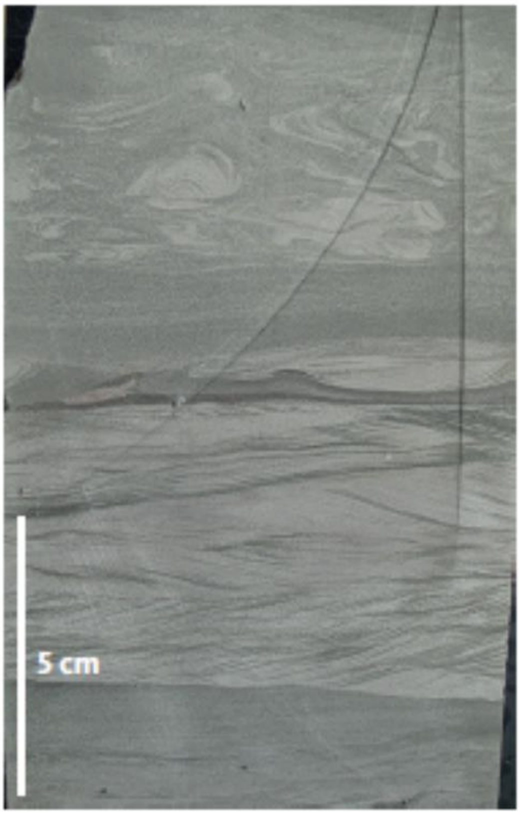
Very fine-grained sandstones with parallel lamination and wave-ripple cross-lamination (Facies 15) represent distal storm sand layers (Figure 21). The shoreface sandstones display a range of physical structures including horizontal to low angle lamination, more rarely cross-bedding and varying degree of bioturbation (Figures 22 and 23).

Fine grained, heterolithic sandstone. Gassum Fm. Flyvbjerg-1, core 6, box 4, 1316 m

Very fine grained sandstone, primary sedimentary structures obliterated due to bioturbation. Stenlille-4, core 2, box 6.

Figure 22. *Examples of heterolithic shoreface sandstones (facies 8).*

Figur 22*. Eksempler på vekslende sand- og siltlag aflejret i et kystnært miljø (facies 8)*



Fjerritslev Fm. fine grained sandstone displaying crosslamination and soft sediment deformation structures. Stenlille-1, core 5, 1496 m

Medium grained shoreface sandstone, Frederikshavn Fm, Haldager-1, 1498 m, box 1, 3040'-3060'.

***Figure 23**. Examples of shoreface sandstones.*

***Figur 23.** Eksempler på sandsten aflejret i kystnært miljø.*

5.2.1. The Fjerritslev Formation

The Fjerritslev Formation constitutes a major part of the Lower Jurassic succession. The paleogeographic maps in Figure 4 show that most of onshore Denmark was covered by a deep marine depositional environment where marine sediments were deposited in the Danish Basin during the early Jurassic (Michelsen et al. 2003). The maps also show that the Fjerritslev Formation is the only Jurassic formation that extends across the entire Danish onshore area.

In the central part of the Danish Basin, offshore mudstones form a laterally continuous unit increasing in thickness from ca. 450 meters in Kvols-1 to more than 600 meters in Hyllebjerg-1, Figure 18. Interbedded mudstones and sandstones in the basal part of the Haldager-1 well (Figures 11 and 12) illustrate that lateral facies changes and interfingering between shallow marine sand dominated environments at the basin margins to the north and offshore marine depositional systems dominated by mud is common in the depocenter (Fig 4, grey area). Jurassic mudstones are not exposed in outcrops in Denmark, but an example of an equivalent to the Fjerritslev Formation is shown in Figure 24. This mudstone section was formerly exposed in a pit at Gantofta in Skåne, southern Sweden (Frandsen & Surlyk 2003; Figure 24.

***Figure 24**. Lower Jurassic mudstone exposed in a former clay pit at Gantofta, Skåne. The colour variations are caused by varying ratios, and thicknesses of claystone to silt- or very fine-grained sandstone laminae.*

***Figur 24**. Nedre jurassiske muddersten i en tidligere lergrav ved Gantofta, Skåne. Farvevariationerne skyldes variationer i forholdet mellem ler, og silt- til meget finkornet sandsten.*

Sedimentary facies representing deep to shallow marine depositional environments are recorded in the Fjerritslev Formation, an example is presented in Figure 25. The mudstone composition ranges from laminated claystone, and silt-streaked mudstone (Figure 20) to heterolithic mudstone (Figure 21) and, less commonly, heterolithic sandstone (Figure 22). Small scale variations occur on a 1–10 cm scale (Figures 19-21), but larger scale variations (on a meter scale) are also present.

In some wells, the lower part of the Fjerritslev Formation is sandy whereas the upper part is dominated by silt and mudstone, an example is the Stenlille-1 well, Figure 25.

The thick mudstone succession in Kvols-1 and Hyllebjerg-1 shows minor lithological variations on both cm scale and on a 10–20 meters scale (Michelsen 1989b). The cores from the Stenlille wells (drilled around 1980) have enabled the identification of a wealth of details in the mudstone facies and indicate that the sedimentary facies are laterally continuous in the Stenlille area (Mathiassen et al. 1989, Lindström et al. 2015).

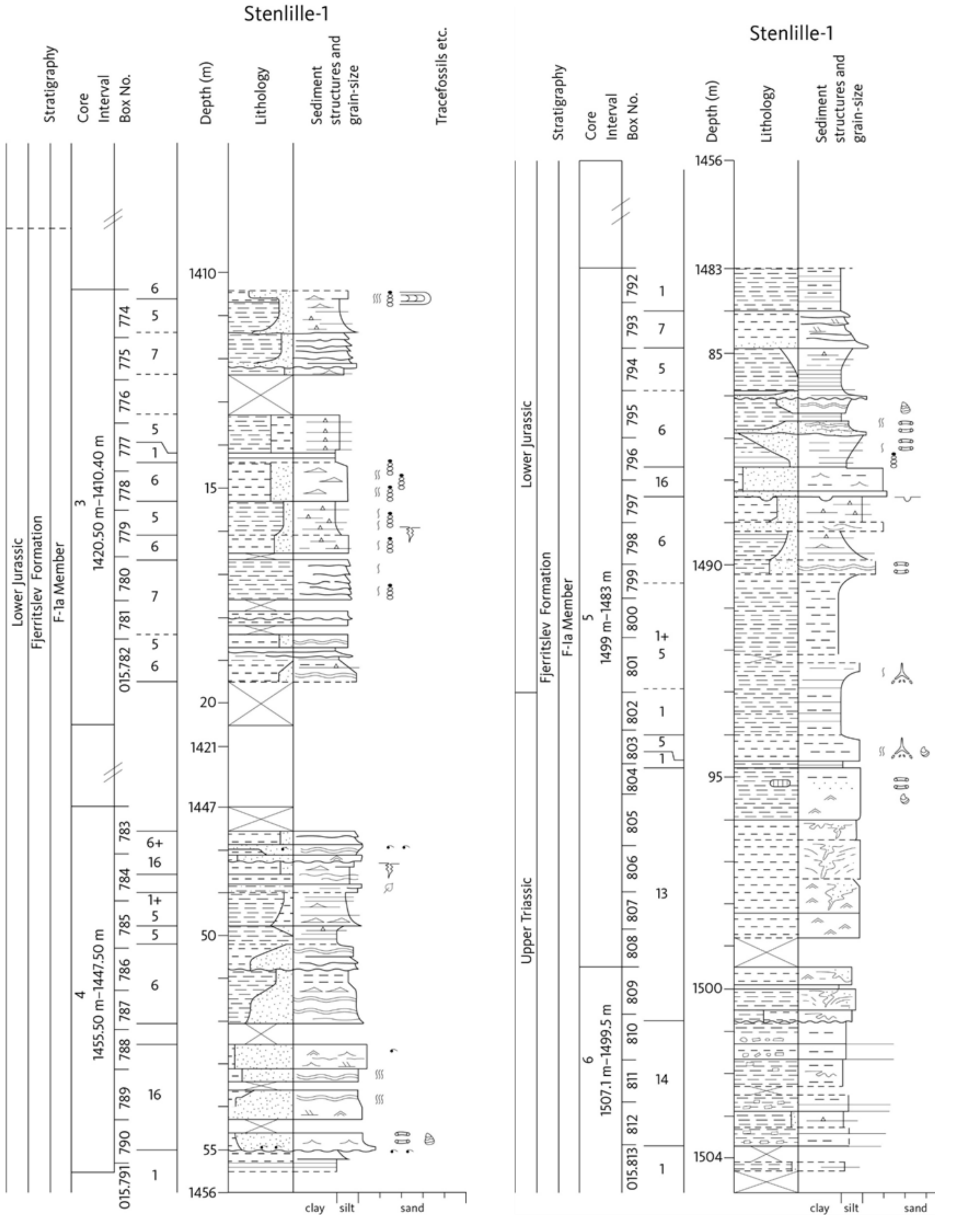


Figure 25. *Examples of the interbedded lithologies as identified in Stenlille-1 cores from the Fjerritslev Formation and uppermost part of the Upper Triassic Gassum Formation. Facies numbers are indicated in the column between Box no. and Depth.*

Figur 25*. Eksempel på vekslende lag der forekommer i Fjerritslev Formationen og øverste del af Gassum Formationen, opmålt i kerner fra Stenlille-1.*

5.2.2 The Haldager Sand Formation

The Haldager Sand Formation is dominated by shallow marine sandstones deposited at the northern margin of the Danish Basin in northern Jylland (Figure 4) and the maximum thickness encountered is around 150 meters in the Haldager-1 well (Figure 5). The Haldager Sand Formation comprises sand-dominated, coastal to non-marine deposits and only few cores have been studied (Table 1, 17A, B). In Vedsted-1 and Haldager-1, the formation comprises stacked fluvial and coastal sandstones separated by thin marine, lacustrine and lagoonal mudstones, and the upper boundary to the Flyvbjerg Formation is gradual and represents a marine flooding surface (Nielsen 2003; Figures.11, 12 & 26). The lower boundary is, based on well logs, sharp (erosional) to gradational.

5.2.3 The Flyvbjerg Formation

The Flyvbjerg Formation comprises lower shoreface silty mudstones, siltstones, and fine-grained sandstones to deep marine mudstones. It is up to 64 meters thick (average around 30 meters) and the formation is characterized by interbedding of 1-8 meters thick, muddy siltstones and sandstones throughout the formation (Michelsen et al. 2003, Nielsen 2003). Lithological variations can be seen in the log panels (Figures 5-7) and in the sedimentological log in Figure 26.

The formation may be regarded as representing a gradual transition from shallow marine sand dominated depositional environments of the Haldager Formation to the more distal offshore setting with deposition of the clay dominated sediments, which constitute the Børglum Formation. Thus, the Flyvbjerg Formation forms a heterogeneous section of sand, silt and clay with different thicknesses, and different facies/lithology distributions in each well.

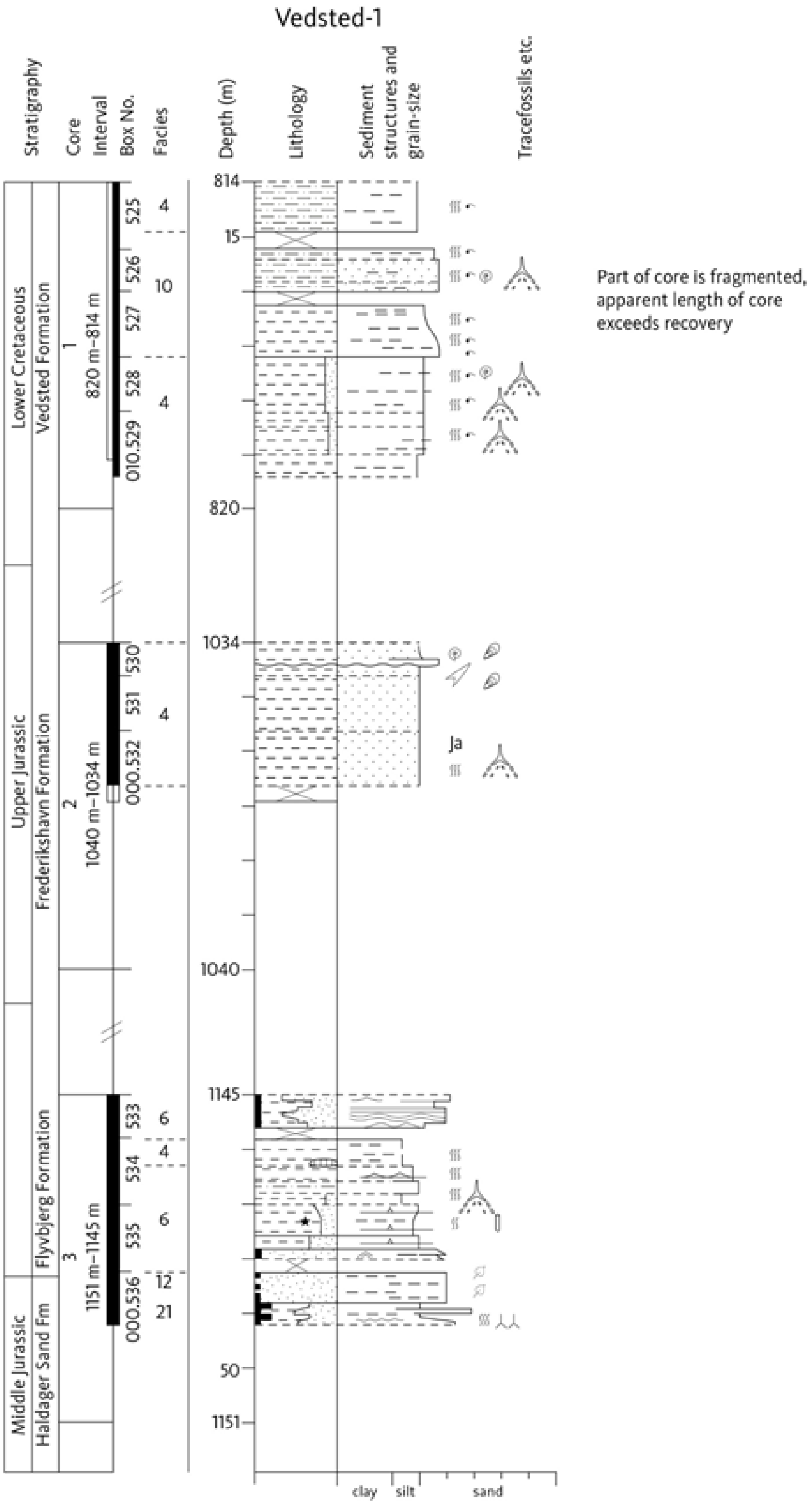


Figure 26. *Sedimentological log with examples of lithologies and facies in the Haldager Sand Formation, the Flyvbjerg Formation, the Frederikshavn Formation and L. Cretaceous Vedsted Formation, Vedsted-1 well. The short 6 meters cores are cut every c. 100 meters of the well.*

Figur 26*. Sedimentologisk log af dele af Haldager Sand Formationen, Flyvbjerg Formationen, Frederikshavn Formationen og Vedsted Formationen, kerne fra Vedsted-1 boringen.*

5.2.4 The Børglum Formation

The Børglum Formation is generally less than 50 meters thick in wells drilled in the central Danish Basin in northern and central Jylland and up to 100-111 meters thick in offshore wells NW of Hanstholm (Nielsen & Japsen 1991). The formation comprises a rather homogeneous unit of mudstones which in the upper part represents a time equivalent to the Frederikshavn Formation shoreface sandstones (Figure 3). On well logs, the Børglum Formation is defined by continuously high levels of gamma readings indicating rather uniform sections of mudstone (Michelsen et al. 2003) (Figures 5-7). The Børglum Formation is fully cored only in the Frede-rikshavn-1 well, and partly in the Haldager-1 well. Sedimentary facies of inner shelf to lower shoreface heterolithic mudstones dominate in the Børglum Formation (Figures 19-21).

The palaeogeographic maps of the Kimmeridgian and Volgian–Early Ryazanian (Figure 4) shows that the marine Børglum Formation mud was deposited in a widespread basin extending across the northern parts of Jylland and with a relatively narrow fringe of shoreface sands along the southern margin.

5.2.5 The Frederikshavn Formation

The Frederikshavn Formation is known from wells drilled in the Danish Basin in northern and central Jylland, where it is 50–250 meters thick (Nielsen & Japsen 1991). It is partly co-eval with mudstones of the Børglum Formation, thus representing the shallow marine environments at the basin margin, as illustrated on the paleogeographic maps in Figure 4.

The formation typically comprises two to three units coarsening-upwards from mudstone to shoreface sand, best developed in the central and northern part of the Kattegat–Skagerrak Platform (Figure1). The formation is cored continuously in the Frederikshavn-1 well and Haldager-1 wells (Figures 5). Shelf to lower shoreface mudstones occur in most wells interbedded with shoreface sandstones (Figures 3, 17A, B & 27). Locally, the Frederikshavn Formation mudstones have relatively high amounts of organic material and TOC values up to 2-3% (Petersen et al. 2008).

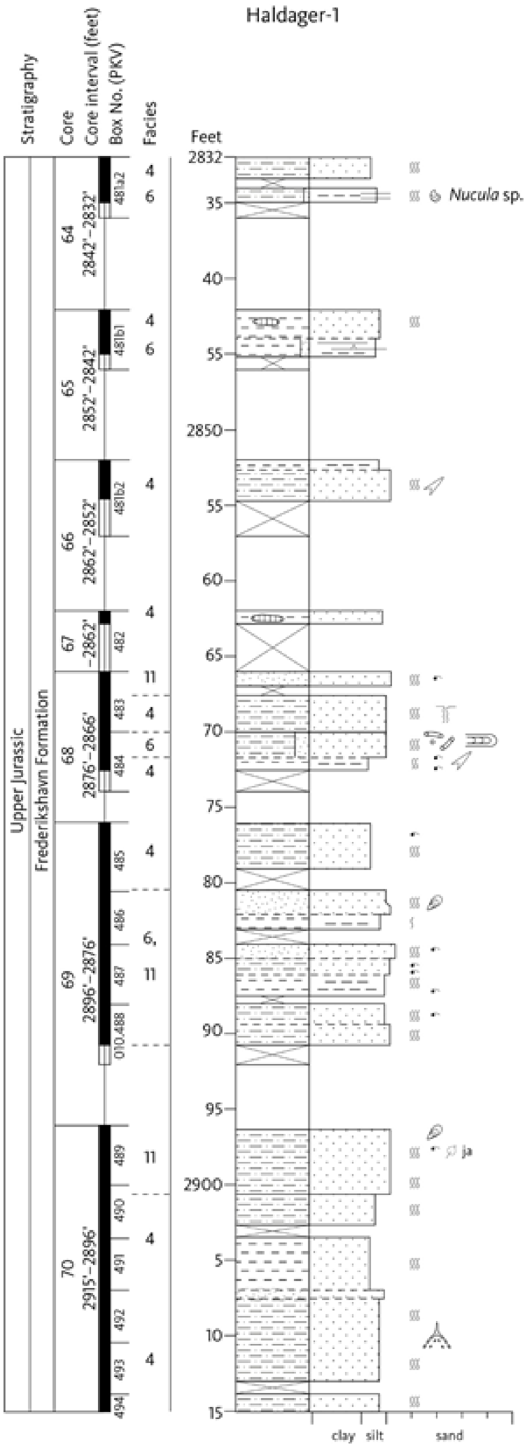


Figure 27. *Sedimentological log illustrating lithology and facies variations in the Frederikshavn Formation as cored in the Haldager-1 well.*

Figur 27. *Sedimentologisk log der viser litologiske variationer i Frederikshavn Formationen baseret på kerner fra Haldager-1 boringen.*

5.2.6 Regional variations of facies and thickness in the Jurassic

During the Early Jurassic offshore marine settings existed across most of the Danish area with deposition of several hundred meters of marine mud as seen in Vedsted-1, Fjerritslev-2 and Farsø-1. In the northernmost part of Jylland (in e.g., the Frederikshavn-2, Sæby-1, Haldager-1) and on Sjælland and Lolland (Lavø-1, Stenlille-1 and Rødby-1) the section comprises numerous thin sand layers representing interfingering between the offshore mud dominated environments and the shallow marine sand dominated, high energy environments. In northern Jylland the Gassum and Fjerritslev Formations co-existed in the Hettangian and early Sinemurian (Pedersen 1985, Nielsen 2003).

Greatest thickness is found in the Fjerritslev-2 with 900 meters whereas thicknesses of 100-200 meters are generally found on Sjælland representing the basin margin areas with less accommodation space.

Middle and Upper Jurassic deposits are found only in the northern part of Jylland. The Børglum Formation is the only claystone dominated section and has the thickest section around 110 meters found in Fjerritslev-2) where both underlying and overlying formations comprise sand dominated sediments deposited at the basin margin as illustrated in the paleogeographic maps in Figure 4. The deposits are absent in other parts of Denmark indicating these areas were dominated by non-deposition and/or erosion.

Based on well data the only areas where Jurassic mudstone sections are found at depths around 500 meters are in Ørslev-1, Søllested-1, and Rødby-1. In northern Jylland the mudstone dominated sections occur at depths greater than 500 meters. The well logs indicate however, the presence of numerous sand layers (Figure 6) as also seen on the sedimentological log from Rødby-1 (Appendix A).

5.3 Sedimentology of the Lower Cretaceous mudstones

The Lower Cretaceous section is dominated by mudstones forming a range of lithologies from claystone, siltstone, sandstone and marl to calcareous mudstone and limestone. The mudstones are often laminated, displaying varying colours from white, light grey, greenish grey to grey and red reflecting various amounts of argillaceous material including high amounts of kaolinite, and carbonate. The drilled sections are dominated by marine shelf to offshore mudstones, and less common lagoonal mudstones and shoreface sandstones. Thicker beds of lower shoreface sandstones have been recognised only in the Lavø-1 well near the Sorgenfrei-Tornquist fault zone (Figure 6 shows well logs from Lavø-1).

The carbonate content of the Lower Cretaceous lithologies has not been measured systematically, but the available data are listed in Table 13. This shows a highly varying carbonate content from less than 10 % to more than 80 %. High carbonate contents occur in the uppermost part of the Lower Cretaceous section (Aptian – Albian).

The widespread occurrence of Lower Cretaceous marine mudstones indicate that a marine depositional environment prevailed during the late Jurassic and the early Cretaceous, with varying supply of argillaceous sediments. Onset of pelagic carbonate production occurred in the late Early Cretaceous and high rates of pelagic carbonate production resulted in the deposition of carbonate beds during the Aptian and Albian. Mudstones and carbonate beds forming the upper part of the Vedsted Formation and the overlying Rødby Formation were deposited in a mixed siliciclastic-calcareous depositional system (Figure 18, Ineson et al. 1993).

The Vedsted Formation and the Rødby Formation comprise mainly offshore and shelf mudstones with varying proportions of carbonate and argillaceous sediments with high amounts of kaolinite (Table 2). The major difference seems to be that sediments in the Rødby Formation are often red, but with a large variety of colours besides grey. The occasional presence of belemnites demonstrates a fully marine offshore depositional environment.

Deposition of late Early Cretaceous clay, calcareous mud, and carbonate is inferred to have been controlled by the paleogeographic position and the sea-level, as illustrated in Figure 18. During periods of high sea-level deposition of pelagic carbonates became widespread and the influx of sand and clay is reduced as these sediments are stored in more landwards settings. During periods of low sea-level, the influx of sediment from rivers dominate deposition at basin margins, but also extends into the basin centre. Highest concentrations of pelagic carbonate accumulation (microfossils) occurred in the basin centre far from the siliciclastic sediment sources, thus composing large proportions of the sediments during periods with minor supply of argillaceous material.

5.3.1 The Vedsted Formation

Cores from the Vedsted Formation are of highly varying quality and the formation is cored continuously only in Frederikshavn-1 and in most of Haldager-1.

Offshore mudstones occur interbedded with lower shoreface mudstones and sandstones dominate the lower part of the Vedsted Formation (Figures 28-31) whereas the upper part is characterised by argillaceous sediments interbedded with carbonate-rich layers which occur more frequently towards the top of the formation (Figures 32-33). Sandy beds of a few meters thickness occur occasionally.

Offshore mudstones and heterolithic shoreface deposits of sand and mudstone characterise the Vedsted Formation in the central part of the Danish Basin, in northern Jylland and at Fyn (Ringe-1), and the Lavø-1 well on Sjælland (Figures 5 and 28). In Stenlille-1, the formation includes calcareous mudstones, and siliciclastic mudstones. Examples of sedimentological logs with facies interpretations are shown in Figure 28. The log measured from Stenlille-1 reveals sedimentological details, however, compared to the log from Frederikshavn-1 they both show a section dominated by silt with the occasional occurrence of sandy intervals, or distinct sand layers.

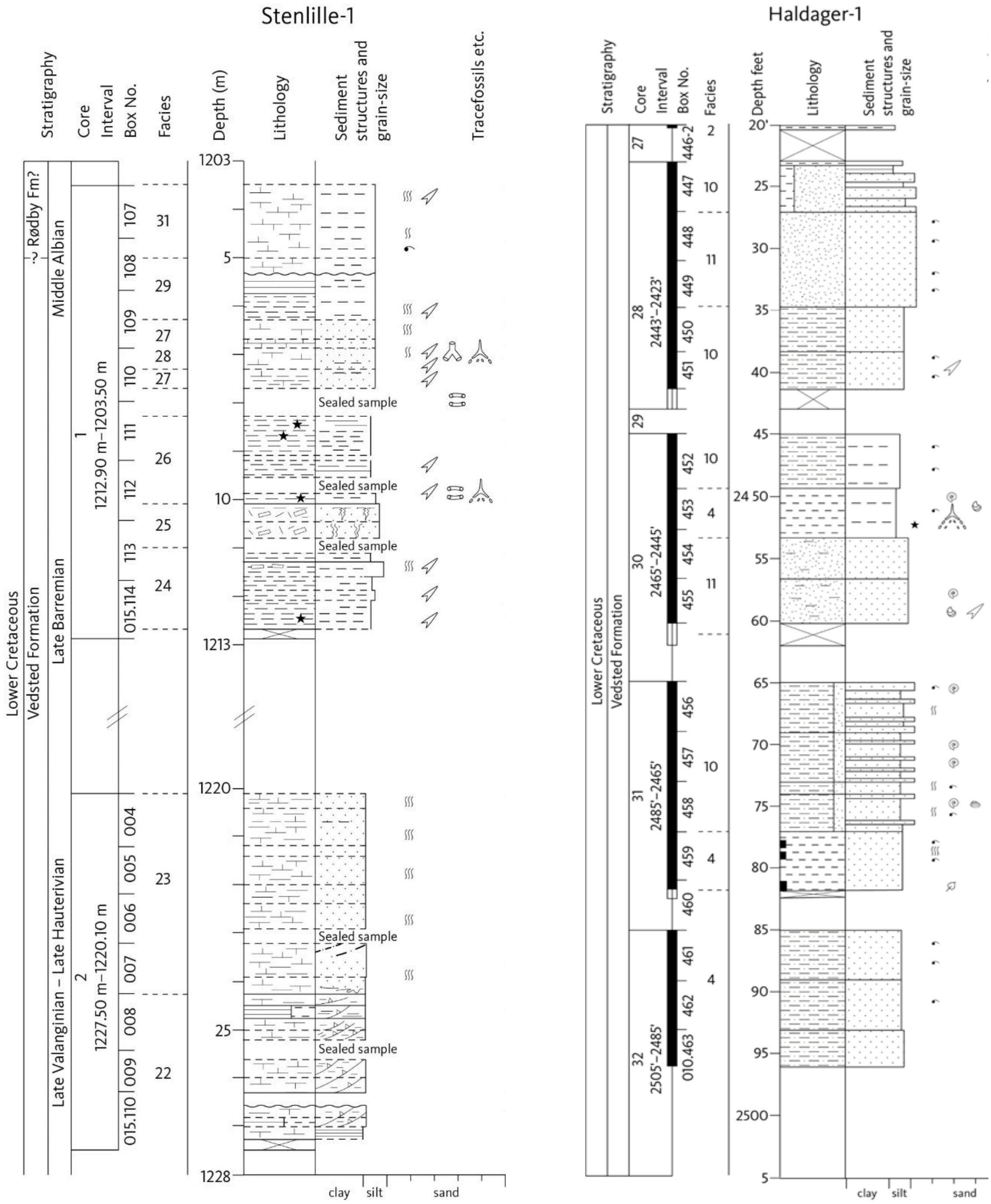
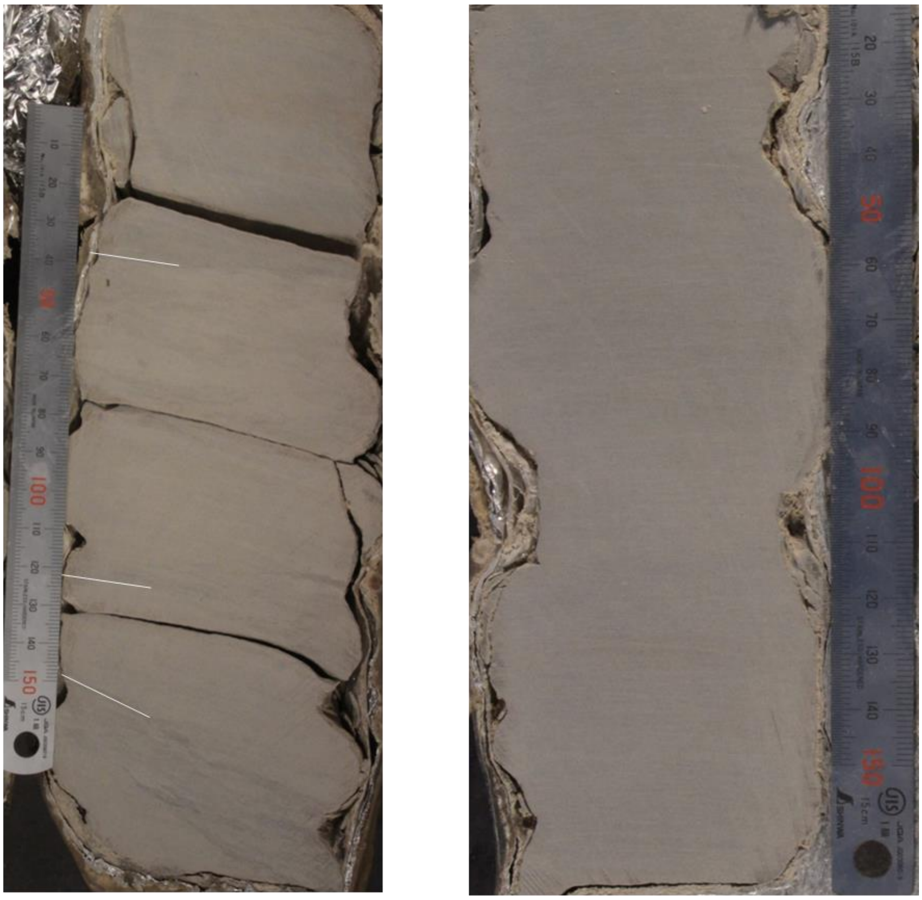


Figure 28. *Sedimentological logs of the Vedsted Formation in Stenlille-1, and Haldager-1.*

Figur 28. *Sedimentologiske logs af Vedsted Formationen i Stenlille-1 og Haldager-1.*

Figure 29*. Laminated mudstone, facies 22, Vedsted Formation in Stenlille-1.*

Figur 29*. Lamineret muddersten, facies 22, Vedsted Formationen, Stenlille-1.*

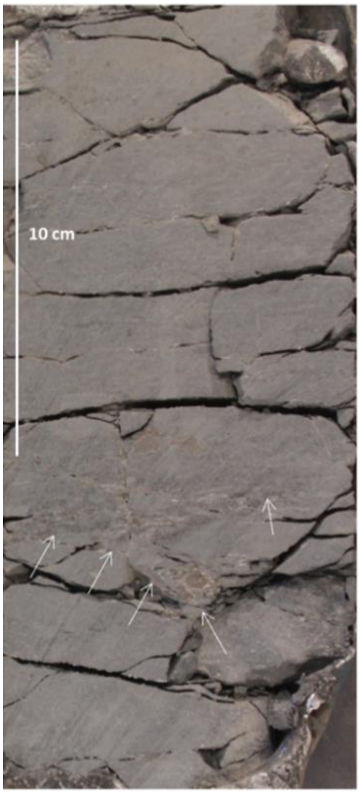


Stenlille–1, core 2, box 4, 1223.62–.88 m

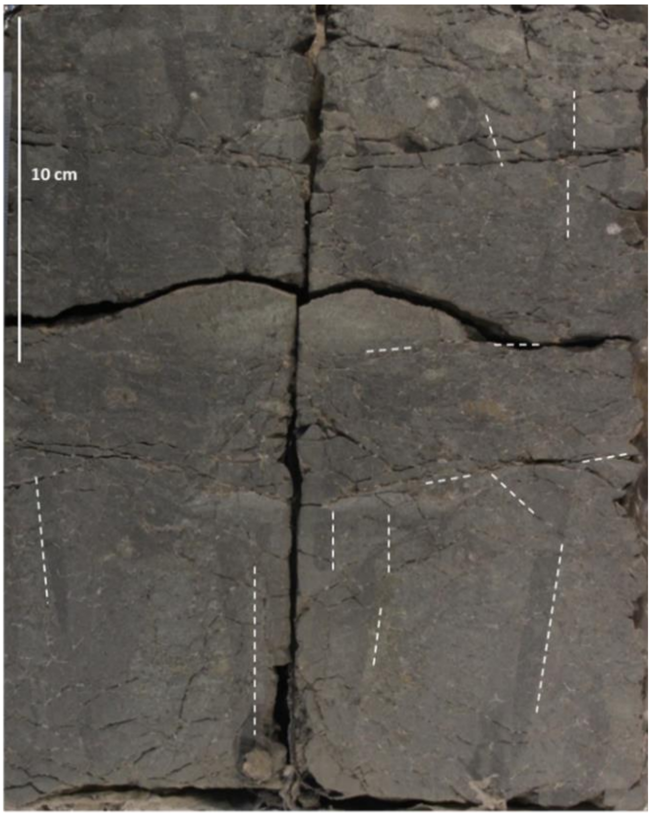
Stenlille-1, core 2, box 2, 1221.64–.82 m

Figure 30*: Grey-green mudstone with indistinct lamination (Facies 23), Vedsted Formation.*

Figur 30*. Grågrøn strukturløs muddersten (facies 23) fra Vedsted Formationen.*



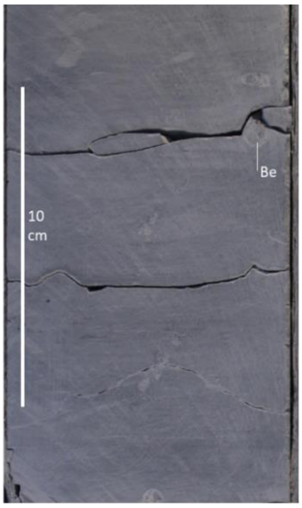
Facies 24, box 8b, 1212,45-64 m.



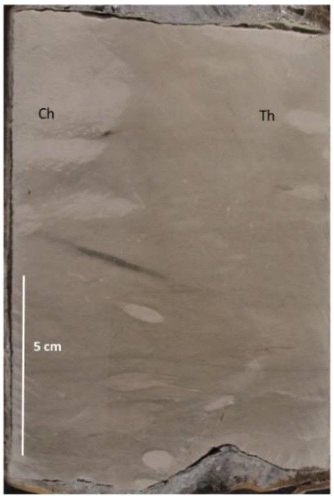
Facies 25 of sandy, silty mudstone with vertical water escape structures indicated with white dotted lines). Box 6, 1210.05-.29 m

***Figure 31**. Grey structureless mudstones of facies 24 and 25 with local occurrence of sand and shell debris as indicated with white arrows. Vedsted Formation, Stenlille-1, core-1.*

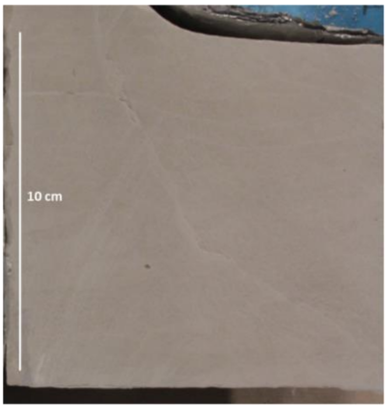
***Figur 31**. Grå strukturløse muddersten, facies 24 og 25. Vedsted Formationen, Stenlille-1, kerne-1.*



Facies 26. Grey mudstone, bioturbated, with belemnite (Be). Box 4, 1207.14–.33 m



Facies 27. Pale olive brown marl or very fine-grained limestone, bioturbated, *Chondrites* (Ch) and *Thalassinoides*? (Th). Box 4, 1206.90–1207.02 m



Facies 28. Limestone, white, structureless. Facies 28 is observed only as one 11 cm thick bed in Stenlille-1. Box 3, 1206.72–.83 m

Figur 32

***Figure 32 (previous page)**. Mudstone, marl, and limestone in a 60 cm thick succession of the Vedsted Formation in Stenlille-1, core-1 (facies 26, 27, 28).*

***Figur 32 (forrige side)**. Muddersten, mergel og kalksten der tilsammen udgør et 60 cm tykt lag i Vedsted Formationen i Stenlille-1, kerne-1, (facies 26, 27, 28).*

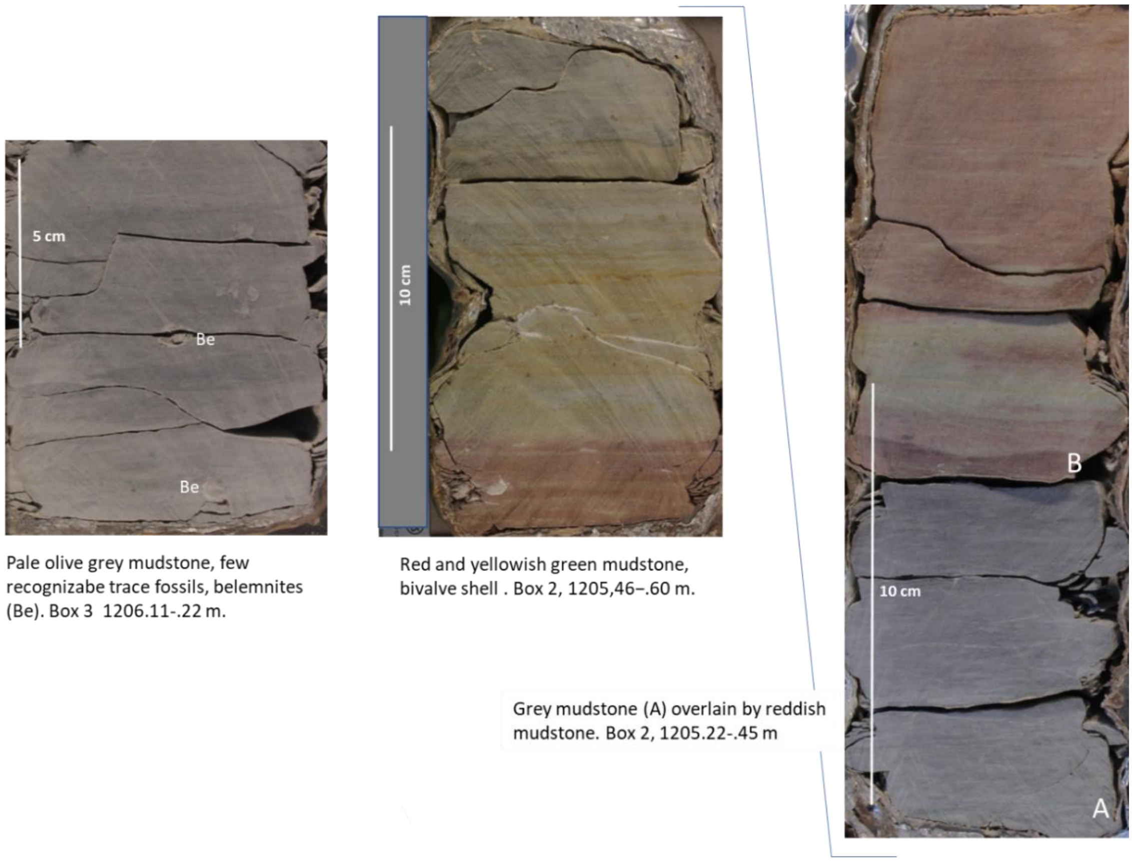


***Figure 33**. Variegated mudstone of facies 29 characterised by colours varying between grey, yellowish green, and reddish. This facies occurs at the transition from Vedsted to the Rødby Formation, Stenlille-1.*

***Figur 33**. Fossilførende, brogede muddersten fra facies 29. Der ses farveskift fra grå til gul-grøn og til rødlig. Overgangen mellem Vedsted og Rødby Formationerne, Stenlille-1.*

An example of the lateral variations within the Vedsted Formation exists from a new study of cores from Vinding-1 located at the southern margin of the Danish Basin (Figures 2 & 14-16). The new biostratigraphic ages indicate the presence of several hiati in the sedimentary record suggesting that sedimentation was discontinuous, or interrupted by several erosional events, possibly a combination, with erosion occurring most pronounced along the basin margins (Figure 15). Compared to the Lower Cretaceous successions in the central part of the Danish Basin in northern Jylland, the succession in Vinding-1 is systematically thinner, reflecting a location with less accommodation space along the basin margin (Figure 16). The deposition of calcareous mudstones possibly continued in the early Cenomanian (Upper Cretaceous, Table 2). Local occurrences of glauconitic shallow marine sandstones in the Lavø-

1 well drilled at the basin margin are possibly of Late Cretaceous age and may be time equivalent to the Arnager Greensand on Bornholm. In the Danish onshore areas, green glauconitic sandstones are generally referred to the lowermost part of the Chalk Group.

An example of interbedded carbonate and clay rich limestone (marl) in the overlying Upper Cretaceous section is shown in Figure 34.

Facies 30 comprising alternating layers of greyish-white limestone and pale grey marl (calcareous mudstone). Water-escape structure is indicated with (arrows). Core 4, 1095−1105’.

Facies 32. Grey, laminated, calcareous mudstone, Upper Cretaceous . Core 7, 1125−1135’.

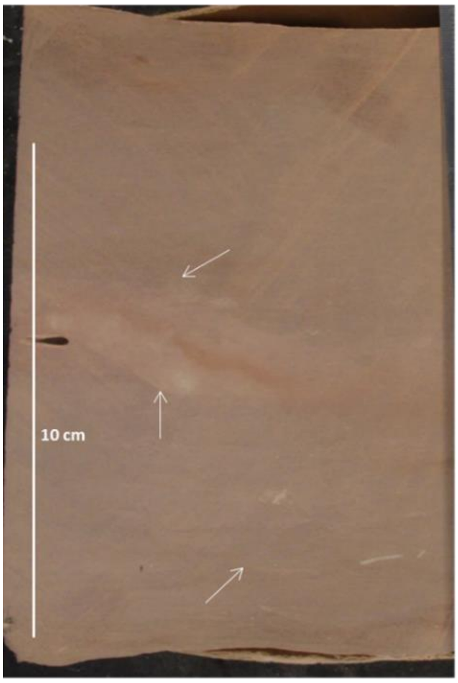
***Figure 34**. Upper Cretaceous (Cenomanian), pale grey marl and calcareous clayey mudstone, which overlie the Vedsted Formation in the Frederikshavn-1 well.*

***Figur 34**. Lys grå kalksten og kalkholdig muddersten fra Øvre Kridt (Cenomanien) overlejrer Vedsted Formationen i Frederikshavn-1 boringen.*

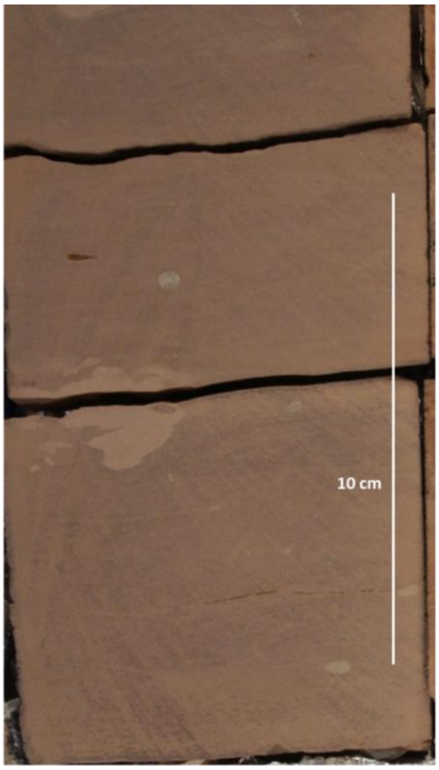
5.3.2 The Rødby Formation

The Rødby Formation is in onshore areas characterized by red mudstones and occasional calcareous mudstone deposited in marine shelf to lower offshore environments (Figures 33, 35 & 36). The type section is in the Rødby-1 well drilled in the North German Basin, south of the Ringkøbing – Fyn High (Figure 1). A small section of the Rødby Formation is logged from Stenlille-1 cores (Figure 28). It has the same log signature and facies as the underlying Vedsted Formation and as indicated on the log there is not a well-defined lithological boundary between the two formations.

In the Danish onshore area, the Rødby Formation is most common in wells drilled in eastern Denmark including Rødby-1, Stenlille-1, Lavø-1, Ringe-1, but has also been recognised in Vinding-1, Fjerritslev-2 and Frederikshavn-1 in the Danish Basin in northern Jylland. The formation comprises red mudstones, marls, and red calcareous mudstones in most wells, but in Frederikshavn-1, the Rødby Formation is dominated by grey and pale grey mudstones, claystones and calcareous mudstones. The origin of the various colours of sediments in the Rødby Formation is unknown, but it is probably of diagenetic origin rather than a depositional feature.



Faint burrows are indicated with arrows.
1203.95-.08 m



Pale spots are diagenetic features.
1203.50-.67 m

Figure 35. *Homogeneous, red mudstone of the Rødby Formation (facies 31) from Stenlille-1, core-1.*

Figur 35. *Rød homogen muddersten (facies 31) der er karakteristisk for Rødby Formationen. Stenlille-1, kerne-1.*

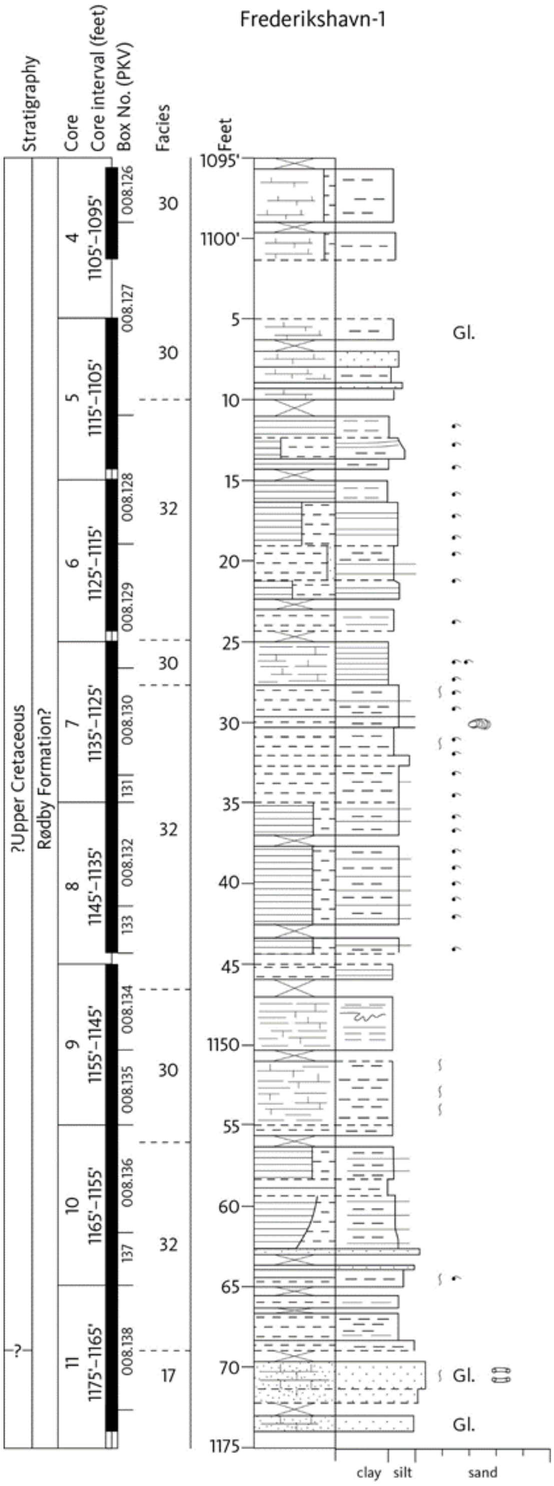


Figure 36. *Sedimentological log of the Rødby Formation in the Frederikshavn-1 well.*

Figur 36. *Sedimentologisk log af Rødby Formationen i Frederikshavn-1 boringen.*

5.3.3 Regional facies and thickness variations in the Lower Cretaceous

The Lower Cretaceous succession reaches its greatest thicknesses in northern Jylland, with 200–400 meters in Børglum-1, Farsø-1, Flyvbjerg-1, Frederikshavn-3, Haldager-1, Hyllebjerg-1, Mejrup-1, Mors-1, Vedsted-1 and Aars-1, and a maximum of 700 meters in

Fjerritslev-2 (for well locations see Figure 2). In this area, representing the depo-centre of the Danish Basin, the combined thickness of the Middle Jurassic to Lower Cretaceous reaches values in the range from 600 meters to a maximum of more than 1600 meters in the rim-synclines adjacent to salt diapirs (Figures 4 & 8). At the eastern margin of the Danish Basin, for instance in the Stenlille-1, Ringe-1, and Søllested-1 wells, the Lower Cretaceous succession is thin and condensed, generally less than 50 meters thick.

The (vertical) stratigraphic change in lithology from sandy mudstone to mixed argillaceous and calcareous mudstone represents a significant change in the depositional environment, and the occurrence of a blooming production of pelagic carbonate particles. The increasing pelagic production during late Early Cretaceous resulted in the accumulation of carbonate rich layers with a high content of calcareous nannofossils in the stratigraphic record. Thus, the oldest part of the Vedsted Formation (pre-Hauterivian) has a low carbonate content, whereas a higher carbonate content is observed in the Hauterivian–Albian parts of the Vedsted Formation (Table 2). In addition to the stratigraphic control, the paleogeography is also assumed to have influenced the deposition of carbonates, where the part of the basin located at greatest distance from points of terrestrial influx accumulated relatively more carbonate than argillaceous material (Figure 18).

As for the Jurassic sediments, the most homogeneous and fine-grained sections are found in the basin centre which can be identified in gross terms based on isochore maps (Figure 2). Along the basin margins the relatively thin sections of Lower Cretaceous sediments may be a result of condensed sedimentation due to low rates of sediment supply (on structural highs?) and locally also due to erosion. These condensed sections can be rather homogeneous comprising mudstone and calcareous mudstone, whereas sand is absent.

Significant amounts of sand have been reported from the Lavø-1 well (Figure 6), located in Nordsjælland close to the Sorgenfrei – Tornquist Zone, and may thus be related to a position near the basin margin. Sand is also present in Stenlille-1 and Haldager-1, as seen on the sedimentological logs in Figure 28. It should be noted that these sands cannot always be identified based on the well logs. An example is the Frederikshavn-1 well where the presence of sand shown on the log in Figure 5 is based on core observations only. This illustrates that the interpretation of sand in the Vedsted Formation based on well logs is uncertain and may be (highly) underestimated, when there are no cores that can be used for calibration. Further complicating the identification of sand is that the distinction between limestone beds and sand beds may be difficult as both lithologies will result in low GR-readings.

Since core data, high resolution well logs, and biostratigraphic analysis from the Lower Cretaceous section are scarce, it is at present not possible to make detailed paleogeographic models for the Early Cretaceous depositional environments onshore Denmark. An additional complexity with regards to predicting the sediment distribution for the late Early Cretaceous is the relationship between pelagic carbonate production and climate changes as well as the sea-level control on carbonate and argillaceous clay and sand deposition.

6. Characterisation of rock properties

Jurassic and Lower Cretaceous sediments are generally not exposed at surface in Denmark, and they are known only from deep drill holes. An exception is Bornholm where the sediments are locally exposed and dominated by fluvial and shallow marine sand deposited in the Sorgenfrei-Tornquist zone. Sediments on Bornholm are therefore not representative for the shallow to deep marine sediments occurring at depths around 500 meters in the Danish Basin and the North German Basin south of the Ringkøbing-Fyn High.

Previous studies of the Jurassic and Lower Cretaceous successions based on borehole data have provided data on sediment composition, petrophysical properties, and stratigraphy, as briefly summarized below. Most studies have focused on the sandstone formations, the Triassic Skagerrak Formation, the Upper Triassic to Lower Jurassic Gassum Formation, and the Upper Jurassic Frederikshavn Formation which are all potential reservoirs for geothermal energy, storage for natural gas, and possible future storages for CO_2 (Michelsen et al. 1981, Vosgerau et al. 2016a, b; Weibel et al. 2017). The results from these studies are briefly touched upon in this report, because knowledge about the presence of sand formations and their rock properties is important as they usually have high porosity and permeability. Thus, sand presence may compromise safety for a repository for radioactive waste and areas where significant thicknesses of sand may be present, either within a potential repository rock or in the overlying sections, must be avoided.

Very limited information on rock properties is available from the clay and mudstone dominated sections at depths around 500 meters. However, the mudstone dominated Fjerritslev Formation at depths around 1400-1500 meters has proved to be an efficient seal for the natural gas storage at Stenlille for several decades.

An important data source is petrophysical well logs which may provide continuous measurements of physical properties from the borehole and document the larger-scale (1 - >10 meters) variations in lithology. Logs measured since ca. 1975 provide a good basis for interpretations of lithology, especially when supported by, and calibrated to, information from drill cores and cuttings. Most formation boundaries in the Danish onshore areas are defined based on petrophysical logs (Michelsen 1978; 1989a, b; Nielsen 2003). In the Danish onshore areas, approximately 50 % of the wells (39 out of 75) were drilled before 1975 and well data from these wells is generally of limited amount and quality.

The most important data source is drill cores where physical measurements can be made and used for calibration of the petrophysical log interpretations. The available and representative data from various analysis performed on drill core samples, cuttings, and well logs are presented in the following. The resent review has highlighted that large data gaps exist and that thorough and focussed data acquisition programs are needed for future site studies to provide high quality data that will reduce uncertainties and fill in the data gaps.

6.1 Mudstone mineralogy

The amount of clay minerals and the mineralogy of the clay types is important because grain-size and ion exchange capacity are related to the properties of specific clay minerals and because the presence of clay size grains has a significant influence on the porosity and permeability of the sedimentary rock. The clay minerals have been identified by X-Ray diffraction analysis and, more recently, by infrared spectrometry, which has provided measures on the clay mineral fractions, as well as the mineralogical composition, from representative samples from the mudstone dominated sections.

Analysis of the mineralogy by X-ray diffraction produces qualitative and semi-quantitative results. The bulk mineralogy is analysed on crushed whole-rock mudstone samples, whereas the clay mineral analysis examines only clay-sized particles. The Fjerritslev Formation has been analysed in core samples from Stenlille-1, -2, -5, and -6, and cuttings from Kvols-1, Karlebo-1, and Margretheholm-1 (Figures 37-40). Quartz and kaolinite are the dominant detrital minerals accompanied by mica/illite and traces of feldspars. Some samples contain pyrite, calcite (biogenic from shell fragments, or diagenetic) and siderite concretions. The clay mineral assemblage is dominated by kaolinite, accompanied by smaller amounts of illite, vermiculite and mixed-layer minerals. Small amounts of quartz are also present (Figures 37-40) as well as authigenic (diagenetic) minerals such as pyrite, siderite, and ankerite. Some lateral variation is seen, mostly in the amount of detrital feldspar.

Upper Jurassic mudstones in the Børglum Formation have been reported to comprise c. 25 % quartz, 0.5–5 % pyrite and organic matter, up to 70 % clay minerals and varying minor amounts of calcite, dolomite, ankerite or siderite (Lindgreen 1991, his table 5b). The coarse clay fraction (2–0.2μm) of the samples is dominated by kaolinite, mixed-layer (illite/smectite) clay minerals and illite, accompanied by trace amounts of vermiculite or chlorite (Lindgreen 1991, his table 6b).

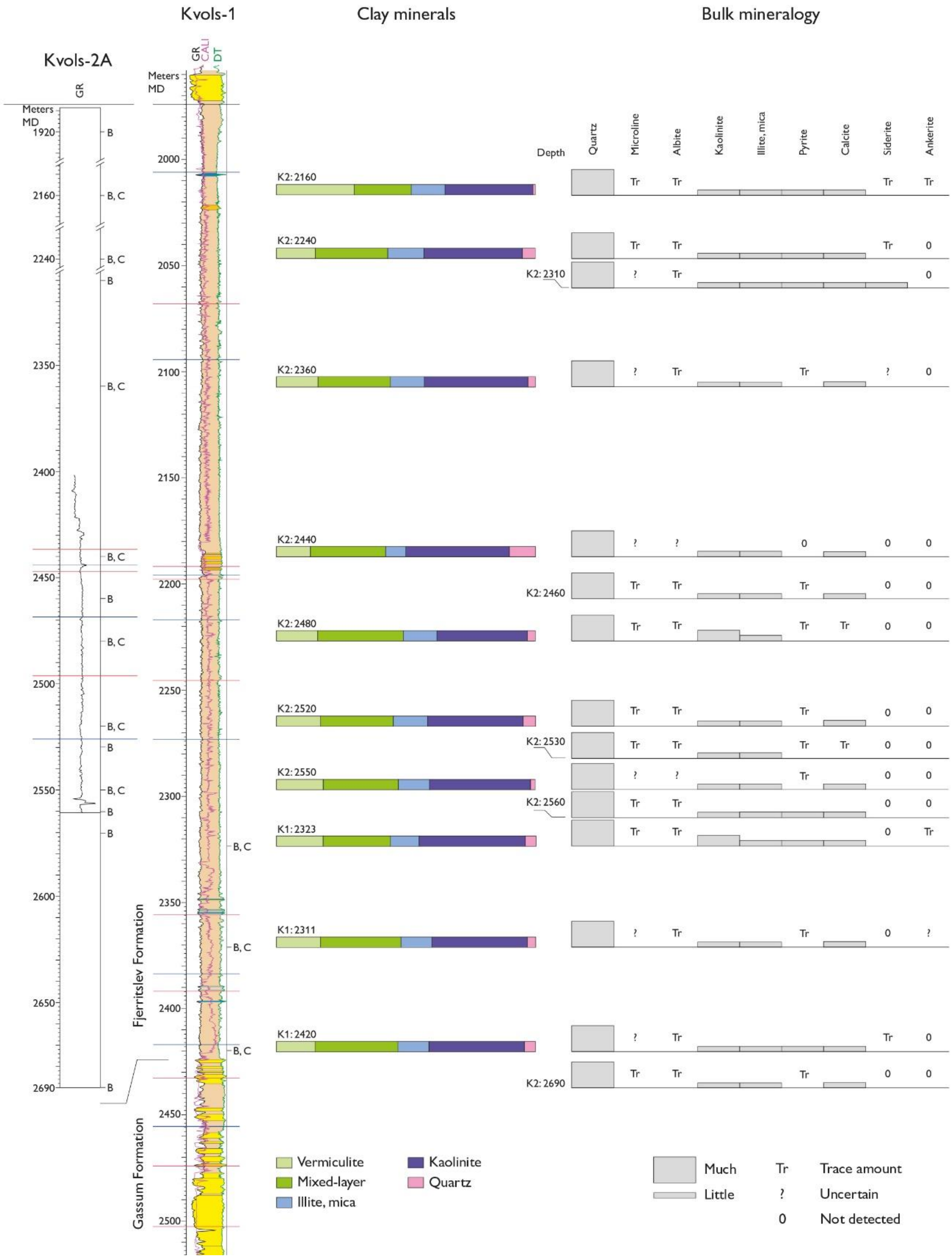


Figure 37. *Bulk mineralogy and clay mineralogy of the Fjerritslev Formation in the Kvols-1 and Kvols-2A wells located in the central part of the Danish Basin (Figure 2).*

Figur 37. *Bulk- og lermineralogi i prøver af muddersten fra Fjerritslev Formationen i boringerne Kvols-1 og Kvols-2A i den centrale del af Det danske Bassin (Figur 2).*

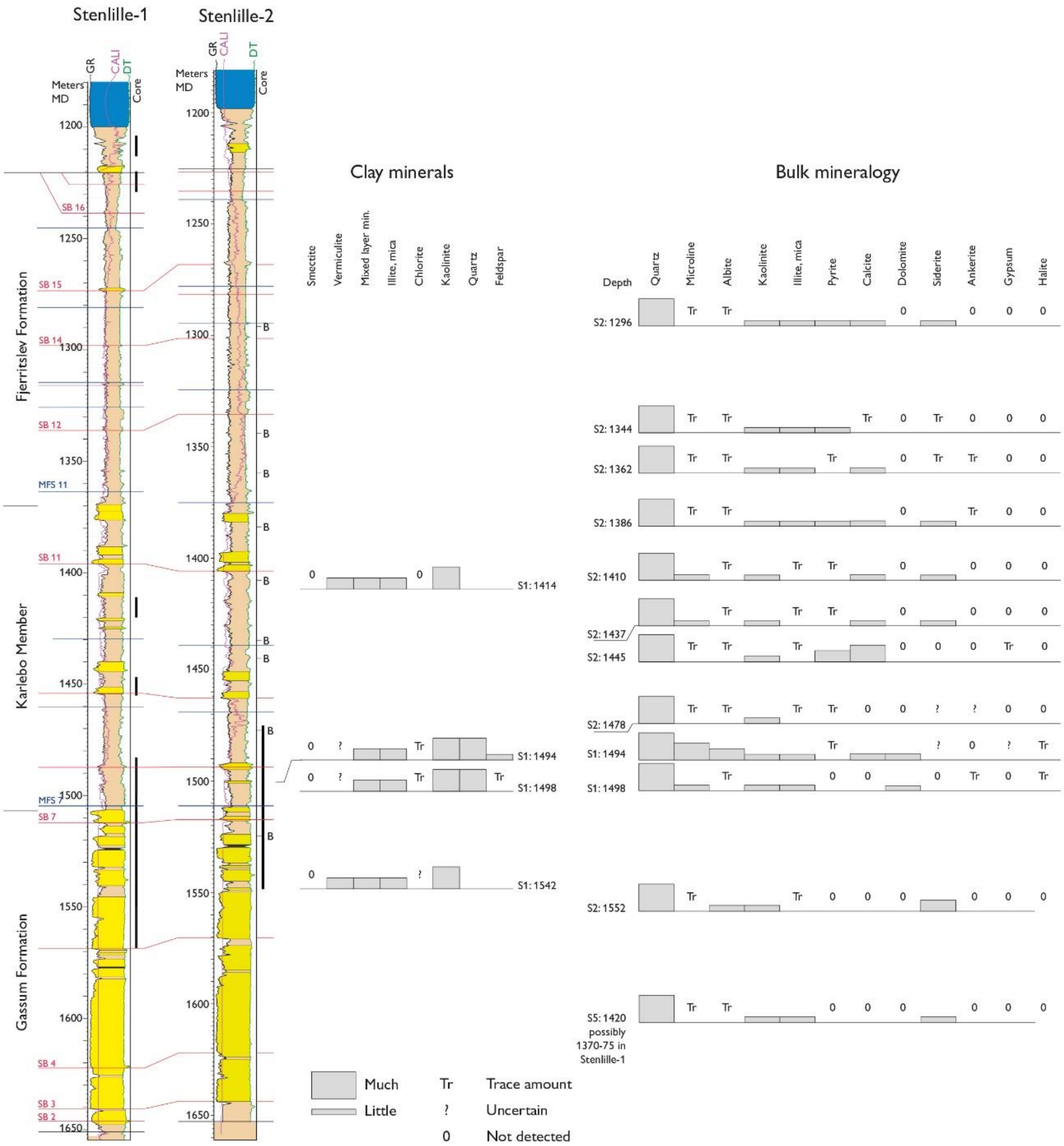


Figure 38. *Bulk mineralogy and clay mineralogy of the Fjerritslev and Gassum Formations in the Stenlille-1 and Stenlille-2 wells located in the central part of the Danish Basin (Figure 2).*

Figur 38. *Bulk- og lermineralogi i muddersten fra Fjerritslev og Gassum Formationerne i boringerne Stenlille-1 og Stenlille-2 i den centrale del af Det danske Bassin (Figur 2).*

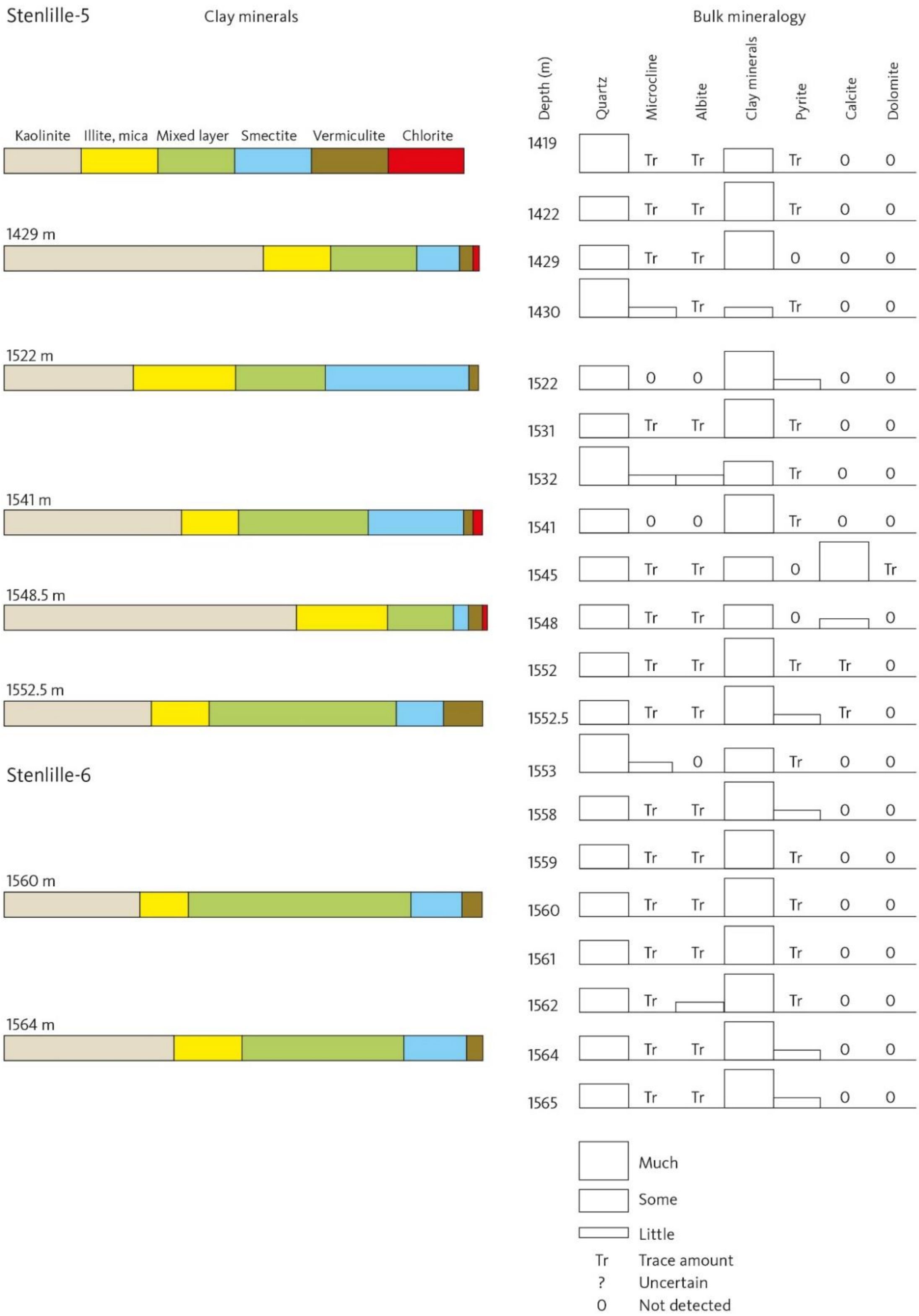


Figure 39. *Bulk mineralogy and clay mineralogy of the Fjerritslev Formation in samples from the Stenlille-5 and Stenlille-6 wells. Data from Mathiassen et al. (1989).*

Figur 39. *Bulk- og lermineralogi i prøver af muddersten fra Fjerritslev Formationen i boringerne Stenlille-5 og Stenlille-6. Data fra Mathiassen et al. (1989).*

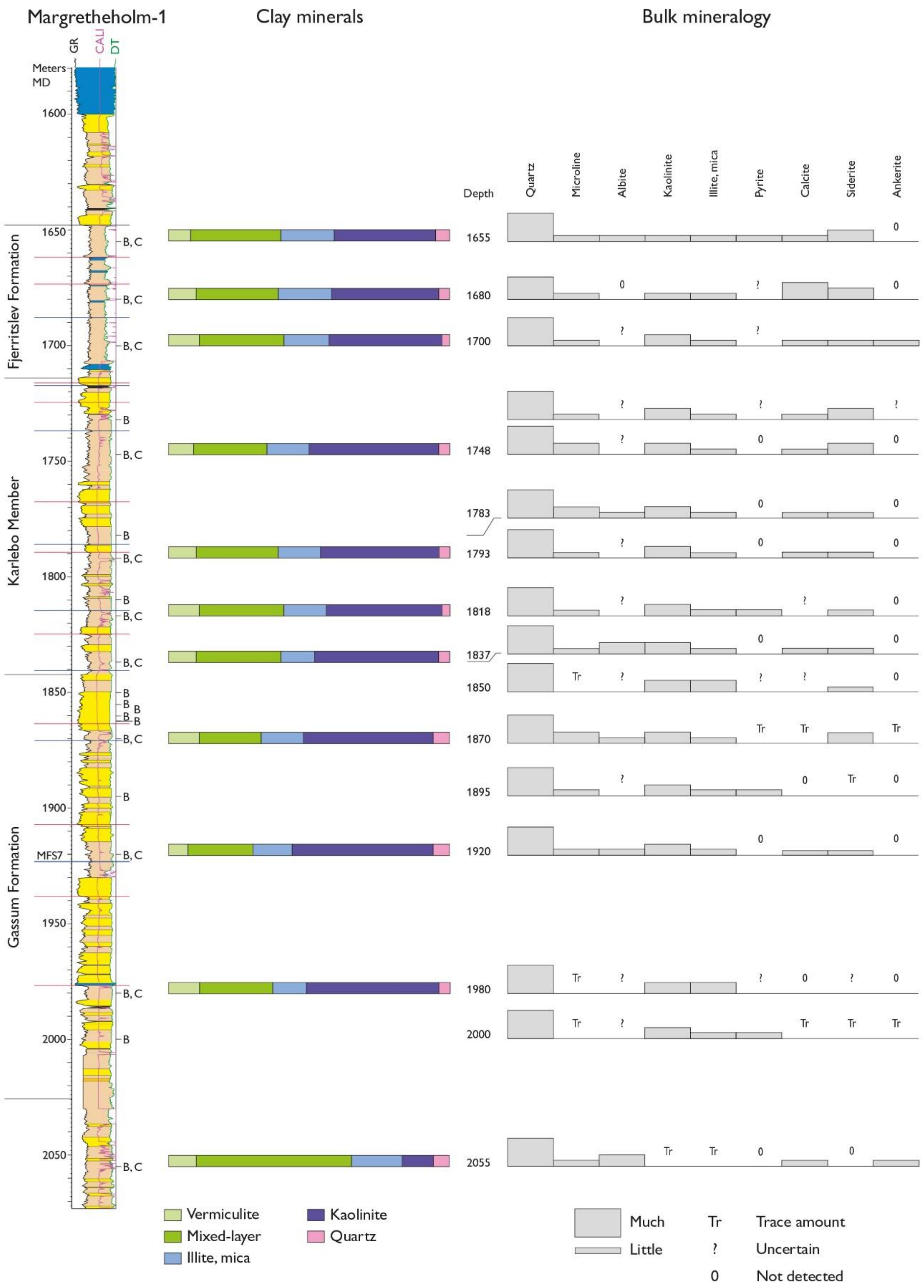


Figure 40. *Bulk mineralogy and clay mineralogy of the Fjerritslev and Gassum Formations in the Margretheholm-1 well located in the eastern part of the Danish Basin (Figure 1).*

Figur 40. *Bulk- og lermineralogi i muddersten fra Fjerritslev og Gassum Formationerne i Margretheholm-1 boringen i den østlige del af Det danske Bassin (Figur 1).*

The SpecCam technique provides detailed, semi-quantitative, discrimination of all clay polytypes, as well as carbonates, sulphates, some heavy minerals, and hydrocarbons. This method of infrared spectroscopy cannot unambiguously identify the tectosilicates, such as quartz and feldspars, and is therefore unable to generate whole-rock data. For future studies it is recommended to perform XRD also on the samples to enable a good calibration.

The following observations are made using only the information derived from the SpecCam results (Figure41). In many cases, those minerals not uniquely identified by this method, including quartz and feldspar, make up more than 50 % of each sample; these are part of the Unknown % data field.

Rødby-1 (Rødby Fm 1521-1560')
The minerals identified are mainly a mix of clays, mainly smectite and kaolinite ranging 5-25 % and 15-20 %, respectively. The low crystalline polymorph of kaolinite is the most abundant. Illite, chlorite and mica are observed in lower amounts (1-2%) with mica-illite present at negligible levels. Calcite is seen at low levels around 2 % and one sample with 14 %.

Rødby-1 (Fjerritslev Fm samples 1560-1753')
The minerals identified are mainly a mix of clays, mainly smectite with 30-40 % and locally 47%, and kaolinite around 8 %. The low crystalline polymorph of kaolinite is the most abundant. Illite (1.6 % avg.), chlorite (0-3%) and mica varying from 0.1-6 % are observed in lower amounts with mica-illite present at negligible levels. Calcite is seen at low levels of 1-2 % and locally as high as 14 %.

Ørslev-1 (Fjerritslev Fm')
The minerals dominating this section are kaolinite and smectite with averages of 14.2% and 8.9 %. Illite, chlorite and mica are observed at lower levels averaging 2.3 %, 2 % and 1.1 % respectively. Calcite is present (2.9 % avg.) and dominates in the first two samples. Dolomite and liquid hydrocarbon are present in very small amounts.

Frederikshavn-1 (Fjerritslev Fm samples 2435-2817´)
Kaolinite and smectite continue to dominate in this section. Kaolinite averages 26.7 % and smectite averages 12 %. Locally, they reach up to 41 % and 28 %, respectively. Illite occurs at moderate levels averaging 5.9 %. Mica (3.2 % avg.) and chlorite (1.9 % avg.) are present at lower levels with mica-illite being observed in very small amounts. Calcite is absent.

Sæby-1 (Vedsted Fm 450-590 meters)
Kaolinite dominates these samples averaging 10.1 % and reaching up to 33 % locally. Illite, smectite and chlorite are observed in more moderate levels with averages of 3 %, 2.8 % and 2.1 %, respectively. Calcite also appears in moderate amounts (3 % avg.) and reaches up 13.8 %. Dolomite and liquid hydrocarbons occur in negligible amounts.

Sæby-1 (?? Fm, 398-406 meters)
The three samples comprise a few percentages of smectite, up to 14% calcite, and around 20% kaolinite. The total clay fraction is around 25% suggesting that high percentages of silt and sand size quartz and feldspar occur, forming the remaining fraction of the sediment.

Fjerritslev-2 (Fjerritslev Fm 646-840 meters)
Smectite is the main clay constituting 30-40%, and kaolinite 5-20%. Illite and chlorite are present at lower levels with respective averages of 5.6 % and 2.3 %. Mica-illite and mica are seen in negligible amounts and calcite is absent.

Fjerritslev-2 (Rødby Fm 334-535 meters)
Kaolinite is the main clay ranging 15-30%, illite is 5-12%, and smectite is relatively low with 1-10%, And chlorite 3-5 %. Mica-illite and mica are seen in negligible amounts and calcite is absent in most samples.

To summarise, samples analysed from the Lower Cretaceous section in Fjerritslev-2 comprise around 40 % clay minerals composed mainly of illite, chlorite and kaolinite. Small amounts of smectite occur, and only traces of carbonate. Samples from Rødby-1 have 30-40 % clay, and kaolinite constitute totally 10-25 % of the sediment samples. The content of illite, mica, and chlorite is a few percentages each. The calcite content is low and varies from 1 % to 14 %, and smectite varies from a few percentages to around 25 %. It may be speculated whether the very high content of kaolinite observed in Rødby-1 is related to specific stratigraphic intervals within the Vedsted Formation, or if it is determined by the paleogeographic setting where different provenance areas supplied different sediments to the local areas. The Rødby-1 well is drilled in the North German Basin, south of the Ringkøbing-Fyn High, which may have received sediments supplied from a different provenance area compared to the Danish Basin and the Fjerritslev Trough in northern Jylland. The large variations both between the two wells and in samples from the Rødby Formation in a single well, indicate that a detailed sampling programme is necessary for future detailed characterisations of the clay mineral composition and the related rock properties.

Large variations are observed also in the Fjerritslev Formation, both stratigraphically and geographically. In the Rødby-1 well, the smectite content is generally 30-40 %, and kaolinite is low, generally less than 10 %.

In the Frederikshavn-1 and Fjerritslev-2 wells drilled in northern Jylland, the kaolinite content varies from a few percentages to > 40 %. The content of smectite varies significantly from 1 % to > 40 %, where the upper part of the Fjerritslev Formation has low values in the range from 0-10% and where significantly higher values of 30->40% are found in the lower part, suggesting a stratigraphic control in this region. With regards to the content of kaolinite, a geographic (and/or stratigraphic?) variation is observed, where the Rødby-1 well has values below 10 % and the wells in northern Jylland comprise up to 40 % of kaolinite, but with large variations.

The Fjerritslev Formation in Ørslev-1 is described as silty, which may explain the clay content ranging as low as from 10 % to 45 %. Smectite constitutes up to 20 %, kaolinite 10-20 % and chlorite up to 3 %.

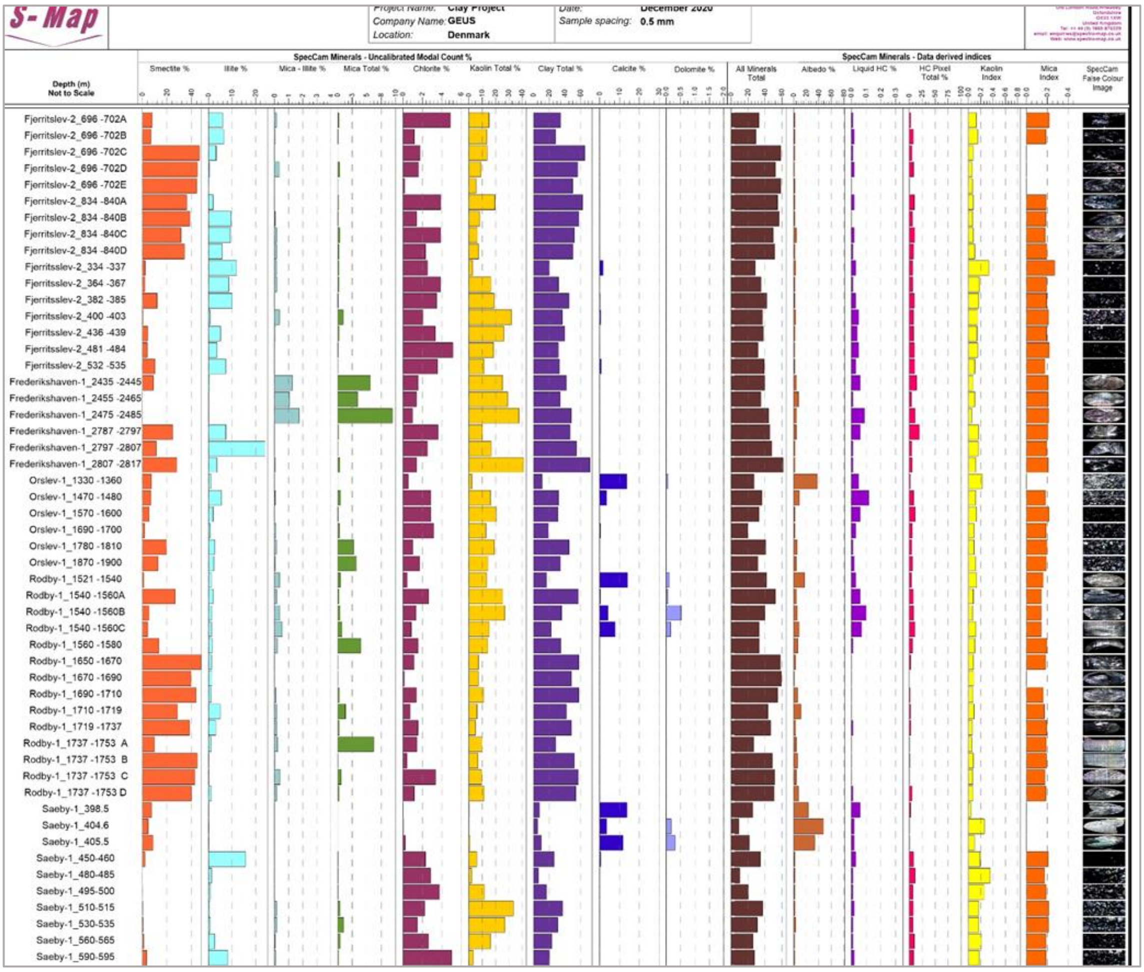


***Figure 41**. Summary of clay minerals identified in cores and cuttings from mudstone dominated Jurassic and L. Cretaceous sections.*

***Figur 41.** Opsummering af lermineraler identificeret i kerner og cuttings fra lerdominerede intervaller i Jura og Nedre Kridt lagserierne.*

4.2 Clay mineral diagenesis related to burial depth

A geothermal gradient of 25-30 °/km in the Danish subsurface was calculated by Kristensen et al. (2016). Various studies have shown that the mineral smectite becomes unstable at temperatures of 70–90 °C and recrystallizes to illite (Dypvik 1983, Lindgreen 1991, Tucker 2001). These alterations are also recognized in clay minerals, which occur as cement in sandstones (Worden & Morad 2003). In the Danish subsurface such temperatures are encountered at maximum burial depths of 2.3−3.6 kilometres which is significantly deeper than the maximum burial depth of mudstones occurring at depths around 500 meters. The mudstones at present depths of 500–1000 meters had maximum burial depths of less than 2000 meters, and it can be assumed, that the detrital clay mineral assemblage has undergone only minor temperature related diagenetic changes. Further, significant amounts of smectite occurring locally (Figures 39 & 41) indicate that such high temperatures have not influenced the investigated mudstones.

4.3 Chemical composition (major elements)

The chemical composition of a few samples for bulk mineralogy, has been analysed (hand-held X-ray fluorescence). Data on the samples are listed in Table 4. below showing wells and depths) for XRD and XRF-analysis of mudstones in the Fjerritslev Formation.

***Table 4**. Chemical analysis (major elements) of mudstones from the Fjerritslev Formation in the following wells ST2: Stenlille-2, ST5: Stenlille-5, KV2: Kvols-2.*

***Tabel 4.** Kemisk analyse af de vigtigste elementer i lersten fra Fjerritslev Formationen i følgende boringer ST2: Stenlille-2, ST5: Stenlille-5, KV2: Kvols-2.*

Measured XRF-values, average of two measurements																			
Lab. No	966-67	968-69	970-71	972-73	974-75	976-77	978-79	980-81	982-83	984-85	986-87	988-89	992-03	994-95	996-97	998-99	1000-01	1002-03	1004-05
	ST2-1296	ST2_1344	ST2-1362	ST2-1386	ST2-1410	ST2-1437	ST-2-1445	ST2-1478	ST2-1522	ST5-1421	Kv2-1920	Kv2-1920	Kv1-2420	Kv2-2690	Kv2-2570	Kv2-2560	Kv2-2570	Kv-2460	Kv2-2310
											bulk	mdst							
Ti	5436	5808	5729	5475	4402	5286	3870	6016	7156	7379	2975	3631	4882	4652	4779	5517	5309	4243	5343
P	891	630	609	348	542	870	235	327	279	355	n.d.	n.d.	252	304	523	479	488	272	898
Mn	1465	1251	1570	1153	977	1028	747	257	1118	1696	553	215	769	1185	2040	1509	1572	2676	720
S	7990	4521	3078	5032	5147	3601	28675	4103	1845	1130	9397	5228	14453	6978	8804	6020	6060	10481	7507
Ca	21875	12999	20324	26880	20668	21598	53402	2495	3077	2993	100989	80737	28652	26888	21124	17472	18475	36405	19339
Fe	78200	57870	57262	57503	51603	50653	63270	41508	56848	50132	41645	37735	50791	47162	58014	51951	50680	51382	51771
K	20386	22985	22288	19979	15564	16846	20715	19415	18727	18731	28540	29208	23135	28942	29406	28157	28696	30034	27258
Mg	5722	7023	5430	4514	2051	4927	6636	2735	3363	3079	7467	3356	5585	4349	5801	6804	5562	4186	5468
Al	69283	72266	73670	68495	53234	63508	59507	64201	60724	66107	58962	61326	70654	67532	77109	76096	72780	72264	71747
Si	201700	216728	210359	206939	226549	229501	180979	217339	234582	220231	183206	193937	209451	206639	211439	215575	205454	198272	207299
Sum	412947	402081	400321	396319	380736	397818	418037	358397	387719	371834	433733	419003	408624	394631	419038	409580	395076	410215	397350
Total ex bal	415372	403384	401120	397582	381121	398636	422849	363734	391518	376084	440287	418979	409741	403702	426932	414763	404385	428572	399634
Bal	585126	596544	598977	602536	619065	601430	577333	636118	606956	622599	557606	580875	590257	595946	571991	584999	595973	570844	600714

- Chemical composition (main elements) of samples of the Gassum Formation, the Karlebo Member of the Fjerritslev Formation, and the Fjerritslev Formation
- XRF-values measured on powdered samples 01.05.2019 at GEUS
- Measured XRF-values, average of two measurements
- Bal: sum of unidentified elements of low weight (especially oxygen)

The accuracy of the measurements increases with the atomic weight of the atoms. The 'light' elements, such as Al, Mg, Si, K and Ca, which are essential in many minerals in sedimentary deposits, are difficult to measure with high precision. It is not possible to calculate the mineralogical composition from the main elements even though the bulk mineralogy is known from XRD-studies.

6.4 Content of organic matter

Clay rich, black marine mudstones usually comprise disseminated organic material of different types varying from terrestrial plant fragments to marine algae and bacteria. Analyses of TOC (total organic carbon) and HI (hydrogen index) characterize the amount and type of organic matter in sedimentary deposits. Depending on the type of organic matter and the burial depth of the mudstones, they may potentially produce hydrocarbons. Under the right circumstances, generated hydrocarbons may be expelled from the rock and migrate towards shallower depth due to buoyancy. In the Danish onshore area neither mature source rocks nor hydrocarbons have been encountered at depths around 1000 meters or shallower (Petersen et al. 2008).

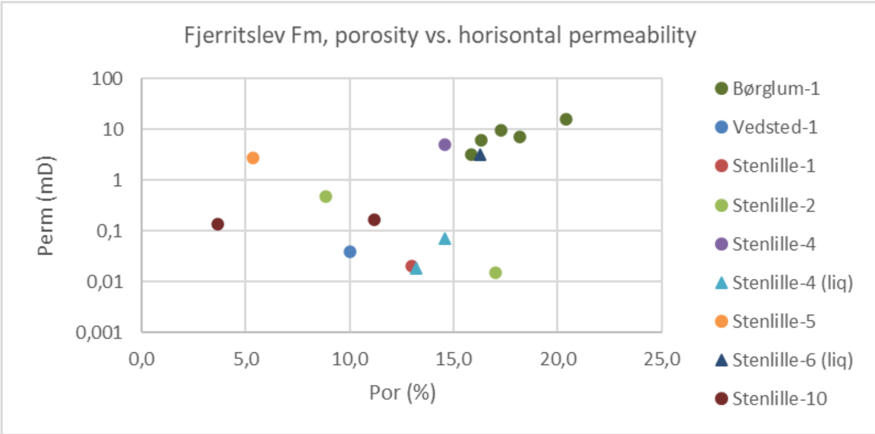
Some intervals in the Fjerritslev and Frederikshavn Formations may have source rock potential, but they have not been buried to depths where the temperature is high enough to have generated hydrocarbons, and all the exploration wells have been classified as dry wells. Systematic analyses of TOC and HI through the Fjerritslev Formation in Hyllebjerg-1 and Kvols-1 show a distinct peak in both TOC (2–3 % wt) and HI (values of 300–600) through the upper part of the F-III Member (Michelsen 1989b). The depth to the F-III Member in the central parts of the Danish Basin is more than 1000 meters thus being too deep for a potential repository and far too shallow for the generation of hydrocarbons. Therefore, it is highly unlikely that hydrocarbons may be encountered at depths around 500 meters.

The Lower Cretaceous mudstones with colours varying from dark and light grey, red, white, and green do not contain carbonaceous organic material.

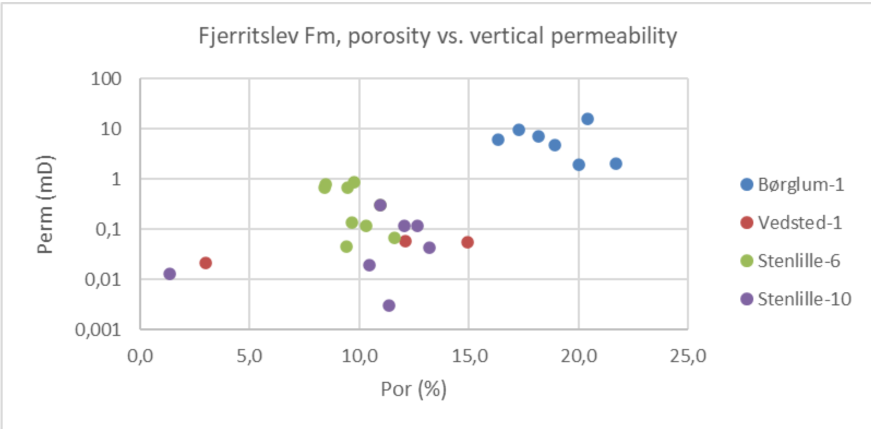
6.5 Porosity and permeability

A general correlation between porosity and depth of burial may be inferred (Kristensen et al. 2016), however, local trends are strongly influenced by the sediment composition, rate of subsidence and burial, and local diagenetic processes. Newly deposited mud has porosities of 70–90 %. During compaction, porosity decreases rapidly to c. 30 % at 1000 meters depth (Tucker 2001), and a parallel, horizontal texture of detrital material develops, which results in a measurable, often significant difference between vertical and horizontal permeability.

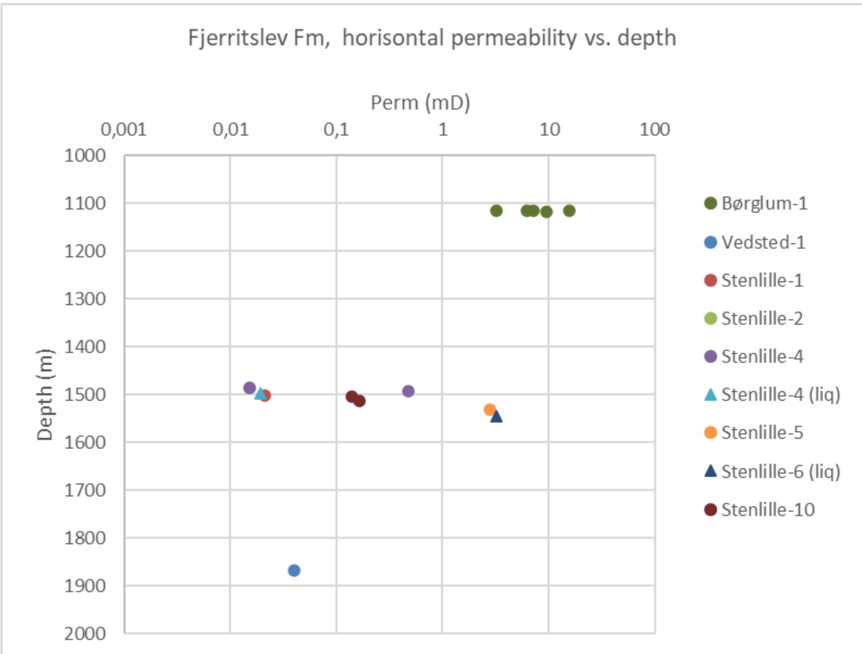
A depth trend could be applied to the small data set (from Olsen & Jørgensen, 2008) plotted in Figure 42.C and 42.D, but it is obvious that a large range of values may occur at the same depth. At depths around 1500 meters, permeability values vary with a factor of 100 for samples from different wells. The permeability vs. porosity is also plotted (Figure 42) showing some correlation might be inferred, but with large variations.



42.A



42.B



42.C

*(**Figure 42.A-C** see text next page)*

42.D

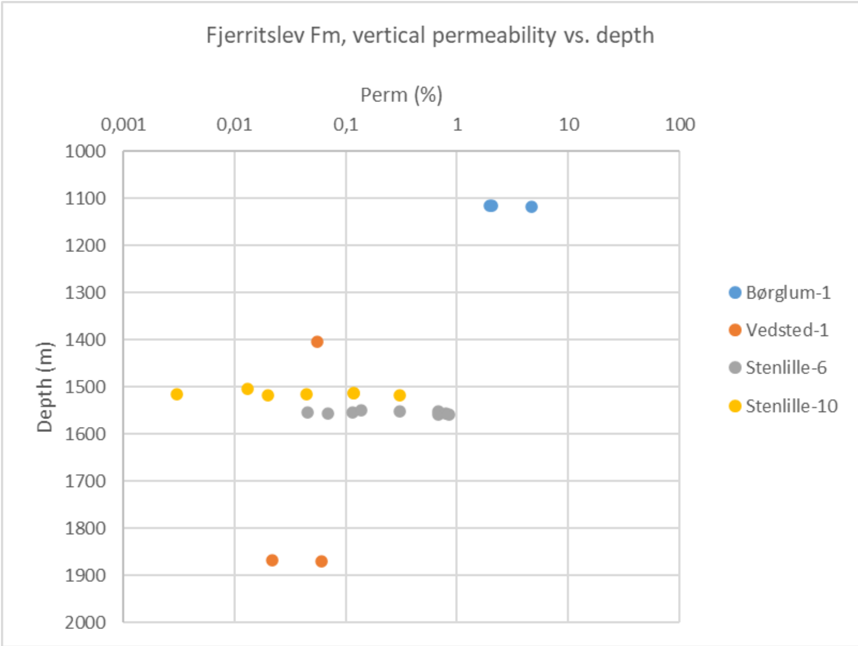


Figure 42. *Core measurements from the Fjerritslev Formation* ***A.*** *Horizontal permeability vs. porosity****,*** ***B.*** *Vertical permeability vs. porosity,* ***C.*** *Horizontal permeability vs. depth and* ***D.*** *Vertical permeability vs. depth.*

Figur 42. *Analyser af borekerner fra Fjerritslev Formationen* ***A.*** *Horisontal permeabilitet vs. porøsitet****,*** ***B.*** *Vertikal permeabilitet vs. porøsitet,* ***C.*** *Horisontal permeabilitet vs. dybde og* ***D.*** *Vertikal permeabilitet vs. dybde.*

The very limited amount of existing data from the Jurassic and Lower Cretaceous mudstones is due to the fact, that most analysis have been made to test and characterise reservoir properties and not the seal capacity. The uncertainty with regards to both porosity and the horizontal and vertical permeabilities is therefore high for mudstones found at 500 meters depth.

Although the Fjerritslev Formation is present in almost all onshore deep Danish wells (Nielsen and Japsen, 1991), very few cores have been cut in the formation with the purpose of core analysis of the low permeable lithologies. A search in the GEUS archive and core analysis database have provided a very limited amount of Routine Core Analysis (RCA) porosity-permeability data presented in Table 5. Additional data from mercury injection tests on cleaned and dried samples have been included from the AQUA-DK Project (Springer et al., 2010). RCA porosity and gas permeability are carried out on small cylindrical plugs drilled in horizontal or vertical direction relative to the bedding in the core, cleaned for formation water (brine) if possible, dried at a specified temperature and then analysed at room conditions for effective porosity by the He-injection method and permeability to N_2 gas at a confining stress of ≈2.8 MPa (400 psi). A few liquid permeability measurements to formation water (brine) are also included in Table 5. The Stenlille-2 data measured for a caprock study outlined in blue in Table 5 represent data measured at reservoir condition on preserved (fresh) core material (Springer et al., 2010). It should be noted that all data are from depths from 1100 to 1800 meters which is significantly deeper that the 500 meters depth focus of the present siting study.

A study by Mbia et al. (2014) also investigated the mineralogy of the sections where porosity, permeability and compressibility of the Fjerritslev Formation in the Vedsted and Stenlille areas were measured. Sampling was based on uncleaned cuttings from 3 wells that, in a comprehensive study, were analysed for porosity by different techniques including the conventional He-porosity, mercury injection (MICP) porosity and nuclear magnetic resonance (NMR) porosity (Table 6). It was reported that the clay mineralogy has a significant impact on the permeability where kaolinite results in permeability values 10-100 times higher than presence of smectite clay for the same porosity. This is interpreted to be a result of higher degree of compaction of sections comprising smectite compared to kaolinite.

The data presented in Table 5 are of varying quality due to the history and inevitable core handling. The Børglum, Farsø and Vedsted wells were drilled many years ago and core material was left to dry in the GEUS core store. Due to salt precipitation from the drying core and the effect of humid conditions in the store, delicate clay minerals like mixed-layers and expandable clays such as smectite are likely to have been damaged. The results presented in Table 5 for these wells were measured on samples taken from core material that was deteriorated. Analyses of Stenlille samples were made within a few weeks after the core was recovered. However, the samples were cleaned and dried before analysis as is normal practice in routine core analysis (API RP40, 1998), and expandable clays will therefore shrink. This will induce microcracks in the mudstone that will enhance the measured permeability, affect the mercury injection data and therefore result in poor quality data indicating too high permeability.

The importance of core handling and quality for the reliability of laboratory measurements is demonstrated by the Stenlille-2 sample at 1484.70 meters depth (Table 5). The porosity and liquid permeability were measured on a preserved (fresh) black shale that was brought to reservoir P and T conditions at ≈ 1500 meters depth (Springer et al. 2020). The measured liquid (brine) permeability of 3 nD is in line with the best petroleum caprocks. From the same depth a small sample was cleaned and dried and used for mercury injection test. The result r10 shows that 10% of the pore volume of the sample consist of pores with a pore throat radius ≥ 600 nm. If this was a reliable result, then the brine permeability would be several orders of magnitude higher than the actual 3 nD measured. The reason for this discrepancy is probably caused by the relatively high content of smectite present in the sample that, when dried, leave microcracks of much larger dimensions than seen for pores in a fresh (wet) core sample.

Table 5. *Petrophysical data for the Fjerritslev Formation obtained from routine core analysis and MICP of the listed onshore wells. The highlighted Stenlille-2 sample at 1484.70 meters is the only reservoir condition result available.*
(From Springer et al., 2020)

Tabel 5*. Petrofysiske data fra Fjerritslev Formationen baseret på standard kerneanalyser og MICP fra de listede boringer. Målingerne fra Stenlille-2 (markeret med blå) er den eneste prøve hvor analysen er foretaget ved reservoir forhold (fra Springer et al. 2020).*

Well ID	MD [m]	Gas permeability [μD]	Liquid permeability [μD]	Porosity [%]	MICP entry $P_{(air\text{-}brine)}$ [MPa]	Pore throat radius r_{50} [nm]	r_{10}	Mean hydraulic radius [μm]
Børglum-1	1114.54	1980		20.0				
	1115.19	2080		21.7				
	1116.79	4740		18.9				
Farsø-1	1976.69	~ 0		9.1				
Vedsted-1	1403.33	55		14.9				
	1403.40			15.2	6.0	10	38	0.16
	1407.10			17.6	7.5	9	22	0.18
	1865.40			8.3	11.0	5	150	0.51
	1868.23	22		3.0				
	1868.60 **H**	40		10.0	9.5	6	300	0.80
	1869.27	60		12.1				
Stenlille-1	1501.33 **H**	21		13.0				
	1501.33			9.5	6.5	9	200	0.76
Stenlille-2	1484.70 **H**	15		17.0				
	1484.70			13.0	7.5	8	600	2.35
	1484.70		0.003	13.8				
	1493.43 **H**	475		8.9				
Stenlille-4	1493.10 **H**	5040	73	14.6				
	1498.10 **H**		19	13.2				
Stenlille-5	1531.60 **H**	2763		5.3				
Stenlille-6	1544.40 **H**		3219	16.3				
	1550.58	137		9.7				
	1551.53	687		9.5				
	1552.44	305		11.0				
	1553.34	116		10.3				
	1554.45	45		9.4				
	1555.83	69		11.6				
	1556.81	798		8.5				
	1557.67	687		8.4				
	1558.88	857		9.8				
Stenlille-10	1503.20 **H**	138		3.7				
	1503.33	13		1.4				
	1513.29	117		12.0				
	1513.90 **H**	166		11.2				
	1514.33	118		12.6				
	1515.33	44		13.2				
	1516.35	3		11.4				
	1517.33	20		10.5				
	1517.93	309		11.0				

Table 6. *A summary of results from analysis of cuttings from the Fjerritslev Formation in 3 onshore wells in the Danish Basin. For further details refer to Mbia et al. (2014), Table 1. Helium (He) and mercury (Hg) porosity is given as an average of between 4 and 10 cuttings samples taken from each well. Results from analysis of a few natural state core plugs are also given in the table below. kBET is a permeability calculated from Kozeny's equation and measured specific surface area by the BET method. kCRS is a measured overburden liquid permeability from a constant rate of strain (CRS) experiment.*

Tabel 6. *Tabellen viser en opsummering af analyser af cuttings fra Fjerritslev Formationen i 3 boringer. For yderligere detaljer se Mbia et al. (2014), Tabel 1. Helium (He) og kviksølv (Hg) porøsitet er angivet som et gennemsnit af mellem 4 og 10 cuttings fra hver boring. Resultater fra analyser af kernestykker er også angivet. kBET er permeabilitet beregnet med Kozeny's ligning og overflade areal målt med BET metoden. kCRS er en væske permeabilitet målt ved konstant rate af belastning (CRS).*

Well ID	Depth interval	He-porosity	Hg-porosity	NMR-porosity	Permeability	Plug permeability *	
	MD [m]	Avg. [%]	Avg. [%]	[%]	k_{BET} [μD]	k_{BET} [μD]	k_{CRS} [μD]
Vedsted-1	1585-2005	22	nd	nd	0.6	nd	nd
Stenlille-2	1475-1486	20	10	21*	0.2	0.2	0.2
Stenlille-5	1419-1576	21	11	18*	0.35	0.2	nd

* Measured on a few preserved (natural state) core plugs.

Despite of the uncertainties and variations mentioned above, Fjerritslev Formation mudstones occurring present day at depths of 1300-1500 meters act as an effective, proven seal for the Stenlille gas-storage facility located in the Gassum Formation sandstones. Here, the lowermost part of the Fjerritslev Formation, referred to as the Karlebo Member, comprises numerous, laterally discontinuous sand laminae and also sand layers with thicknesses of tens of centimetres as indicated on the well log interpretation in Figure 43 and in more detail in the sedimentological logs (Appendix A). The well log interpretation shows that the porosity and permeability are highly variable depending on the lithology. Permeabilities interpreted in the mudstones (shale) vary between 1 and 10 mD. However, no core calibration exists for the Fjerritslev Formation mudstones, only for sandstones in the underlying Gassum Formation (Vosgerau et al. 2016a), and therefore these interpreted values are associated with a significant uncertainty.

6.8 Interpretation of lithology from petrophysical logs

In most of the deep wells, only a minor fraction of the succession is cored, and the lithology is determined mainly from petrophysical well log interpretations. In the oldest wells the logs are restricted to SP-, Sonic- and GR-logs, whereas newer wells have much larger suites of petrophysical logs. The log panels in Figures 5-7 show characteristic GR and Sonic log patterns for the Jurassic and Lower Cretaceous formations and the interpreted lithology.

The gamma log is often used for interpretation of the lithology. Usually, there is a distinct contrast between quartz sandstone and mudstone with a high content of K, Th and U are associated with clay minerals and disseminated organic matter. When sandstones and mudstones are thinly interbedded with layers thinner than 30-40 cm, the gamma log cannot resolve the proportions of sandstone and mudstone because the log tools measure average values across 30-40 cm thick layers. Low gamma readings on the log may indicate a high quartz content, but it makes no distinction between sand- and silt-sized quartz grains and therefore the lithologies interpreted from log patterns should be calibrated to cores, or alternatively cuttings. In addition, the gamma logs should preferably be used in combination with other petrophysical log types to ensure the best possible identification of lithologies which increase the potential for correct sedimentological interpretations.

Based on the GR log alone, mudstones dominated by the clay mineral kaolinite ($Al_2Si_2O_5(OH)_4$) differ only little from quartz-dominated silt- and sandstones due to lack of radioactive elements such as K, Th and U (Pedersen et al. 2013). This is important to be aware of when interpreting lithologies in the Fjerritslev and Vedsted Formations based on well logs, as these formations generally have high contents of kaolinite (Figures 37-40 & 43).

Glauconitic sandstones have relatively high gamma-radiation compared to quartz-rich sandstones and may be misinterpreted as mudstone. This is important to be aware of when interpreting lithologies from well logs through the Frederikshavn and Vedsted Formations as they contain glauconitic sand.

Estimations of porosity and permeability of a rock require a suite of petrophysical well logs which in combination may be used for estimating values. High confidence can be obtained when the log interpretations are calibrated to core analysis data of measured porosity and permeability (Figure 43).

Identification of log patterns can be used for correlation within a sequence stratigraphic framework, as shown in Figure 44 where log-markers in the Fjerritslev Formation have been used for lateral correlation of layers.

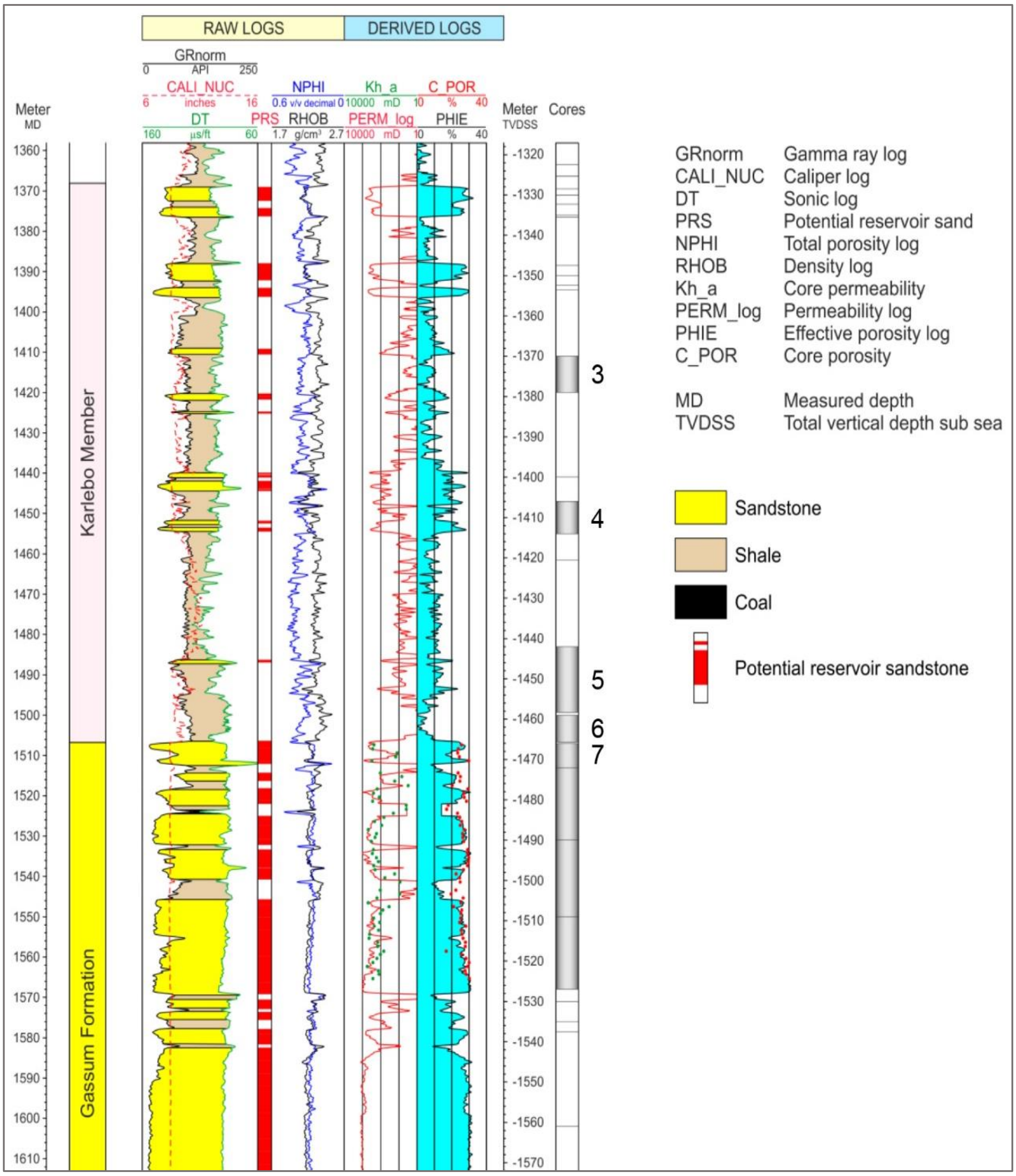


Figure 43. *Stenlille-1 well, example of interpreted petrophysical log, including lithology, porosity, and permeability, calibrated to core analysis data from sandstones in the Gassum Fm (lower part of the log) (Vosgerau et al. 2016a).*

Figur 43. *Eksempel på petrofysisk log tolkning af litologi, porøsitet og permeabilitet, kalibreret til kerne analyse data fra Gassum sandsten i Stenlille-1 (Vosgerau et al. 2016a).*

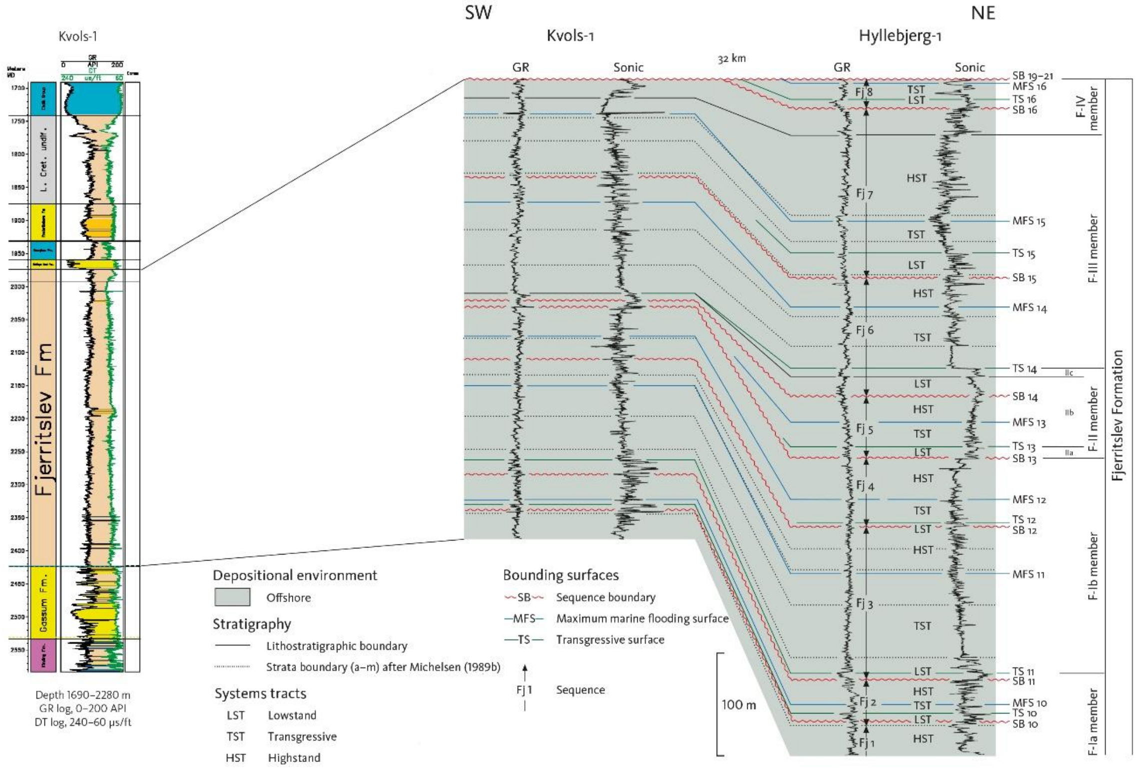


Figure 44. *The Fjerritslev Formation in Kvols-1 and Hyllebjerg-1 (Partly from Nielsen 2003: Figure 21) illustrating the correlation and continuity of log patterns in the two wells across c. 35 kilometres in the central part of the Danish Basin (see Figure 1).*

Figur 44. *Log korrelation der viser at logmønstre og sekvensstratigrafiske flader i Fjerritslev Formationen kan korreleres over en afstand på ca. 35 kilometer fra Kvols-1 til Hyllebjerg-1 i den centrale del af Det danske Bassin.*

7. Summary

The present study is carried out with the purpose to identify, map and characterize clay dominated Jurassic and Lower Cretaceous formations occurring in the Danish subsurface at depths around 500 meters, and with thicknesses of 100 meters or more which might be used as a host rock for disposal of radioactive waste. Most of the clay-dominated formations comprise interbedded thin layers of silt and sand in various amounts, and the relative proportions can usually not be determined based on available well logs. Thus, the general term mudstone is used to indicate the mixed lithology. The mudstones are marine and occur interbedded with formations of predominantly shallow marine sandstones.

Mudstone dominated sediments in the Jurassic and Lower Cretaceous formations are found in the Fjerritslev, Børglum, Vedsted and Rødby Formations where the thickest mudstone sections occur in the Fjerritslev and the Vedsted Formations. Significant variations in thickness, burial depth, and homogeneity occur depending on the structural setting and the local paleogeography. Shallow marine sandstones of the Gassum Formation underlie the base of the Jurassic mudstones in all areas.

This study shows that Jurassic, clay dominated sections are present in the deepest part of the Danish Basin and the Fjerritslev Trough. In areas representing the basin margin, and shallow platform, shallow marine sands are interbedded within the offshore mudstones. The Jurassic deposits are characterised by the presence of several sand dominated intervals of shallow marine sandstones. Sections dominated by continuous mudstone are found in the basin centre where sediments are presently located at depths exceeding 500 meters. Mudstone dominated deposits forming sections thicker than 100 meters are found in northern Jylland in Vedsted-1, Børglum-1, Haldager-1 and Farsø-1, whereas the sections in Stenlille-1, and Søllested-1 seems to comprise numerous sand layers up to 1 meter thick or more based on the GR-log pattern.

The Lower Cretaceous deposits generally seems to be more homogeneous with lithological variations typically on a 1-100 centimeter scale, rather than a 1-50 meters scale, and thick sandstone intervals are less common. However, very limited core data exist for calibration of the well log interpretations, and the interpretations are therefore associated with a significant uncertainty. The new biostratigraphic data have revealed that in some areas, the sections are very condensed.

Based on clay mineral analysis from a few wells, it seems that the total amount of clay minerals varies from around 40% in Fjerritslev-2, 20-40% in Ørslev-1 and Sæby-1 to a range from 20% to 60% in Rødby-1. These values indicate that the lithologies vary considerably in the investigated wells, probably on a rather small scale (< 1-2 meter) which is generally difficult to identify on well logs due to limited log resolution. The potential presence of several, or numerous sand layers 1-2 meters thick is in general not a favourable situation for a repository rock. However, other factors such as the extension and orientation of the sand layers as well as the presence or absence of a hydraulic gradient will have an influence on the repository properties of the claystones.

The Lower Jurassic Fjerritslev Formation occurs widespread and has the most homogeneous, clay dominated sediments in the depocenter of the Danish Basin in northern Jylland, where also the thickest section occurs. Here, depth to the top of the formation exceeds 1 kilometre and the formation is more than 500 meters thick, as for example in the Vedsted-1 well. In general, the thickness of the Fjerritslev Formation decreases toward the basin margins and surrounding platforms, while the sand content increases, indicating more proximal settings with occasional deposition of shallow marine and shoreface sand. An example is the Frederikshavn-1 and -2 wells, which are located on the Skagerrak-Kattegat platform. In these wells, the thickness is less than 200 meters and the formation comprises several thick sand units (5-10 meters) in the middle parts. Likewise, the Fjerritslev Formation comprises numerous interbedded sands as found in wells drilled in northern Sjælland near the Sorgenfrei-Tornquist zone, and southeast Denmark (Lolland-Falster area) south of the Ringkøbing-Fyn High.

The shallowest occurrence of top Fjerritslev Formation in Vendsyssel and northern Jylland is at 650–700 meters (Frederikshavn-1, Sæby-1). In wells drilled in the Lolland−Falster area the depth to the top of the Fjerritslev Formation is 450−600 meters (Rødby-1, Ørslev-1, Søllested-1).

The Børglum Formation is dominated by lower offshore to shelf mudstones deposited in the deepest parts of the Danish Basin. The Børglum Formation is known from deep wells in central and northern Jylland. It has a maximum observed thickness around 100 meters in the Haldager-1, Vedsted-1, and Fjerritslev-2 wells where the formation occurs at depths of 1000 meters or more.

The Frederikshavn Formation comprises interbedded sand and mudstone in varying proportions, reflecting deposition at the basin margin, where sand was deposited mainly during periods of shoreface progradation.

The Lower Cretaceous Vedsted Formation mudstone section varies in thickness from a maximum of 700 meters in the Fjerritslev-2 well in the northern Danish Basin - Fjerritslev Trough, while it is generally around 50 meters or less in the eastern and southeastern parts of Denmark. Based on well logs and descriptions of a few drill cores, the mudstone section seems to be relatively homogeneous with lithological variations mostly seen as slight variations in the content of silt, and occasional 1-2 meters of sand layers. Thicker units of clean sandstone beds are generally not observed, except in the Lavø-1 well where the formation comprises mudstones and interbedded sand units with a maximum thickness of 15 meters. However, the lithologies interpreted from well logs are uncertain, and the sections may be more heterogeneous than suggested by the log patterns. The upper part of the Vedsted Formation has a significant number of marl beds, and occasionally limestones.

The Rødby Formation comprises interbedded mudstone and limestone, and a few thin sandstone beds. In some areas, the upper boundary towards the Upper Cretaceous Chalk Group is transitional, and the Upper Cretaceous section is characterised by the presence of numerous marl layers in the lower 200-300 meters.

In the eastern parts of Denmark, some areas may provide a continuous mudstone section of more than 100 meters when looking at the combined thickness of the Fjerritslev, Vedsted and Rødby Formations where the Middle and Upper Jurassic sand bearing formations are absent. Examples where this situation occurs are Stenlille-1, Rødby-1 and Søllested-1. However, the section in Stenlille-1 is at depths below 1000 meters, and in Rødby-1, the Fjerritslev Fm comprises several 1-2 meters thick sand beds.

In Haldager-1, Børglum-1 and Vedsted-1, the Lower Cretaceous sections seem to be mudstone dominated based on well logs and occur at depths around 500 meters. Some variability on the GR-log might indicate the presence of carbonate or sand layers, which is confirmed by the sedimentological log of core from the Lower Cretaceous in Haldager-1.

Mudstones with a high content of clay minerals (> 50%) have low permeability as clay minerals will orient parallel to bedding during compaction. Thus, a high clay content will enable a higher degree of compaction compared to other fine-grained rock types. Clay percentages above 50% seem to be common in the Fjerritslev Formation, while it varies between 20 and 40 % in the shallower formations.

Porosity and permeability data exist from the Jurassic sandstones, whereas only a few data points of low quality exist from the mudstone sections. Well logs are useful for interpretation of porosity and permeability, however, when the logs are not calibrated to core analysis the interpretation will be highly uncertain. Diagenetic changes and recrystallisation of carbonate in marl and limestone beds may influence the rock properties of the calcareous mudstones in the upper part of Lower Cretaceous and the lower part of Upper Cretaceous.

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8.1 Literature from the project on deep geological disposal

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1. Requirements and criteria for initial evaluation of geological properties and conditions (Midtgaard, H.H., Hjelm, L., Jakobsen, R., Karan, S., Kjøller, C., Nilsson, B. & Poulsen, M.L.K.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 51 pp.

2. Geological setting and structural framework of Danish onshore areas (Gravesen, P., Pedersen, S. A. S. & Midtgaard, H. H.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 72 pp.

3. Upper Cretaceous chalk and Paleocene limestone distribution and properties (Jakobsen, P.R., Frykman, P. & Jakobsen, R.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 76 pp.

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8.2 Literature from previous projects on the Danish radioactive waste

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www.dd.dk
www.dmi.dk
www.geus.dk
www.ufm.dk

Appendix A: Sedimentological logs

Indhold

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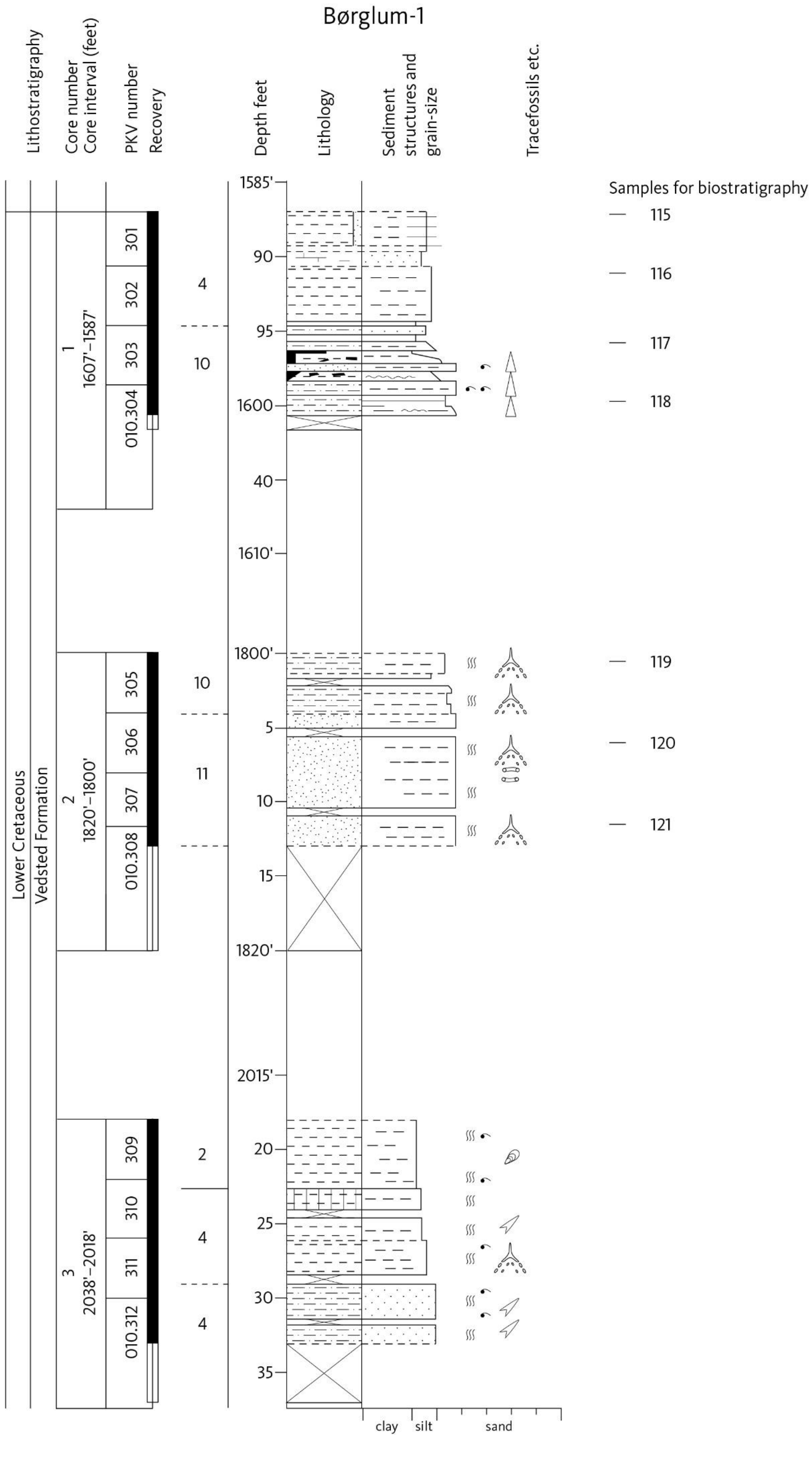
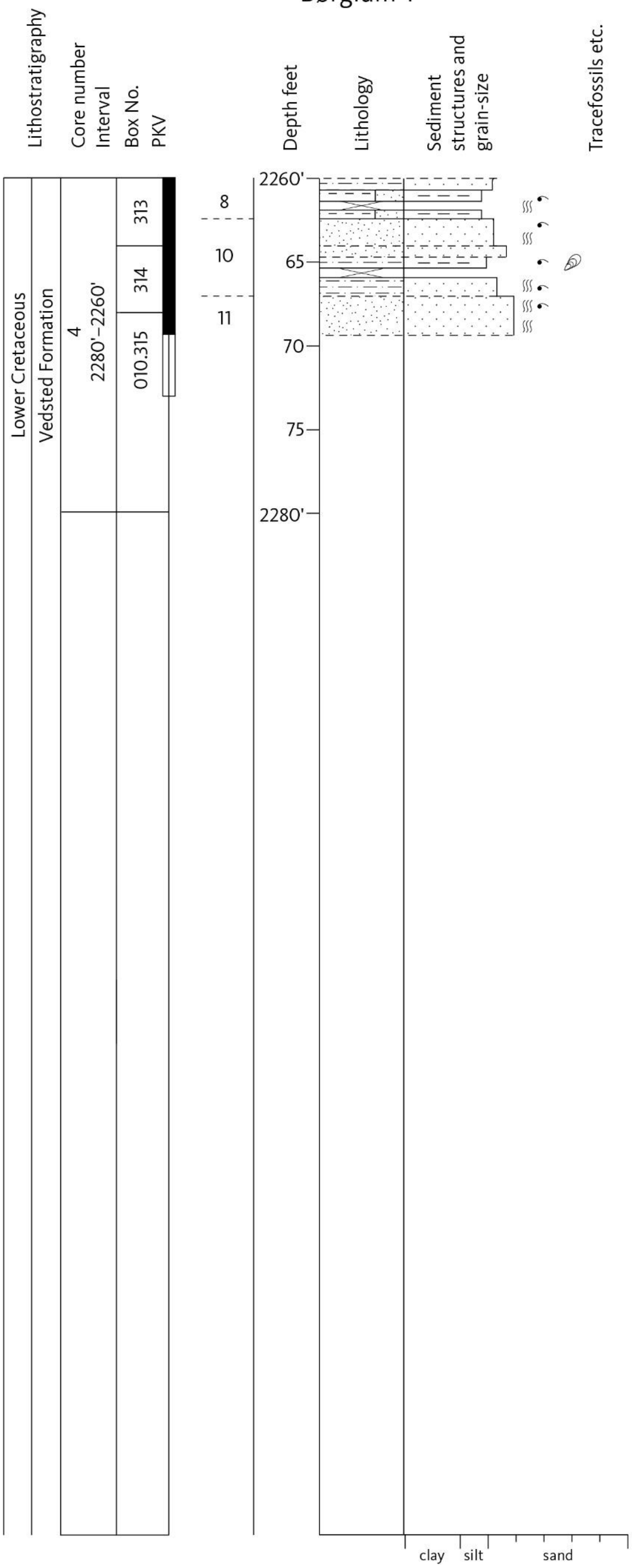
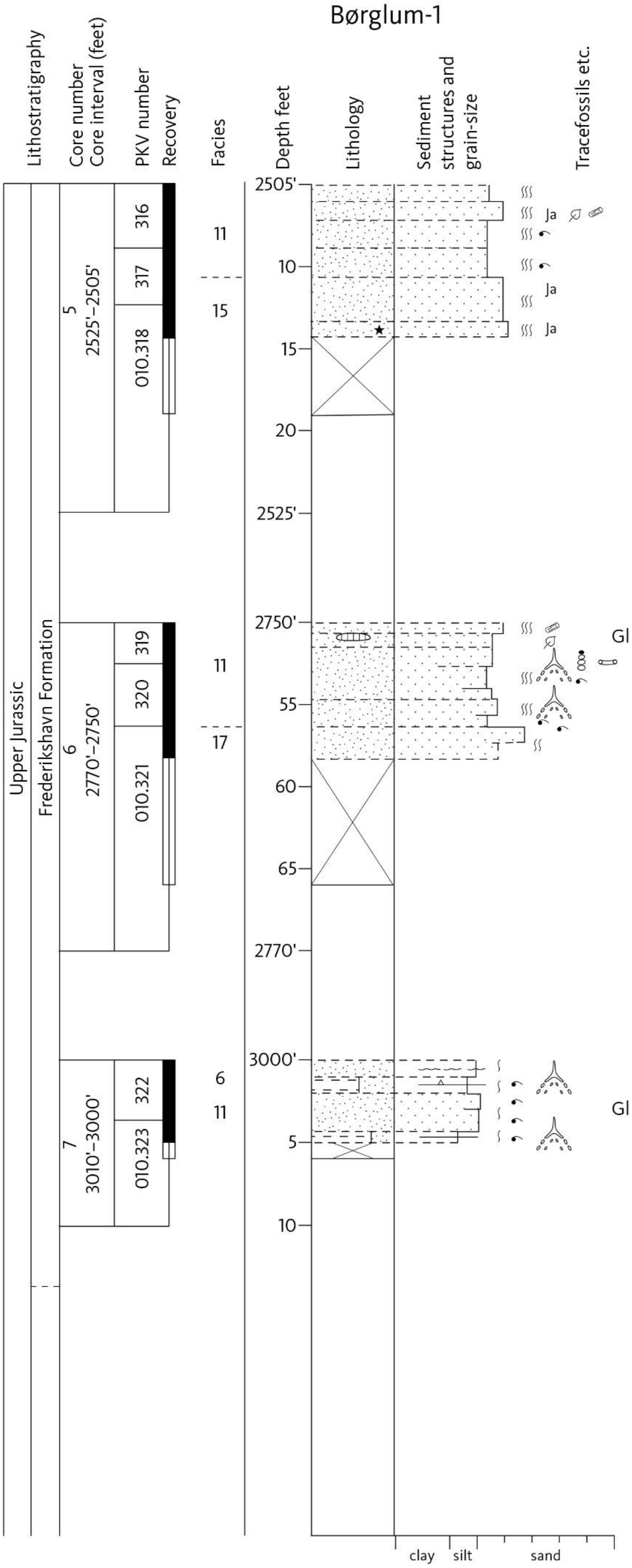
1. Børglum-1



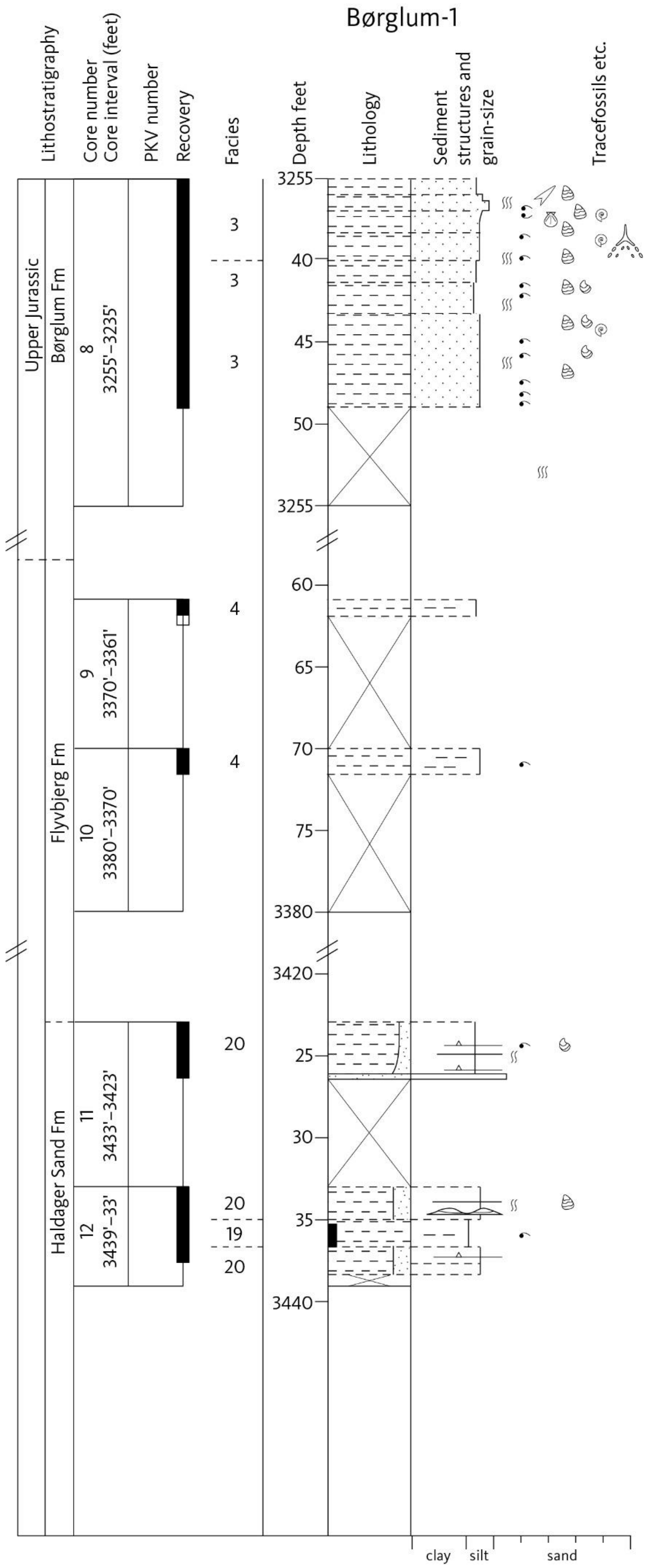
Børglum-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Samples for biostratigraphy
115
116
117
118
119
120
121
Lower Cretaceous
Vedsted Formation
1
1607'–1587'
2
1820'–1800'
3
2038'–2018'
301
302
303
010.304
305
306
307
010.308
309
310
311
010.312
4
10
10
11
2
4
4
1585'
90
95
1600
40
1610'
1800'
5
10
15
1820'
2015'
20
25
30
35
clay
silt
sand

Børglum-1

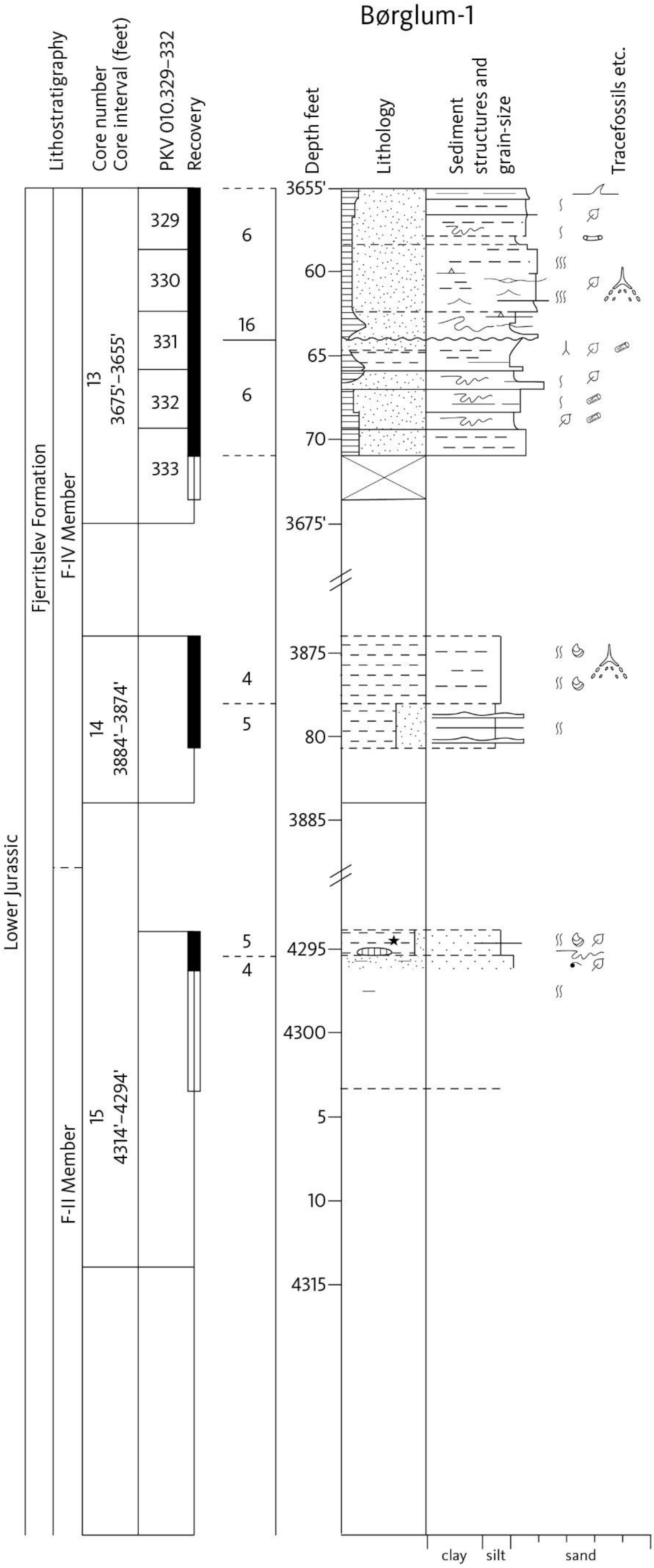

Lithostratigraphy
Core number
Interval
Box No.
PKV
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
4
2280'–2260'
313
314
010.315
8
10
11
2260'
65
70
75
2280'
clay
silt
sand



Børglum-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Jurassic
Frederikshavn Formation
5
2525'–2505'
316
317
010.318
11
15
2505'
10
15
20
2525'
Ja
6
2770'–2750'
319
320
010.321
11
17
2750'
55
60
65
2770'
Gl
7
3010'–3000'
322
010.323
6
11
3000'
5
10
clay
silt
sand



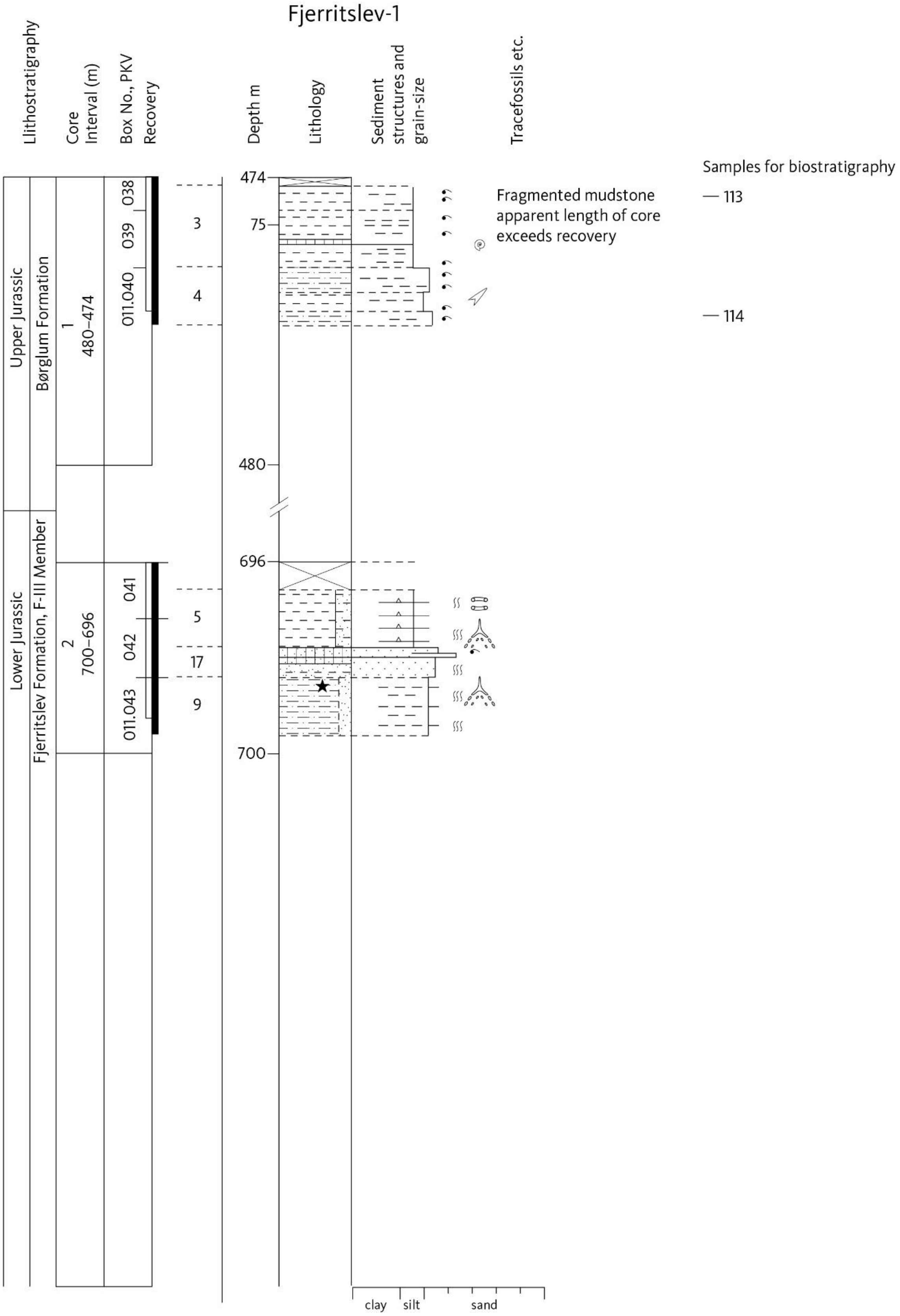
Børglum-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Jurassic
Børglum Fm
8
3255'–3235'
3
3
3
3255
40
45
50
3255
Flyvbjerg Fm
9
3370'–3361'
10
3380'–3370'
4
4
60
65
70
75
3380
Haldager Sand Fm
11
3433'–3423'
12
3439'–33'
20
20
19
20
3420
25
30
35
3440
clay
silt
sand



Børglum-1
Lithostratigraphy
Core number
Core interval (feet)
PKV 010.329–332
Recovery
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-IV Member
F-II Member
13
3675'–3655'
14
3884'–3874'
15
4314'–4294'
329
330
331
332
333
3655'
60
65
70
3675'
3875
80
3885
4295
4300
5
10
4315
clay
silt
sand

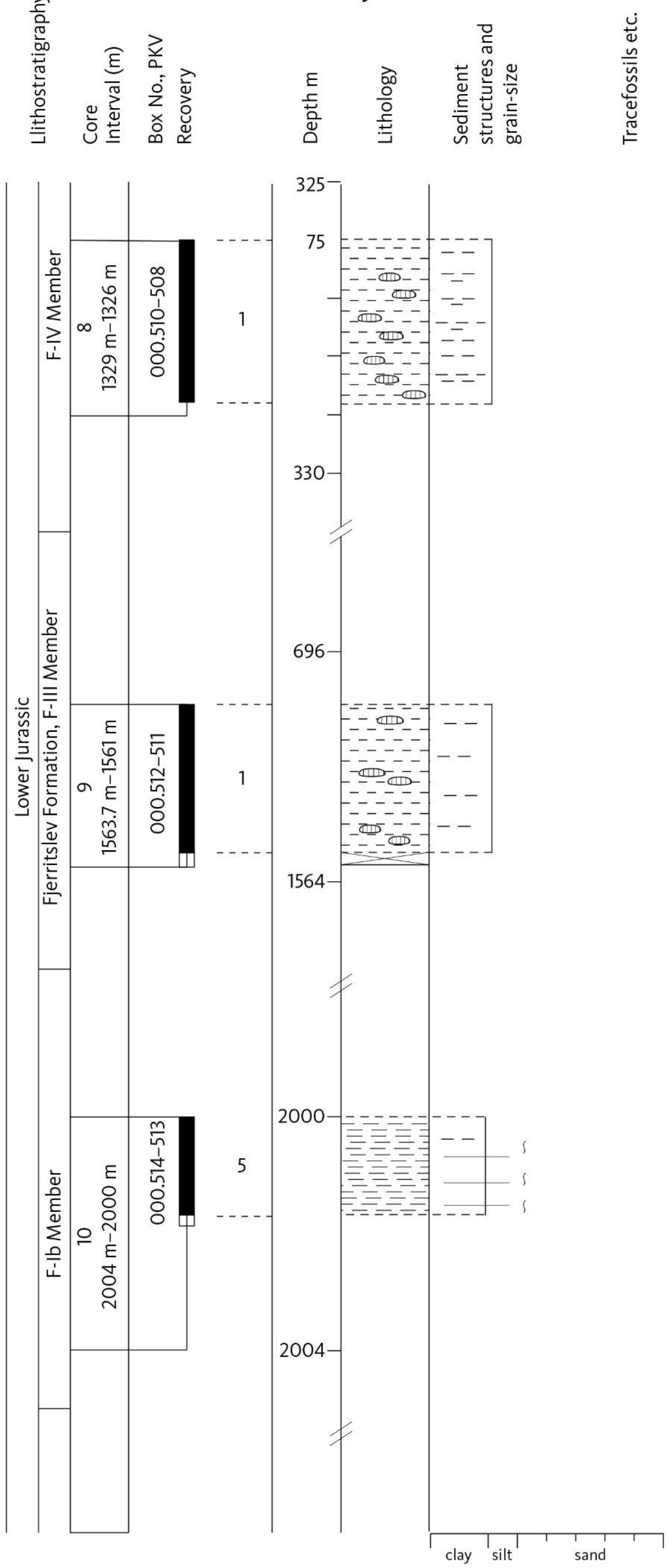
2. Fjerritslev-1

Fjerritslev-1

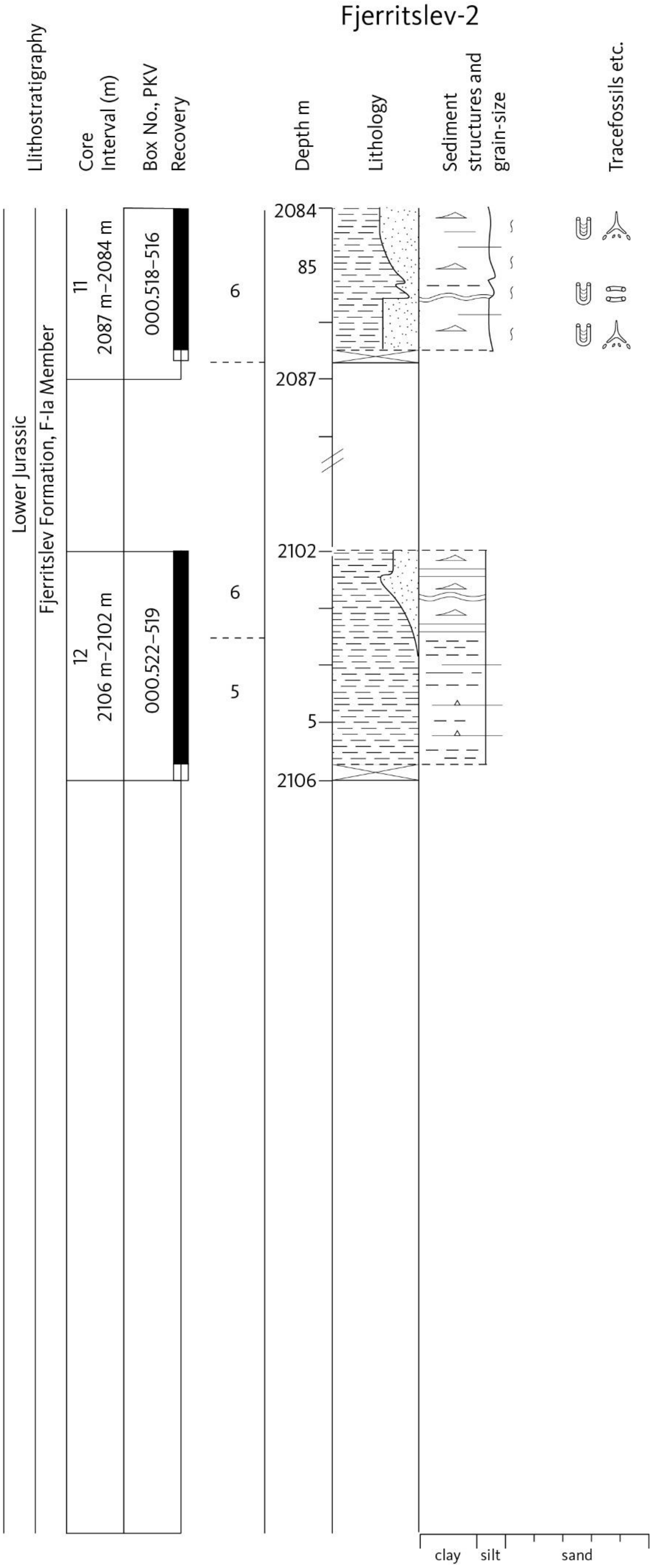


3. Fjerritslev-2

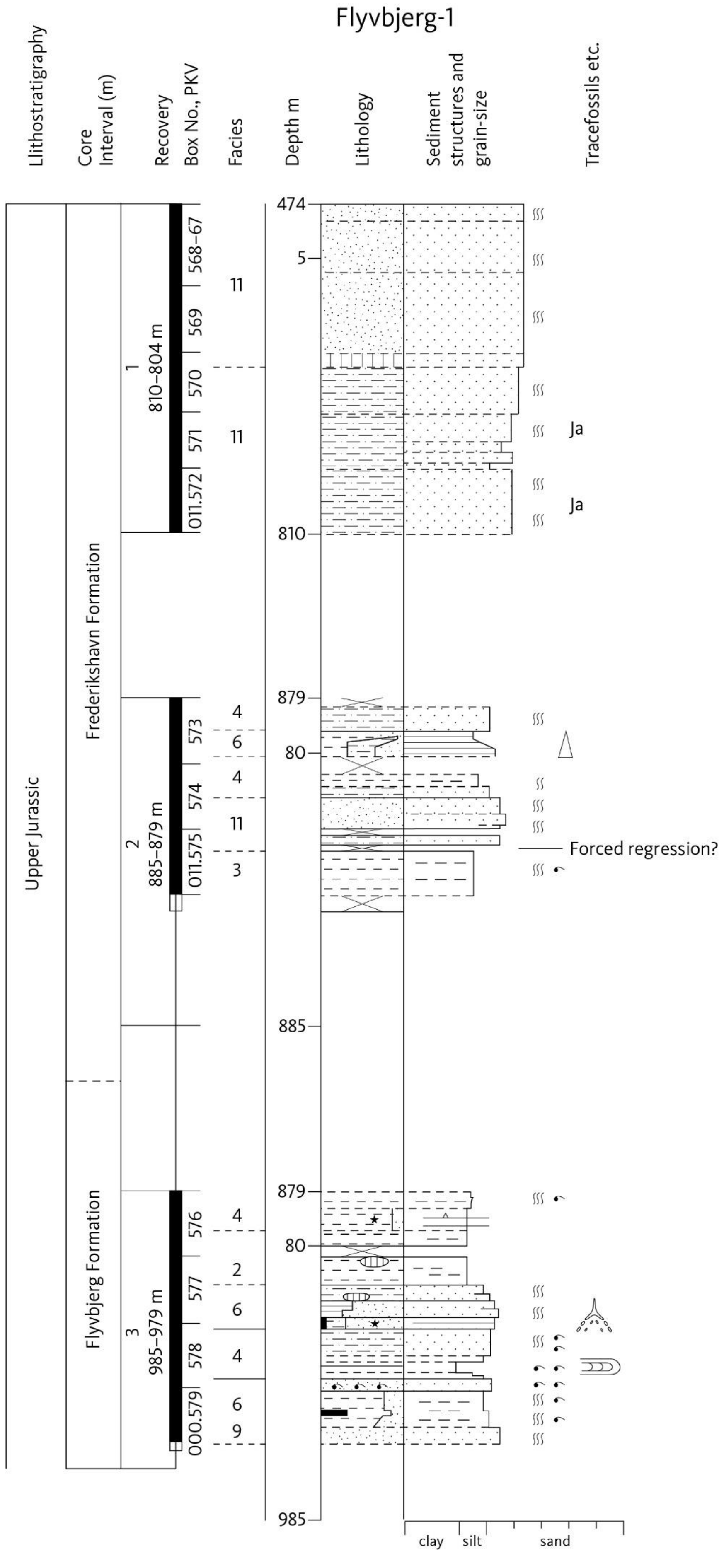
Fjerritslev-2



Fjerritslev-2

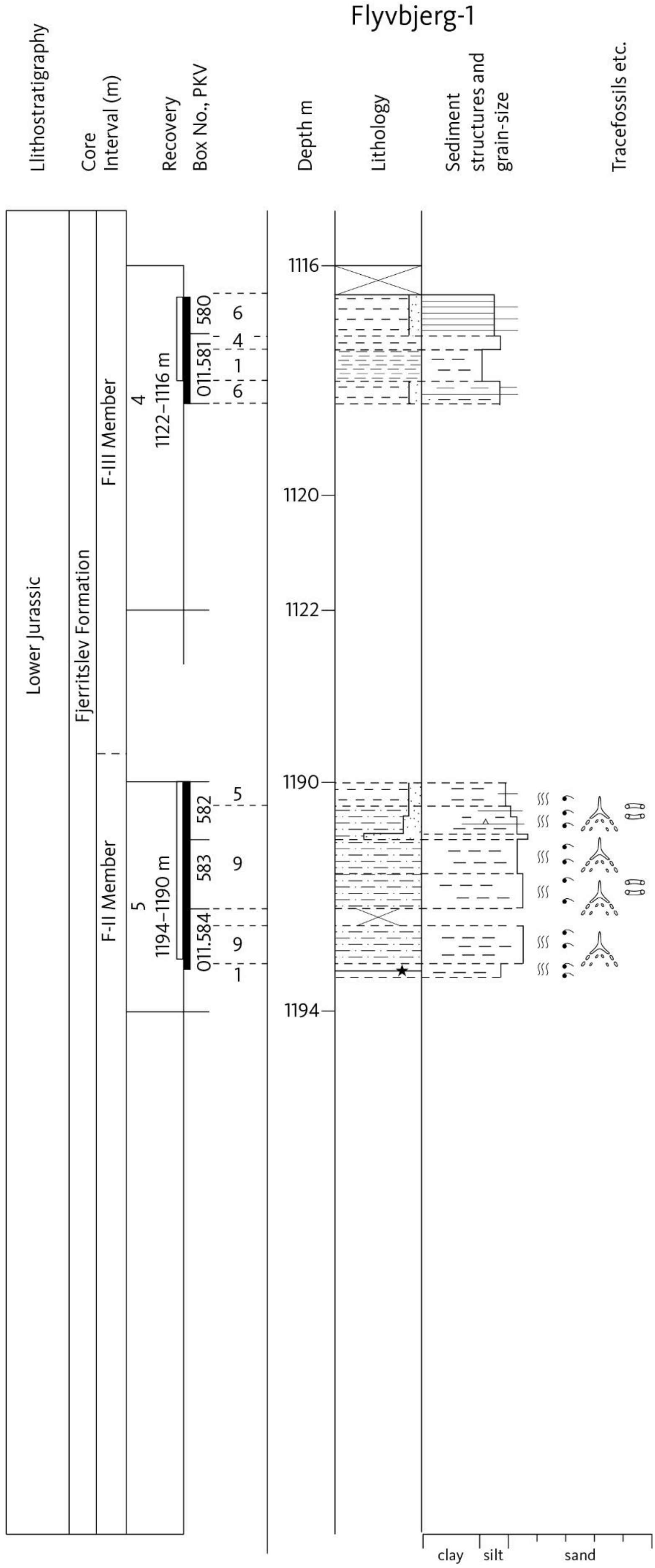


4. Flyvbjerg-1

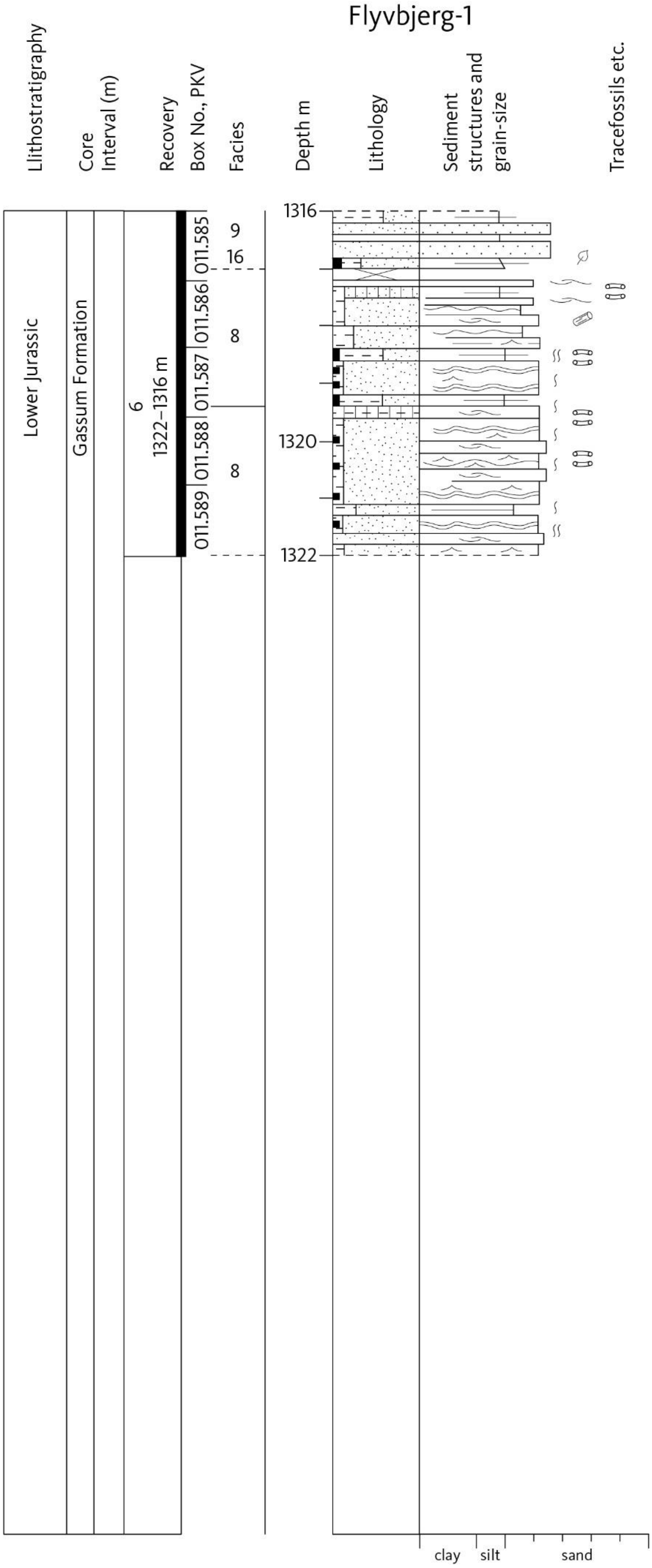


Flyvbjerg-1
Llithostratigraphy
Core Interval (m)
Recovery Box No., PKV
Facies
Depth m
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Jurassic
Frederikshavn Formation
Flyvbjerg Formation
1
810–804 m
2
885–879 m
3
985–979 m
568–67
569
570
571
011.572
573
574
011.575
576
577
578
000.579
11
11
4
6
4
11
3
4
2
6
4
6
9
474
5
810
879
80
885
879
80
985
Ja
Ja
Forced regression?
clay
silt
sand

Flyvbjerg-1

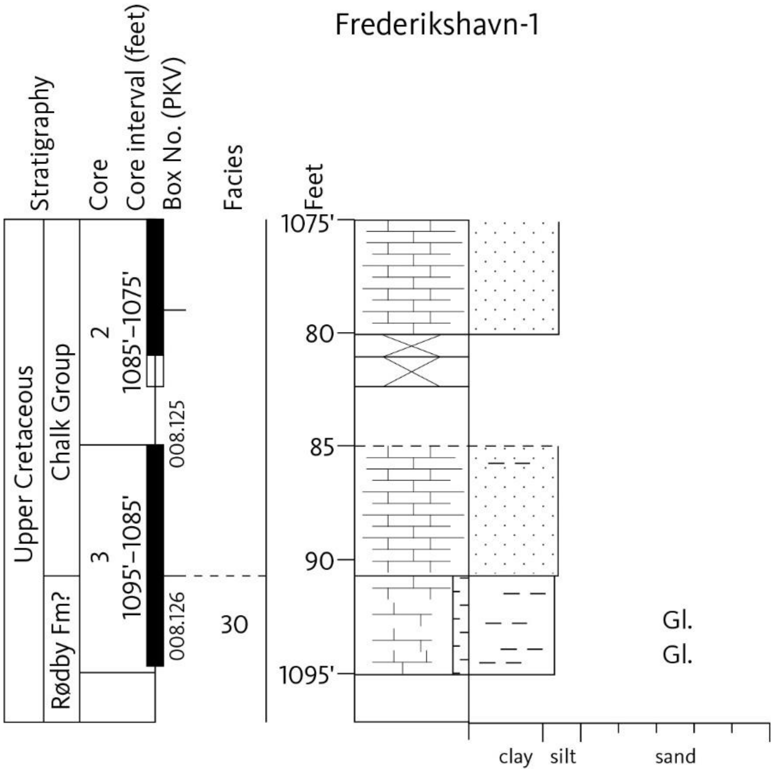

Llithostratigraphy
Core
Interval (m)
Recovery
Box No., PKV
Depth m
Lithology
Sediment
structures and
grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-III Member
F-II Member
4
1122–1116 m
5
1194–1190 m
580
011.581
582
583
011.584
6
4
1
6
5
9
9
1
1116
1120
1122
1190
1194
clay
silt
sand

Flyvbjerg-1



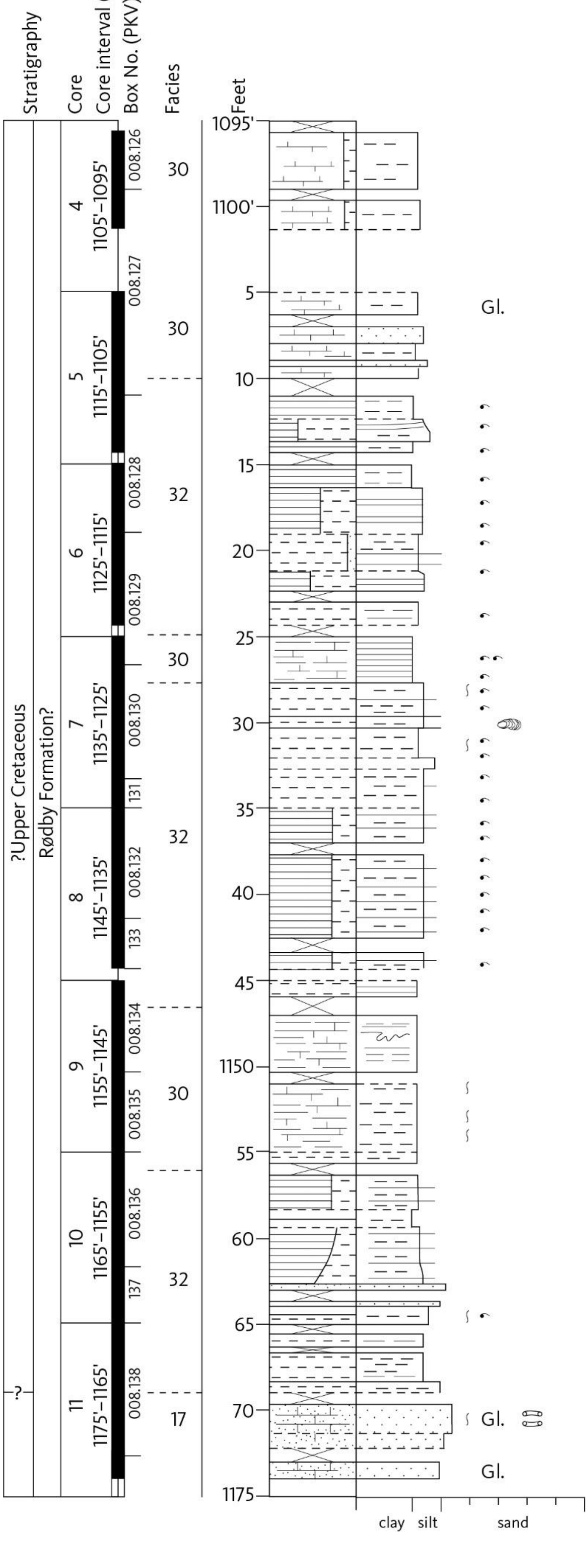
Lithostratigraphy
Core Interval (m)
Recovery
Box No., PKV
Facies
Depth m
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Gassum Formation
6
1322–1316 m
011.585
011.586
011.587
011.588
011.589
9
16
8
8
1316
1320
1322
clay
silt
sand

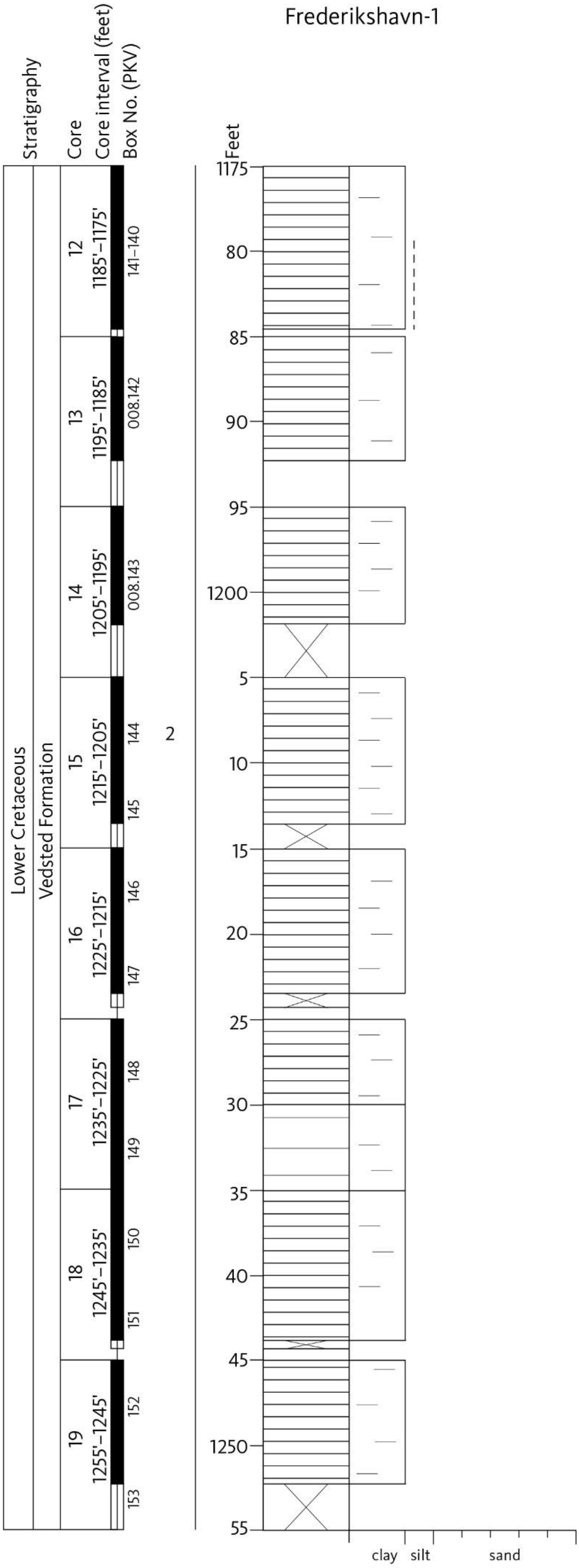
5. Frederikshavn-1



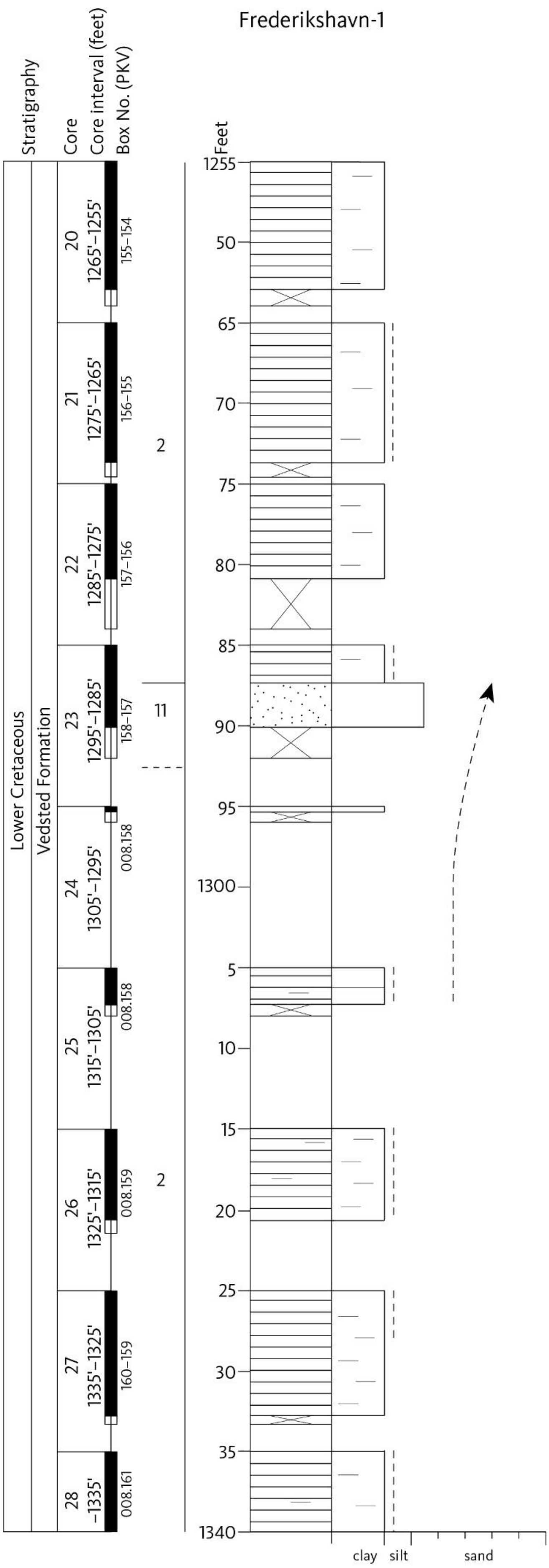
Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Cretaceous
Chalk Group
Rødby Fm?
2
1085'–1075'
3
1095'–1085'
008.125
008.126
30
1075'
80
85
90
1095'
Gl.
Gl.
clay
silt
sand

Frederikshavn-1

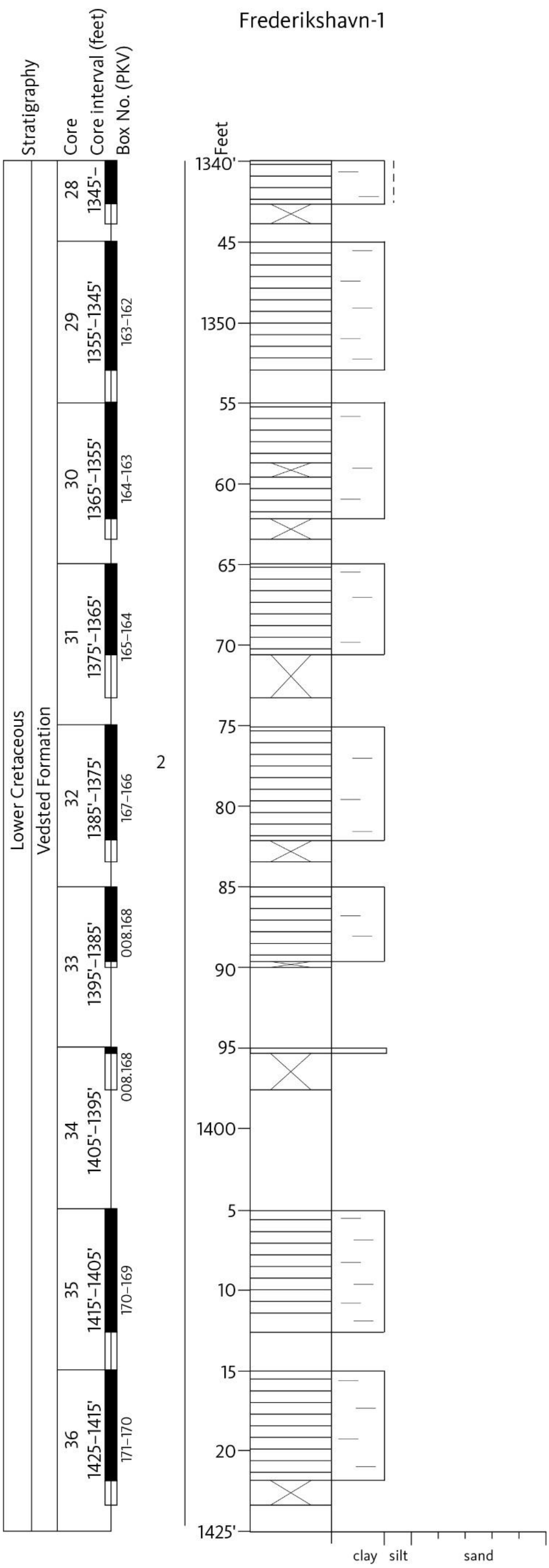


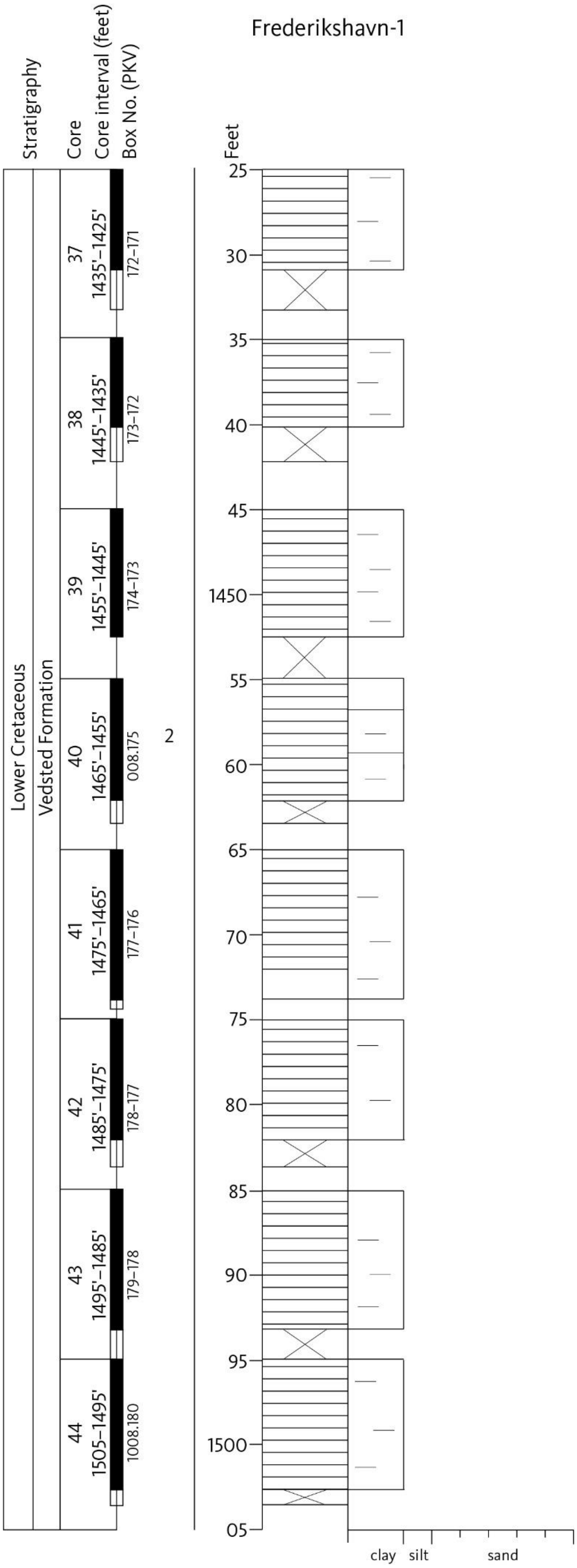

Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Feet
Lower Cretaceous
Vedsted Formation
12
1185'–1175'
141–140
13
1195'–1185'
008.142
14
1205'–1195'
008.143
15
1215'–1205'
144
145
16
1225'–1215'
146
147
17
1235'–1225'
148
149
18
1245'–1235'
150
151
19
1255'–1245'
152
153
2
1175
80
85
90
95
1200
5
10
15
20
25
30
35
40
45
1250
55
clay
silt
sand

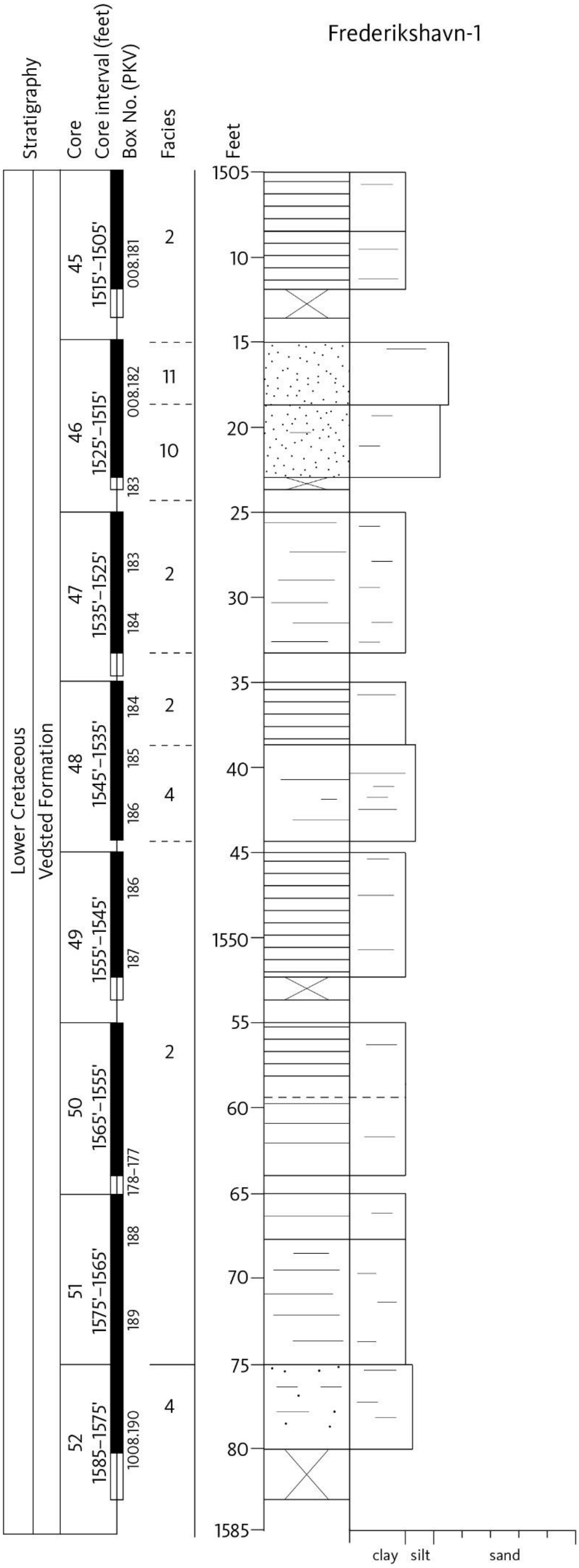
Frederikshavn-1

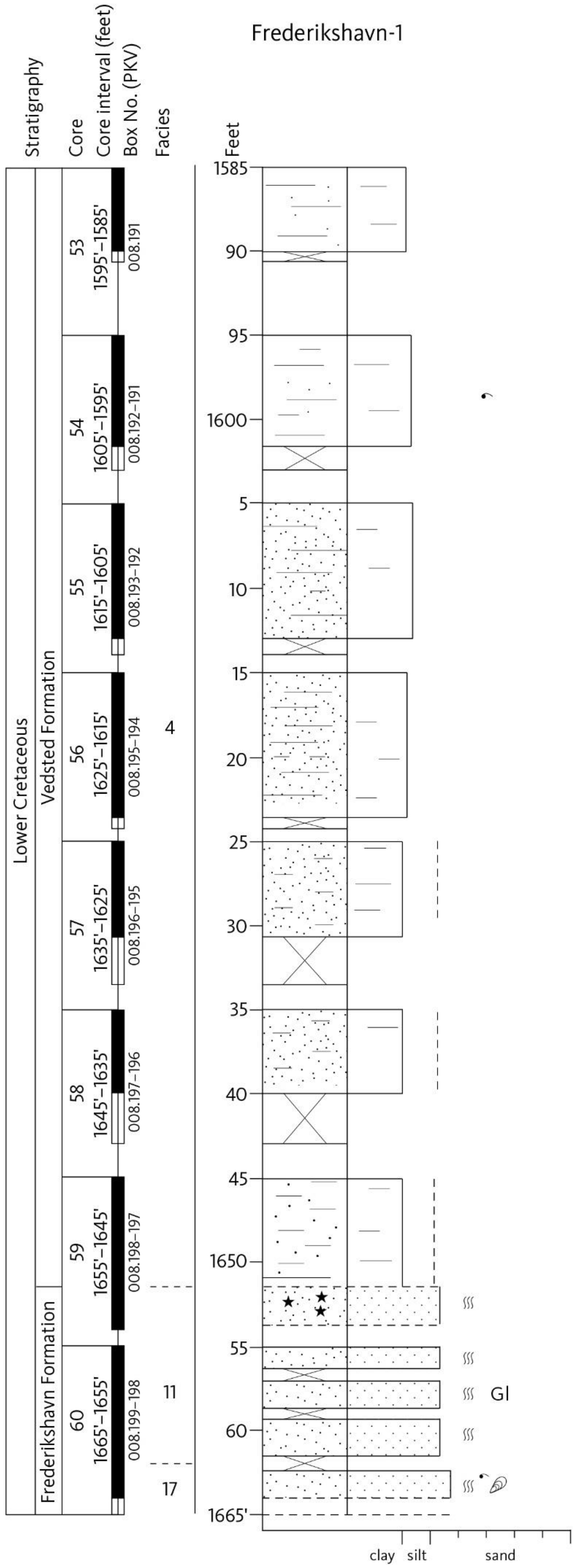


Frederikshavn-1

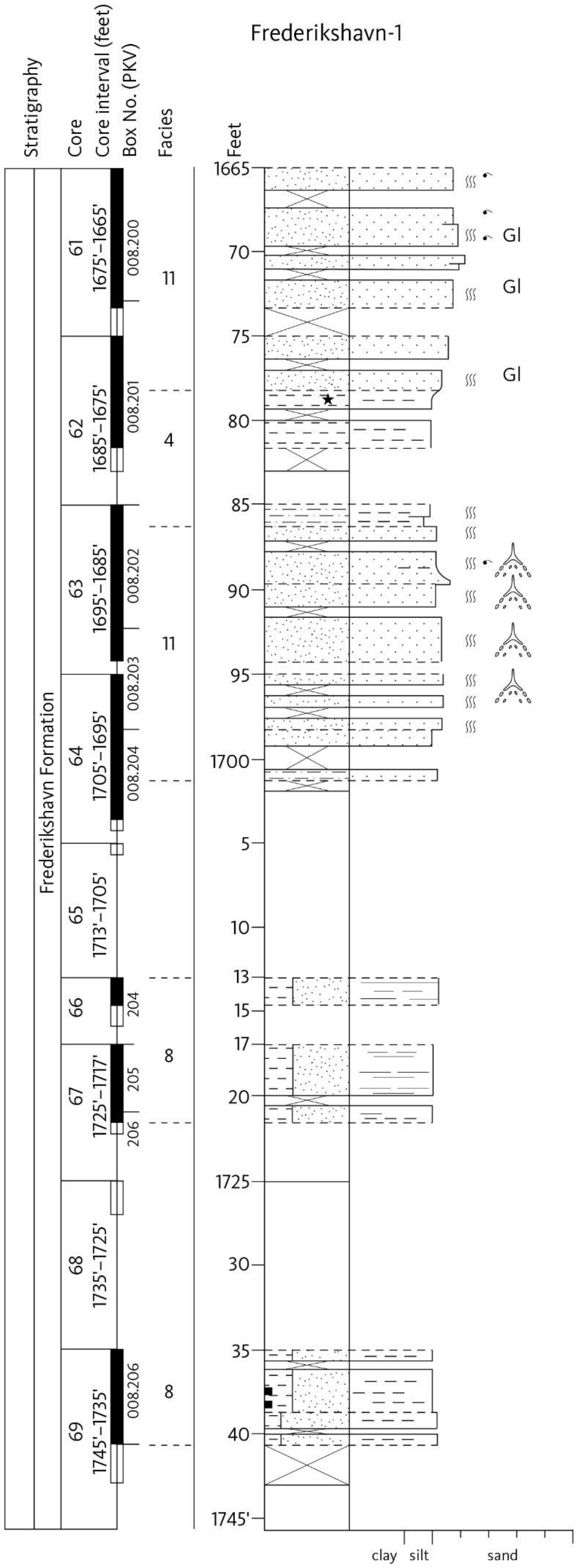


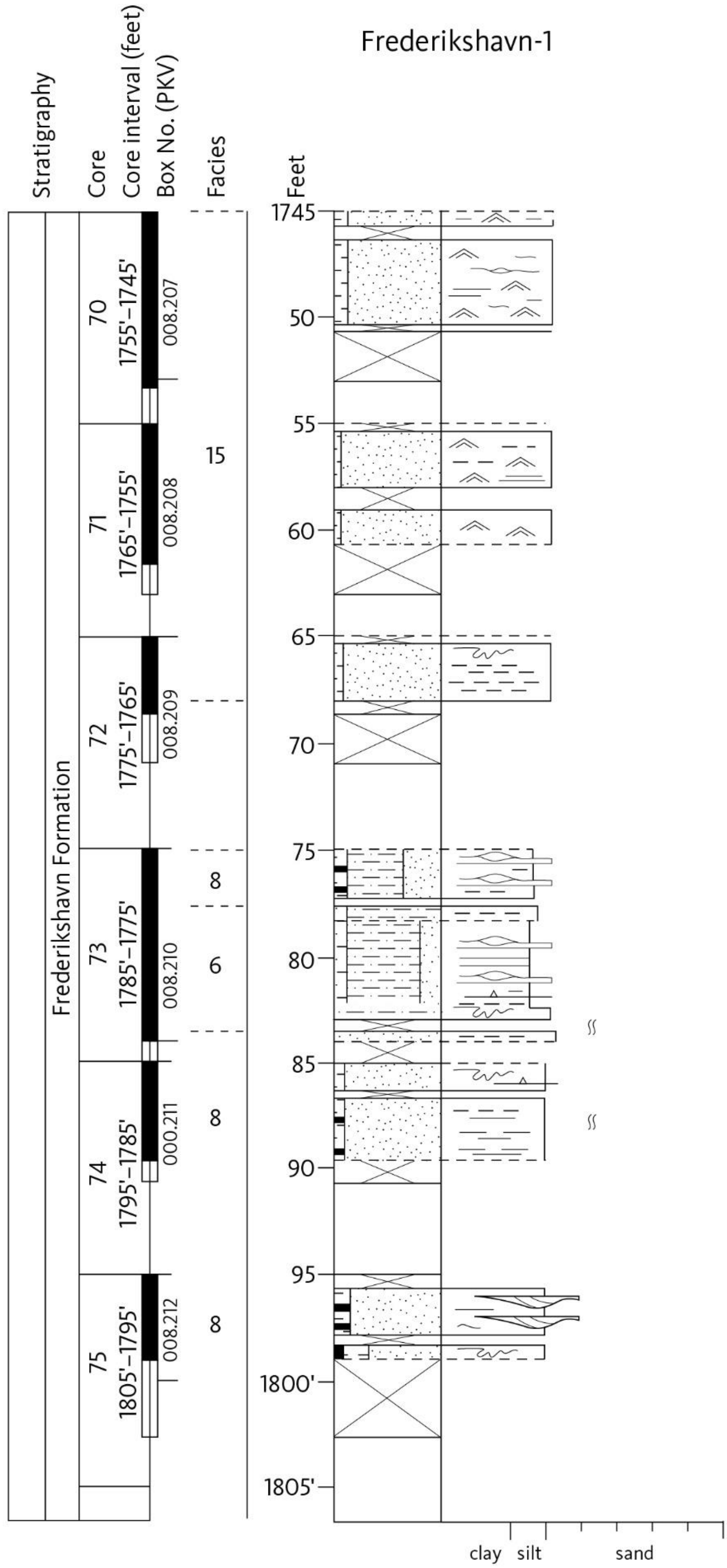

Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Lower Cretaceous
Vedsted Formation
37
1435'–1425'
172–171
38
1445'–1435'
173–172
39
1455'–1445'
174–173
40
1465'–1455'
008.175
41
1475'–1465'
177–176
42
1485'–1475'
178–177
43
1495'–1485'
179–178
44
1505–1495'
1008.180
2
Feet
25
30
35
40
45
1450
55
60
65
70
75
80
85
90
95
1500
05
clay
silt
sand

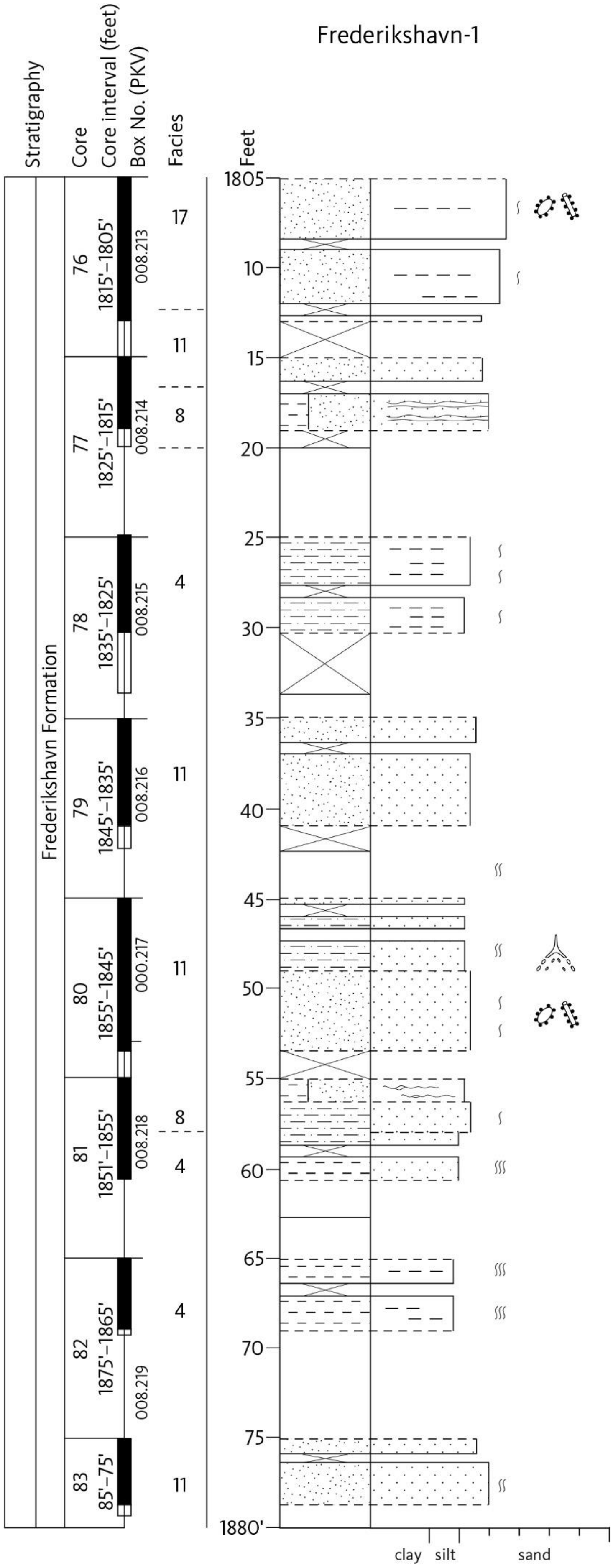

Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Lower Cretaceous
Vedsted Formation
45
1515'–1505'
008.181
46
1525'–1515'
008.182
183
47
1535'–1525'
183
184
48
1545'–1535'
184
185
186
49
1555'–1545'
186
187
50
1565'–1555'
178–177
51
1575'–1565'
188
189
52
1585–1575'
1008.190
2
11
10
2
2
4
2
4
1505
10
15
20
25
30
35
40
45
1550
55
60
65
70
75
80
1585
clay
silt
sand



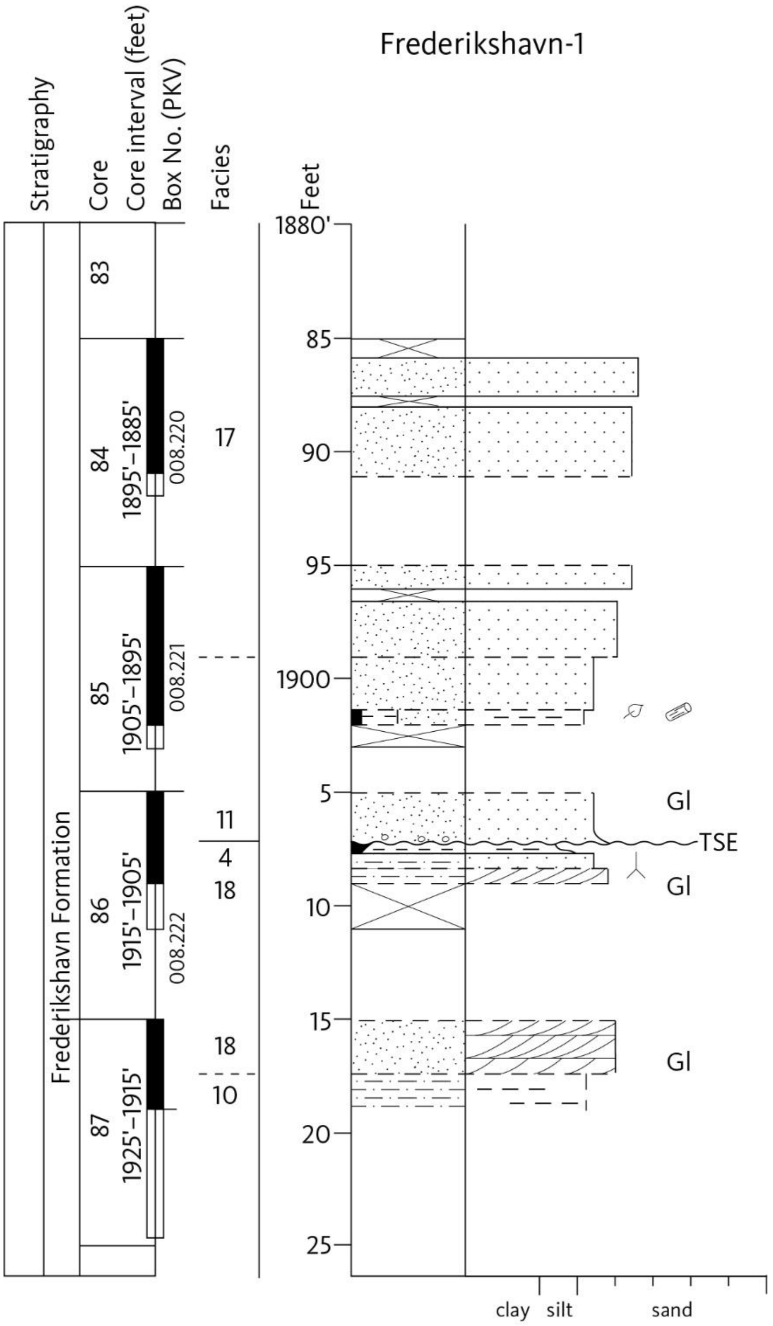
Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Lower Cretaceous
Vedsted Formation
Frederikshavn Formation
53
1595'–1585'
008.191
54
1605'–1595'
008.192–191
55
1615'–1605'
008.193–192
56
1625'–1615'
008.195–194
57
1635'–1625'
008.196–195
58
1645'–1635'
008.197–196
59
1655'–1645'
008.198–197
60
1665'–1655'
008.199–198
4
11
17
1585
90
95
1600
5
10
15
20
25
30
35
40
45
1650
55
60
1665'
Gl
clay
silt
sand

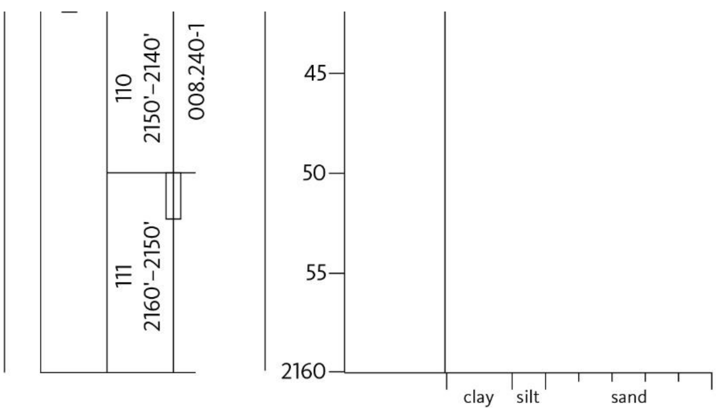

Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Frederikshavn Formation
61
1675'–1665'
008.200
62
1685'–1675'
008.201
63
1695'–1685'
008.202
008.203
64
1705'–1695'
008.204
65
1713'–1705'
66
204
67
1725'–1717'
205
206
68
1735'–1725'
69
1745'–1735'
008.206
11
4
11
8
8
1665
70
75
80
85
90
95
1700
5
10
13
15
17
20
1725
30
35
40
1745'
Gl
Gl
Gl
clay
silt
sand

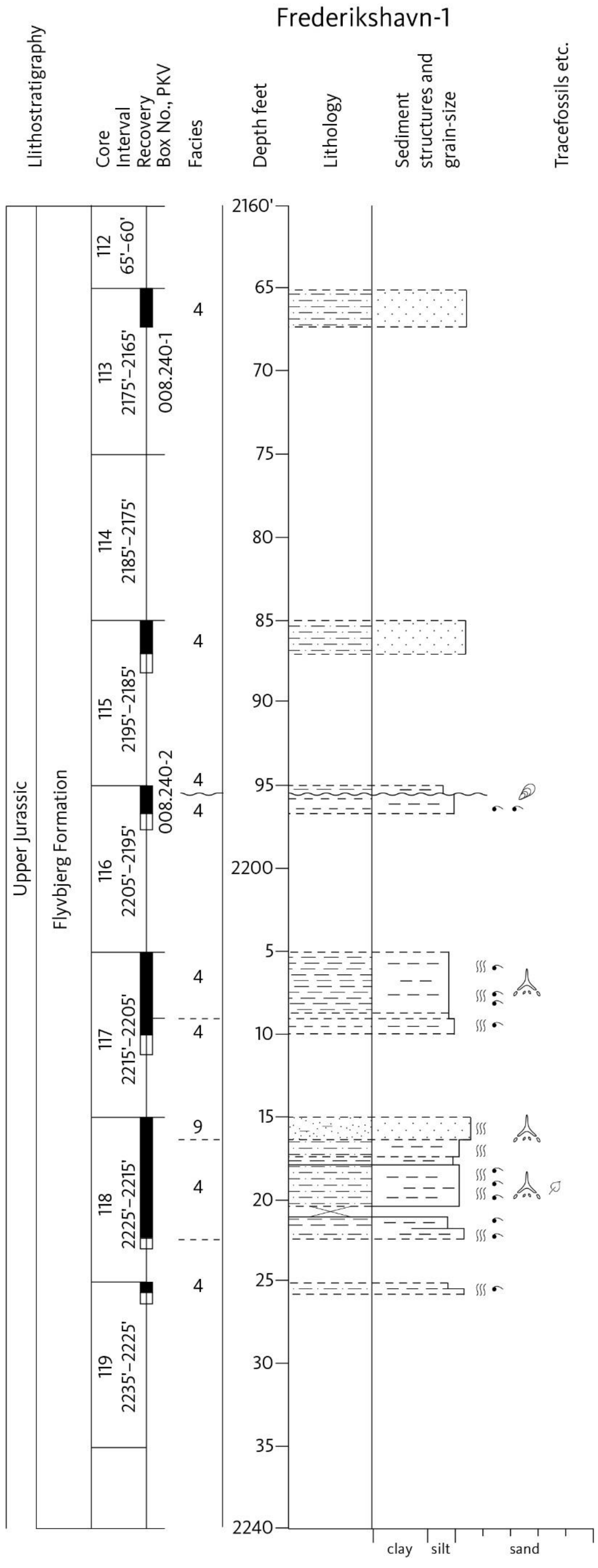

Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Frederikshavn Formation
70
1755'–1745'
008.207
71
1765'–1755'
008.208
72
1775'–1765'
008.209
73
1785'–1775'
008.210
74
1795'–1785'
000.211
75
1805'–1795'
008.212
15
8
6
8
8
1745
50
55
60
65
70
75
80
85
90
95
1800'
1805'
clay
silt
sand


Frederikshavn-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Frederikshavn Formation
76
1815'–1805'
008.213
77
1825'–1815'
008.214
78
1835'–1825'
008.215
79
1845'–1835'
008.216
80
1855'–1845'
000.217
81
1851'–1855'
008.218
82
1875'–1865'
008.219
83
85'–75'
17
11
8
4
11
11
8
4
4
11
1805
10
15
20
25
30
35
40
45
50
55
60
65
70
75
1880'
clay
silt
sand

Frederikshavn-1

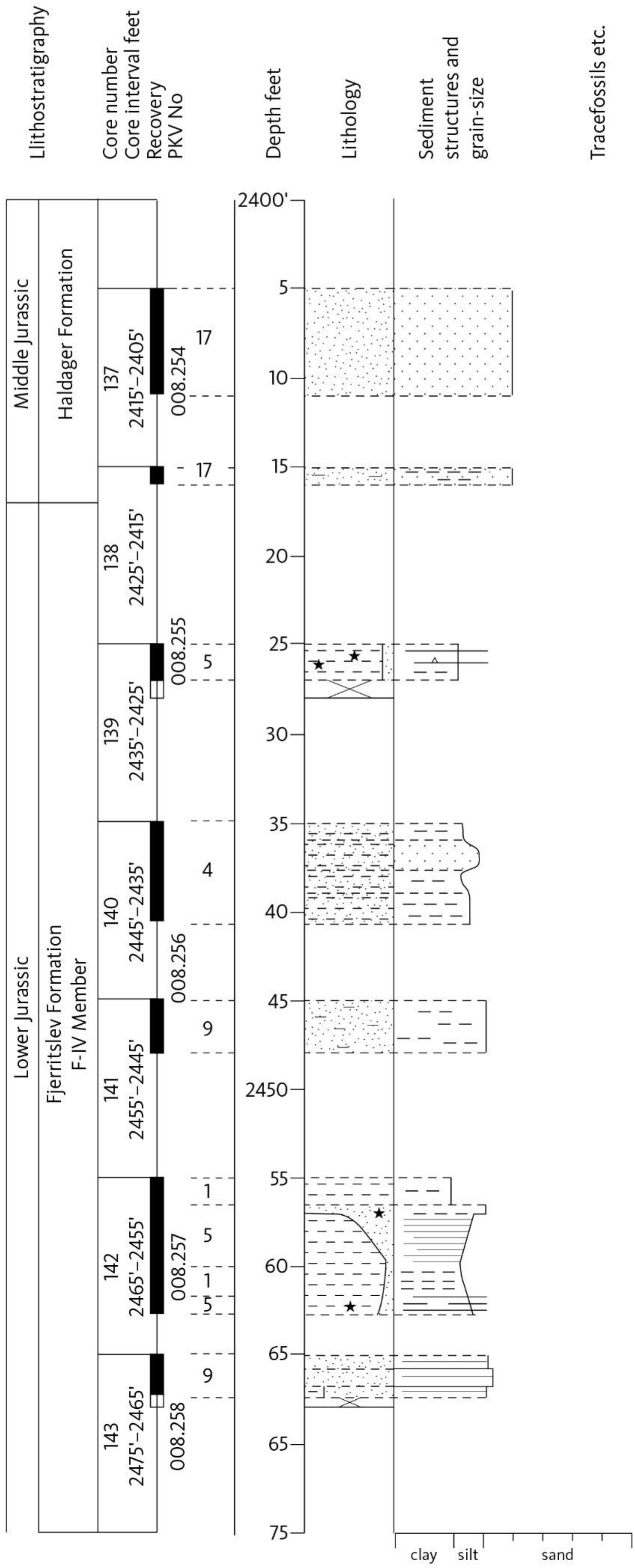


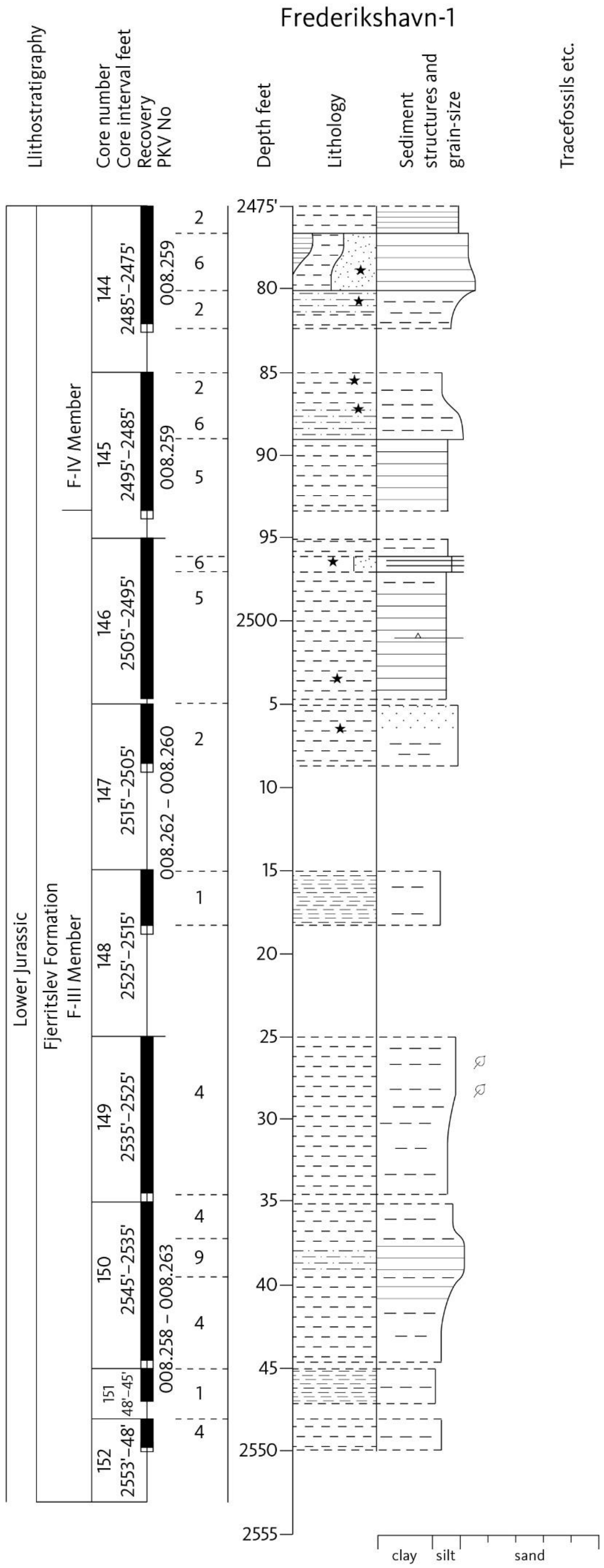




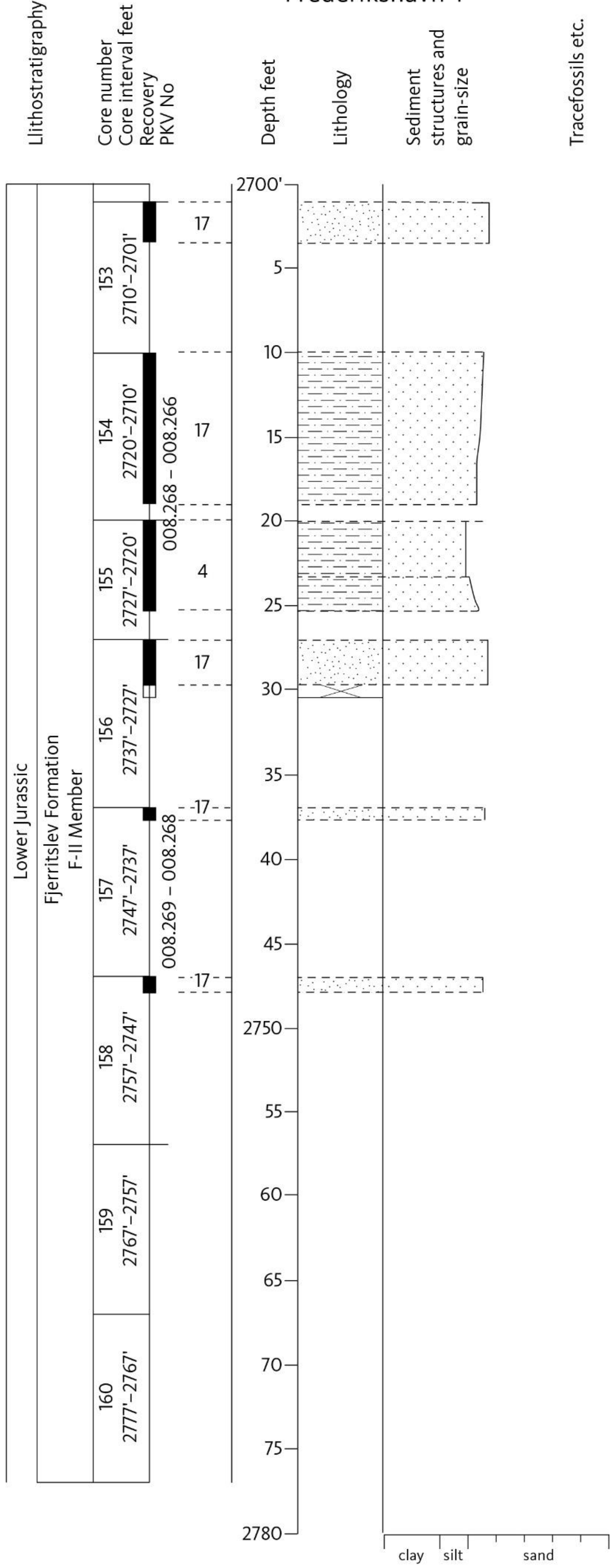
Frederikshavn-1
Lithostratigraphy
Core
Interval
Recovery
Box No., PKV
Facies
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Jurassic
Flyvbjerg Formation
112 65'-60'
113 2175'-2165'
114 2185'-2175'
115 2195'-2185'
116 2205'-2195'
117 2215'-2205'
118 2225'-2215'
119 2235'-2225'
008.240-1
008.240-2
4
4
4
4
4
4
9
4
4
2160'
65
70
75
80
85
90
95
2200
5
10
15
20
25
30
35
2240
clay
silt
sand

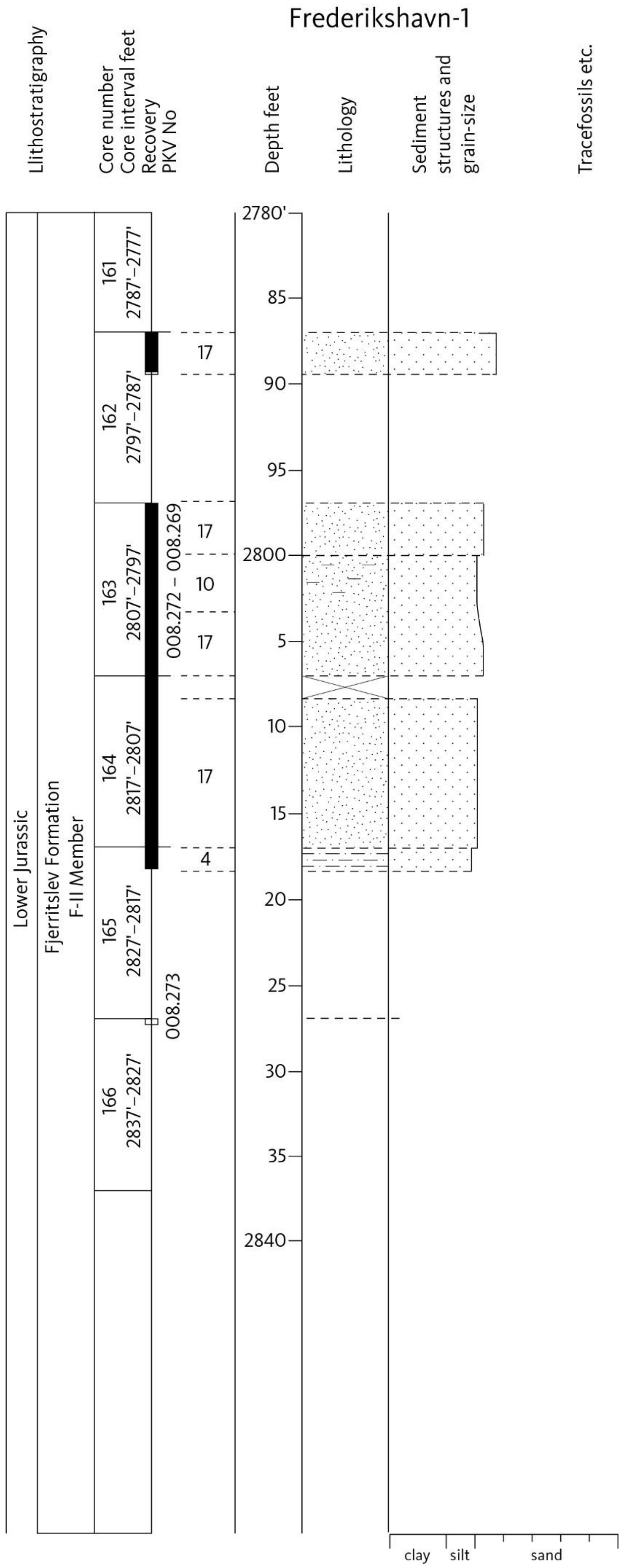
Frederikshavn-1




Frederikshavn-1
Llithostratigraphy
Core number
Core interval feet
Recovery
PKV No
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-IV Member
F-III Member
144 2485'–2475'
145 2495'–2485'
146 2505'–2495'
147 2515'–2505'
148 2525'–2515'
149 2535'–2525'
150 2545'–2535'
151 48'–45'
152 2553'–48'
008.259
008.259
008.262 – 008.260
008.258 – 008.263
2475'
80
85
90
95
2500
5
10
15
20
25
30
35
40
45
2550
2555
clay
silt
sand

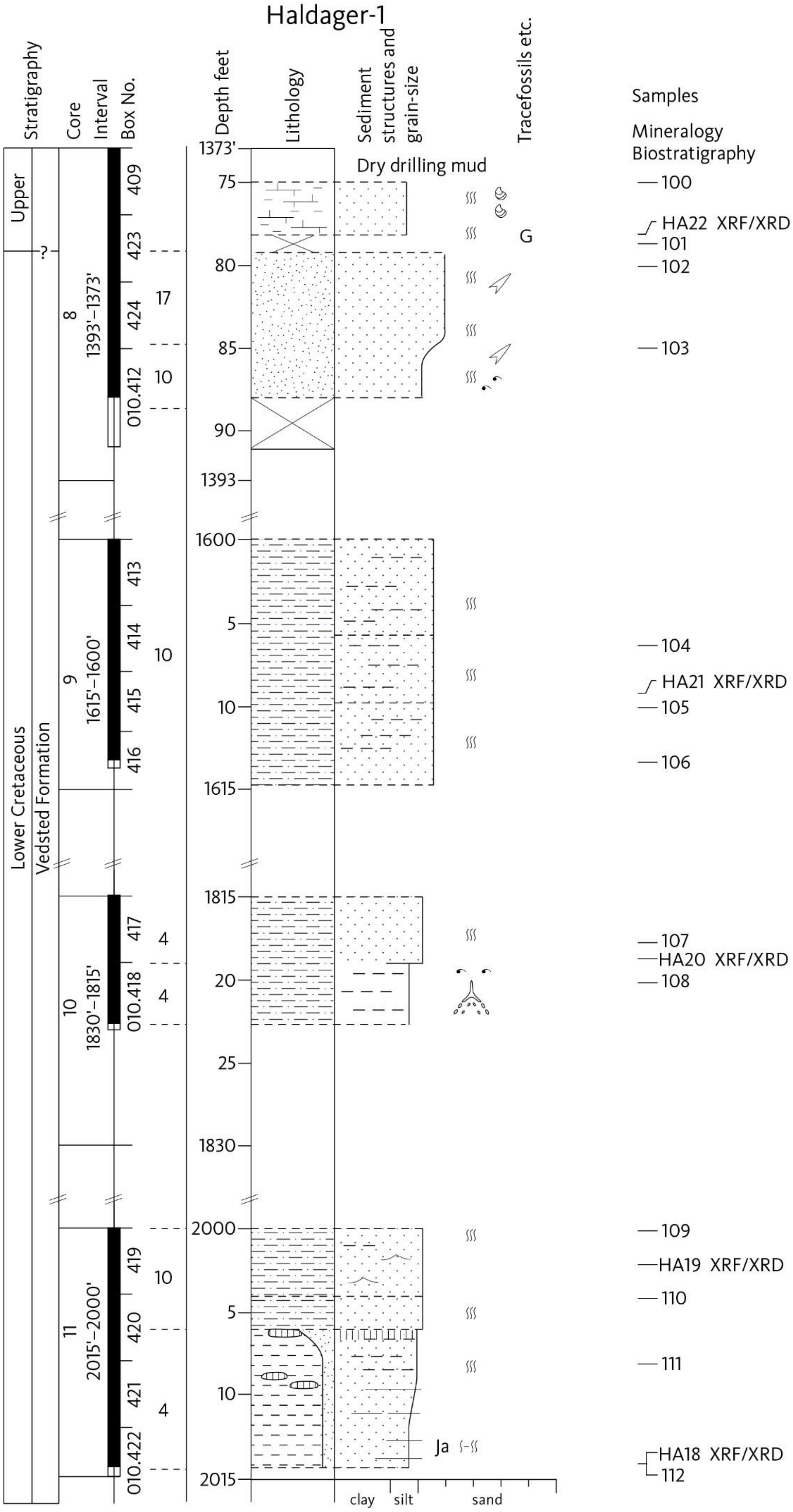
Frederikshavn-1



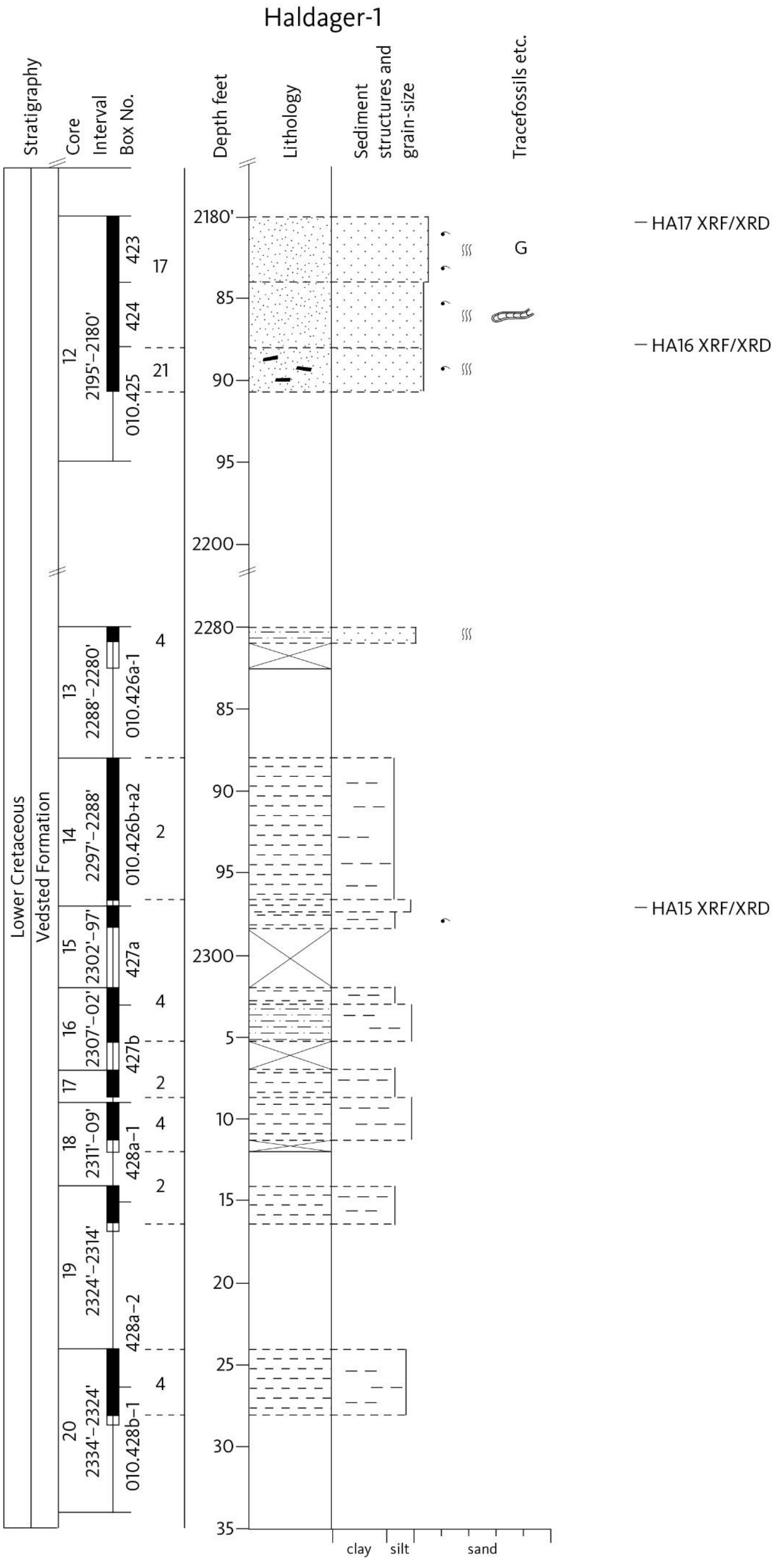


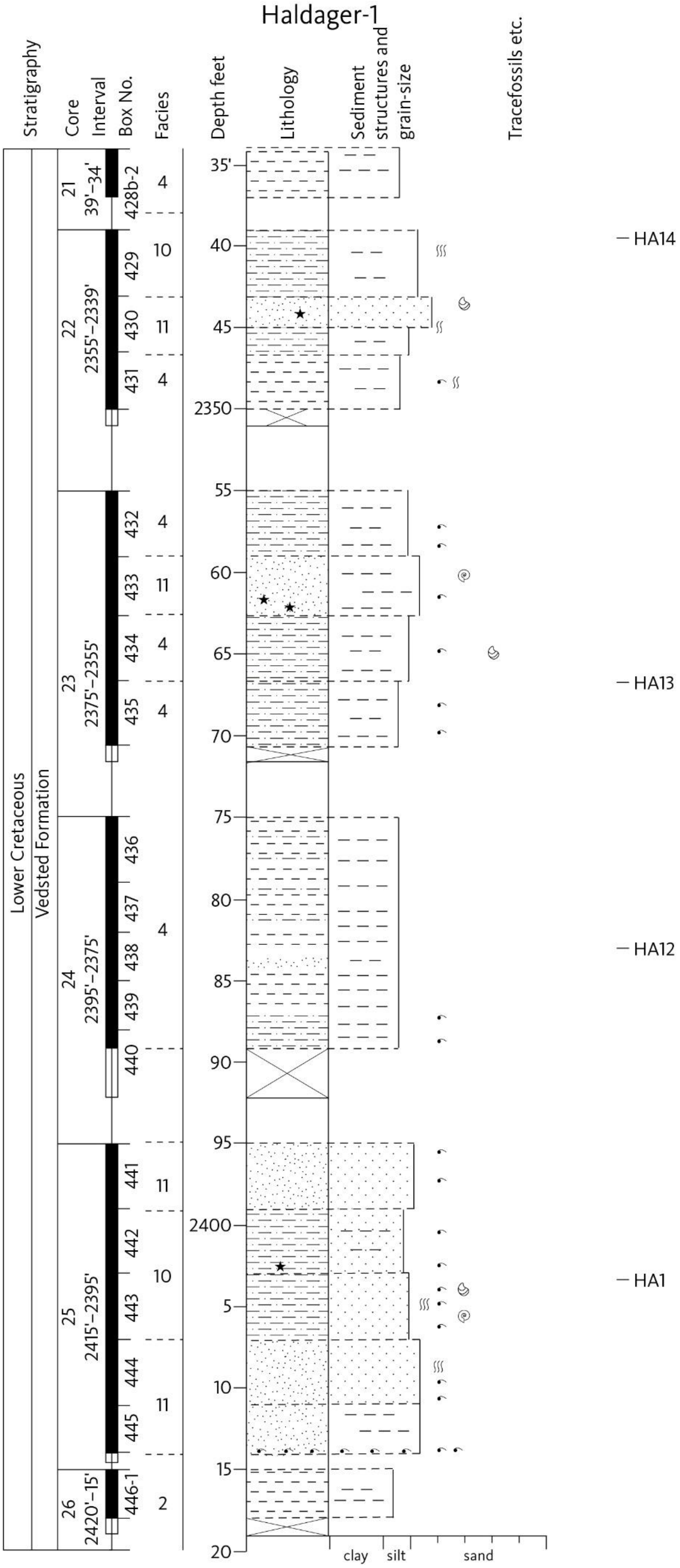
Frederikshavn-1
Lithostratigraphy
Core number
Core interval feet
Recovery
PKV No
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-II Member
161
2787'–2777'
162
2797'–2787'
163
2807'–2797'
164
2817'–2807'
165
2827'–2817'
166
2837'–2827'
008.272 – 008.269
008.273
17
17
10
17
17
4
2780'
85
90
95
2800
5
10
15
20
25
30
35
2840
clay
silt
sand

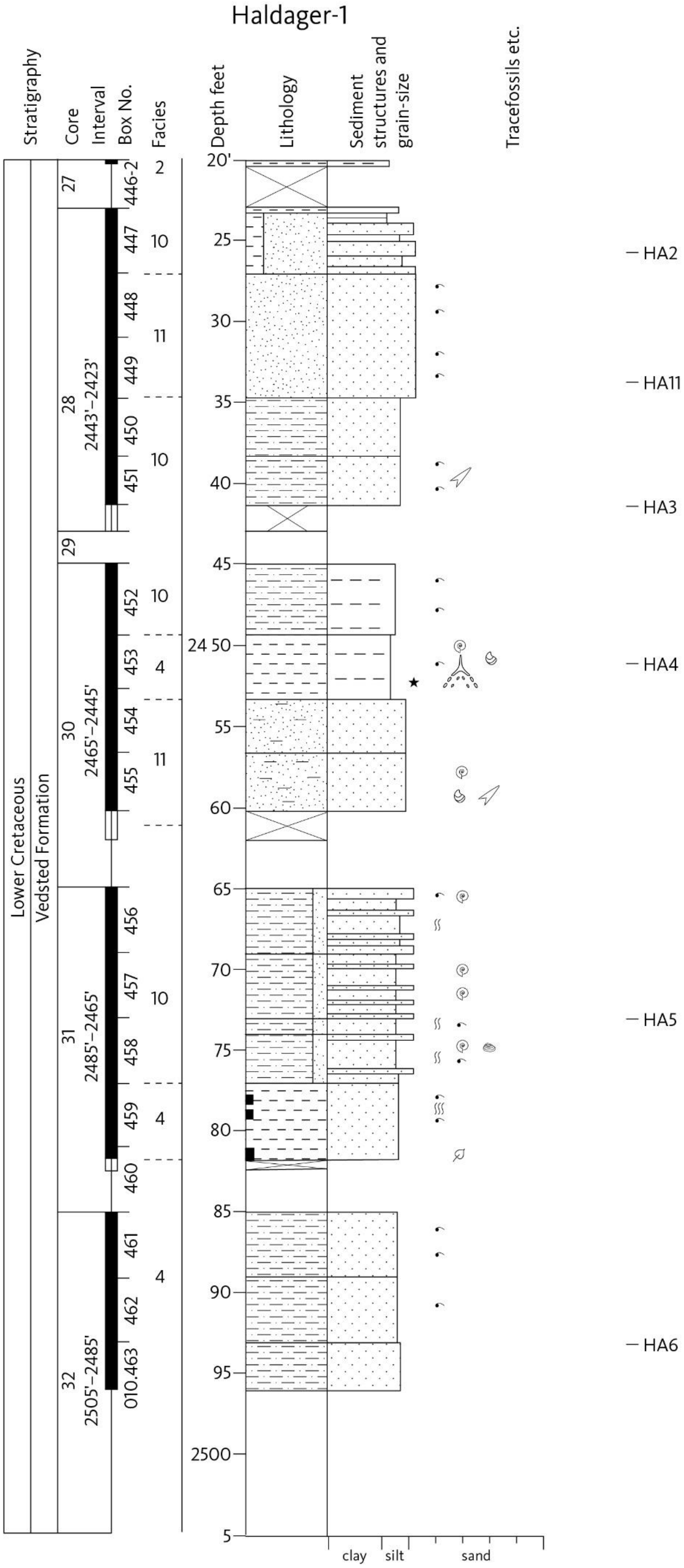
6. Haldager-1

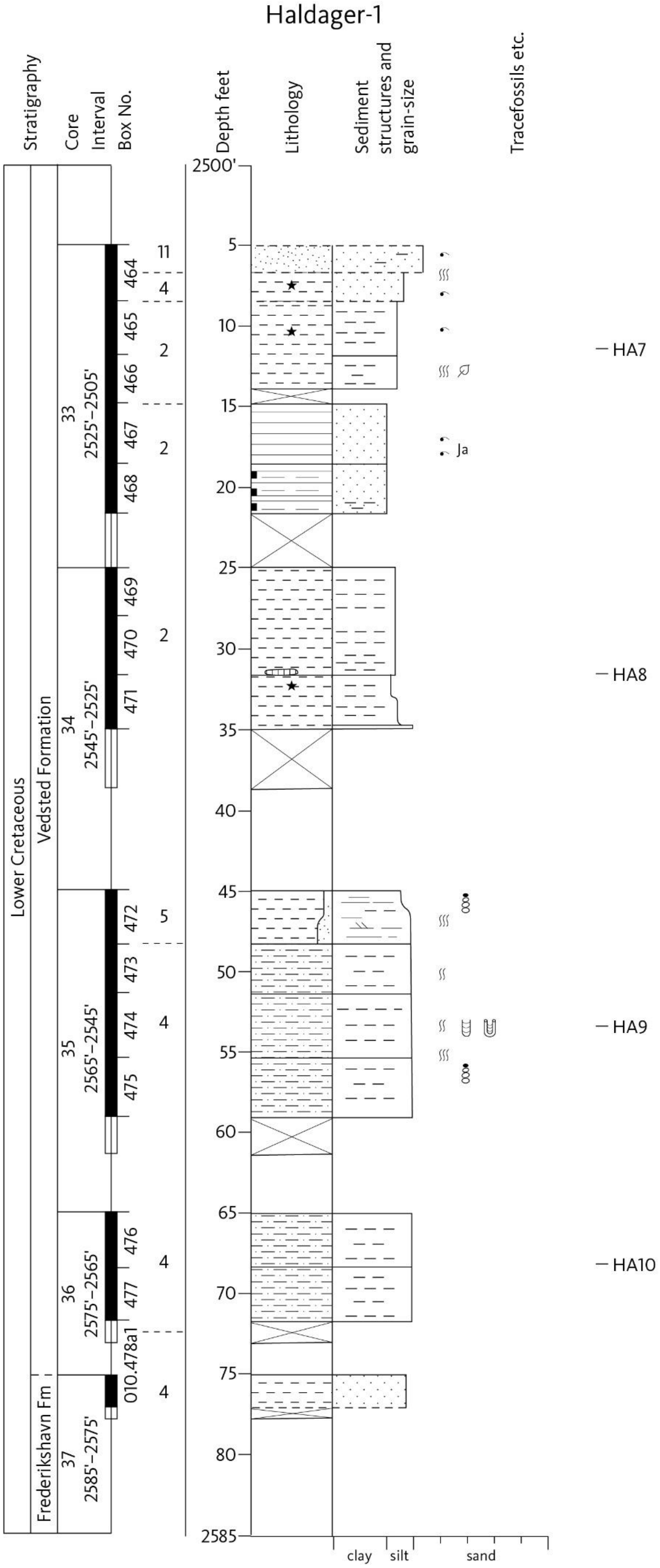


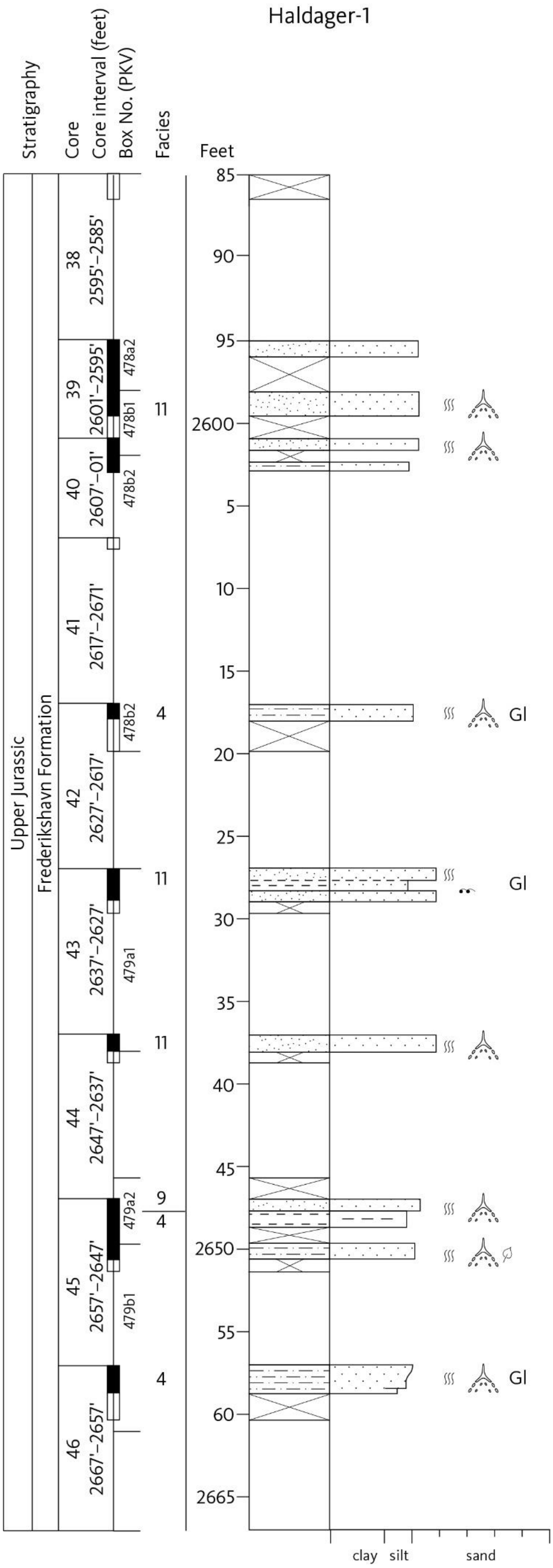
Haldager-1
Stratigraphy
Core
Interval
Box No.
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Samples
Mineralogy
Biostratigraphy
Dry drilling mud
Upper
Lower Cretaceous
Vedsted Formation
?
8
1393'–1373'
9
1615'–1600'
10
1830'–1815'
11
2015'–2000'
409
423
424
010.412
413
414
415
416
417
010.418
419
420
421
010.422
17
10
10
4
4
10
4
1373'
75
80
85
90
1393
1600
5
10
1615
1815
20
25
1830
2000
5
10
2015
G
Ja
clay
silt
sand
100
HA22 XRF/XRD
101
102
103
104
HA21 XRF/XRD
105
106
107
HA20 XRF/XRD
108
109
HA19 XRF/XRD
110
111
HA18 XRF/XRD
112

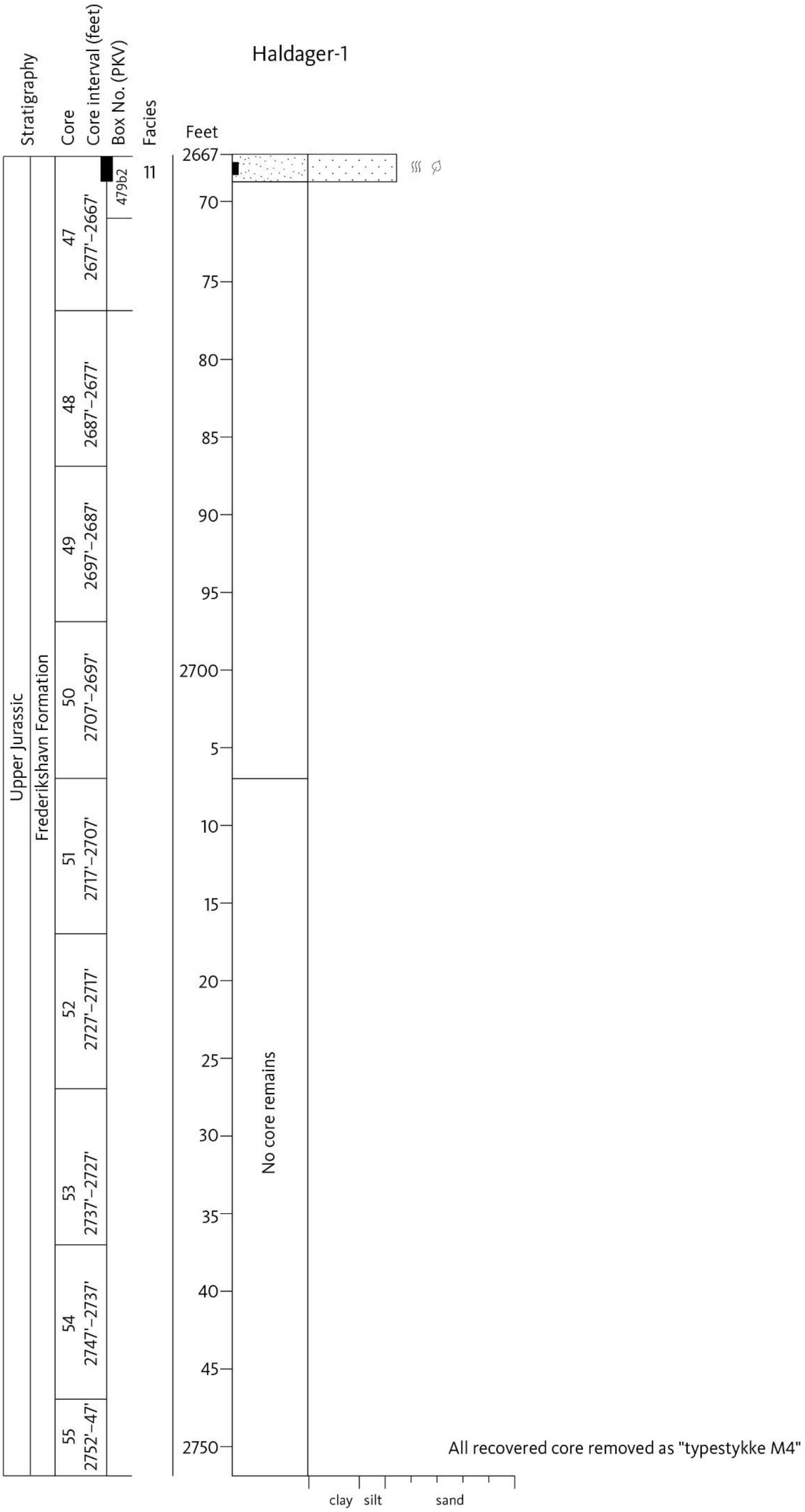

Haldager-1
Stratigraphy
Core
Interval
Box No.
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
12
2195'–2180'
423
424
010.425
17
21
13
2288'–2280'
010.426a-1
14
2297'–2288'
010.426b+a2
15
2302'–97'
427a
16
2307'–02'
427b
17
18
2311'–09'
428a–1
19
2324'–2314'
428a–2
20
2334'–2324'
010.428b-1
2180'
85
90
95
2200
2280
2300
5
10
15
20
25
30
35
G
clay
silt
sand
HA17 XRF/XRD
HA16 XRF/XRD
HA15 XRF/XRD

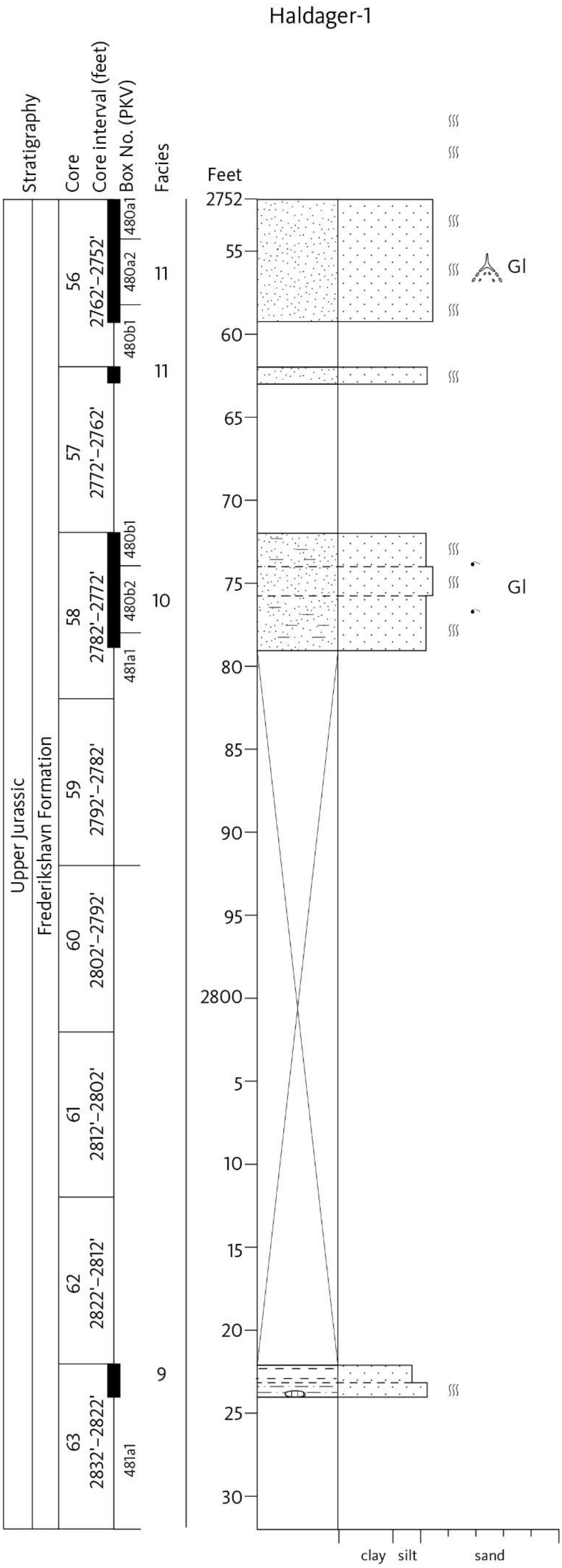

Haldager-1
Stratigraphy
Core
Interval
Box No.
Facies
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
21
39'–34'
22
2355'–2339'
23
2375'–2355'
24
2395'–2375'
25
2415'–2395'
26
2420'–15'
428b-2
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446-1
35'
40
45
2350
55
60
65
70
75
80
85
90
95
2400
5
10
15
20
clay
silt
sand
HA14
HA13
HA12
HA1

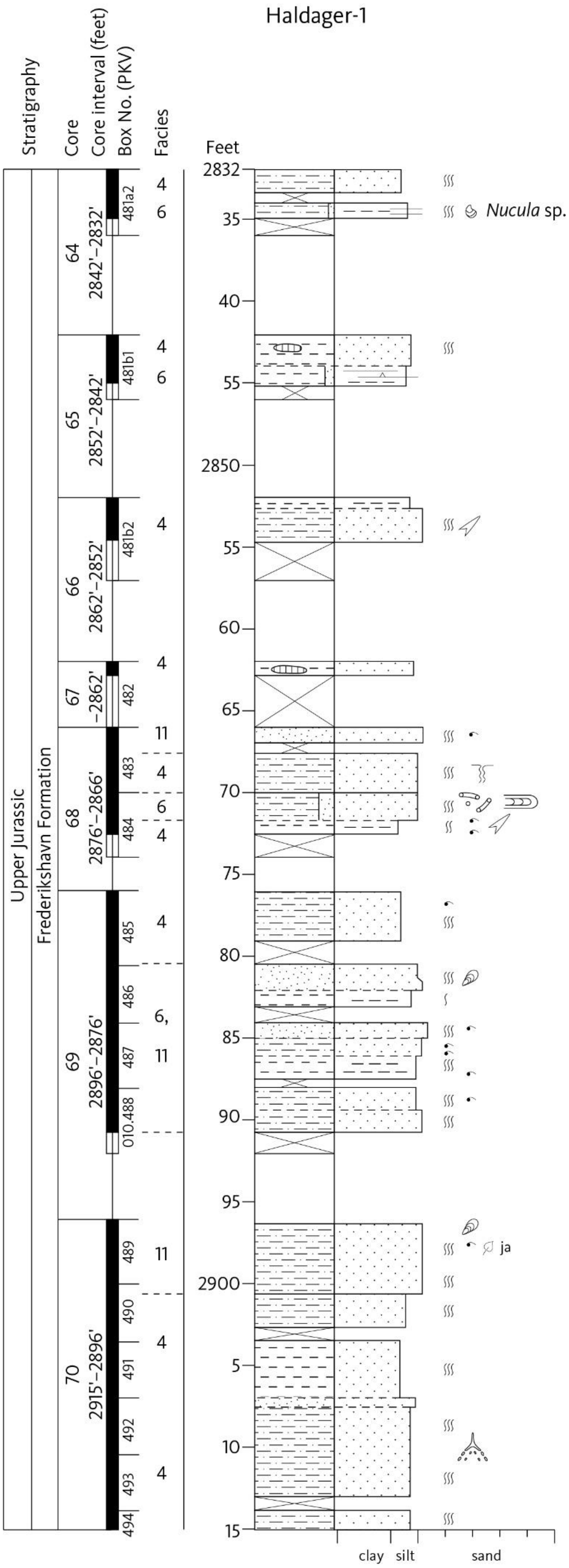

Haldager-1
Stratigraphy
Core
Interval
Box No.
Facies
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
27
28
2443'–2423'
29
30
2465'–2445'
31
2485'–2465'
32
2505'–2485'
446-2
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
010.463
2
10
11
10
10
4
11
10
4
4
20'
25
30
35
40
45
24 50
55
60
65
70
75
80
85
90
95
2500
5
clay
silt
sand
HA2
HA11
HA3
HA4
HA5
HA6


Haldager-1
Stratigraphy
Core
Interval
Box No.
Depth feet
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
Frederikshavn Fm
33
2525'–2505'
34
2545'–2525'
35
2565'–2545'
36
2575'–2565'
37
2585'–2575'
464
465
466
467
468
469
470
471
472
473
474
475
476
477
010.478a1
11
4
2
2
2
5
4
4
4
2500'
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
2585
Ja
clay
silt
sand
HA7
HA8
HA9
HA10

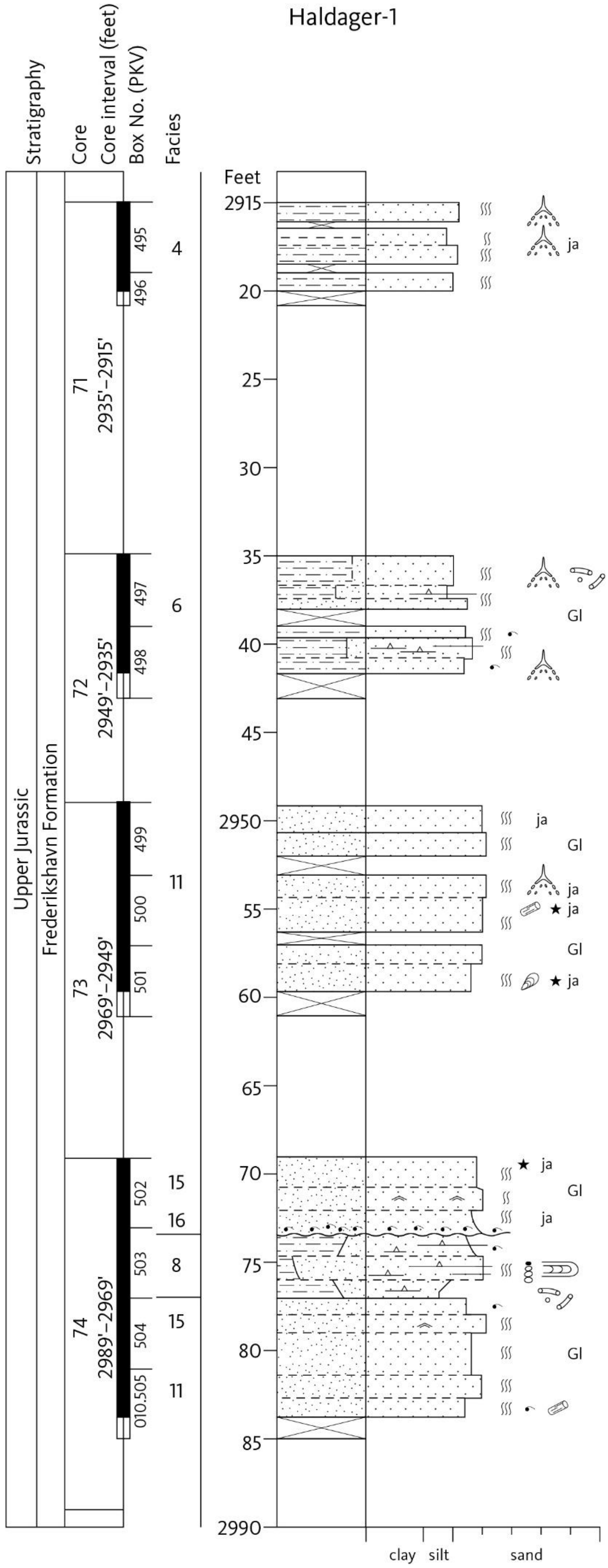

Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
38
2595'–2585'
39
2601'–2595'
40
2607'–01'
41
2617'–2671'
42
2627'–2617'
43
2637'–2627'
44
2647'–2637'
45
2657'–2647'
46
2667'–2657'
478a2
478b1
478b2
478b2
479a1
479a2
479b1
11
4
11
11
9
4
4
85
90
95
2600
5
10
15
20
25
30
35
40
45
2650
55
60
2665
Gl
Gl
Gl
Gl
clay
silt
sand

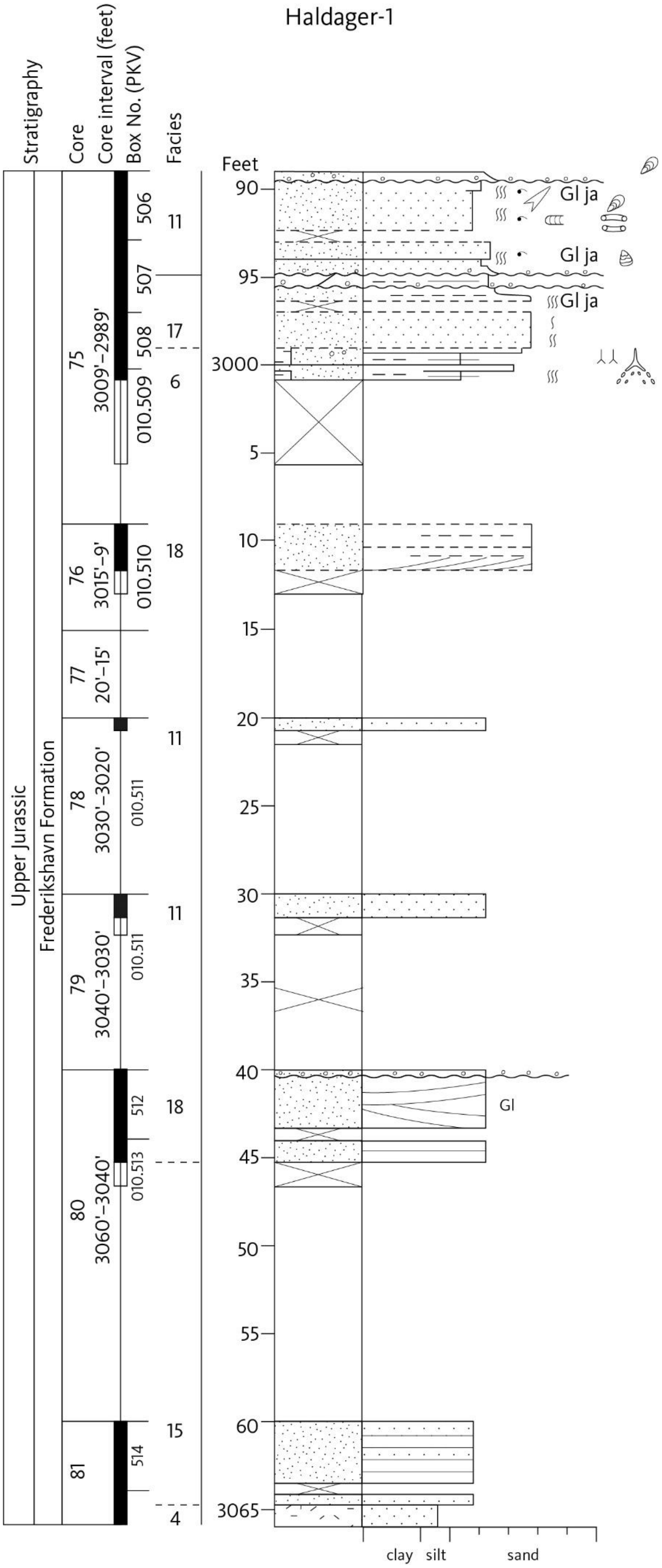

Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
47
2677'–2667'
48
2687'–2677'
49
2697'–2687'
50
2707'–2697'
51
2717'–2707'
52
2727'–2717'
53
2737'–2727'
54
2747'–2737'
55
2752'–47'
479b2
11
2667
70
75
80
85
90
95
2700
5
10
15
20
25
30
35
40
45
2750
No core remains
All recovered core removed as "typestykke M4"
clay
silt
sand


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
56
2762'–2752'
57
2772'–2762'
58
2782'–2772'
59
2792'–2782'
60
2802'–2792'
61
2812'–2802'
62
2822'–2812'
63
2832'–2822'
480a1
480a2
480b1
480b1
480b2
481a1
481a1
11
11
10
9
2752
55
60
65
70
75
80
85
90
95
2800
5
10
15
20
25
30
Gl
Gl
clay
silt
sand

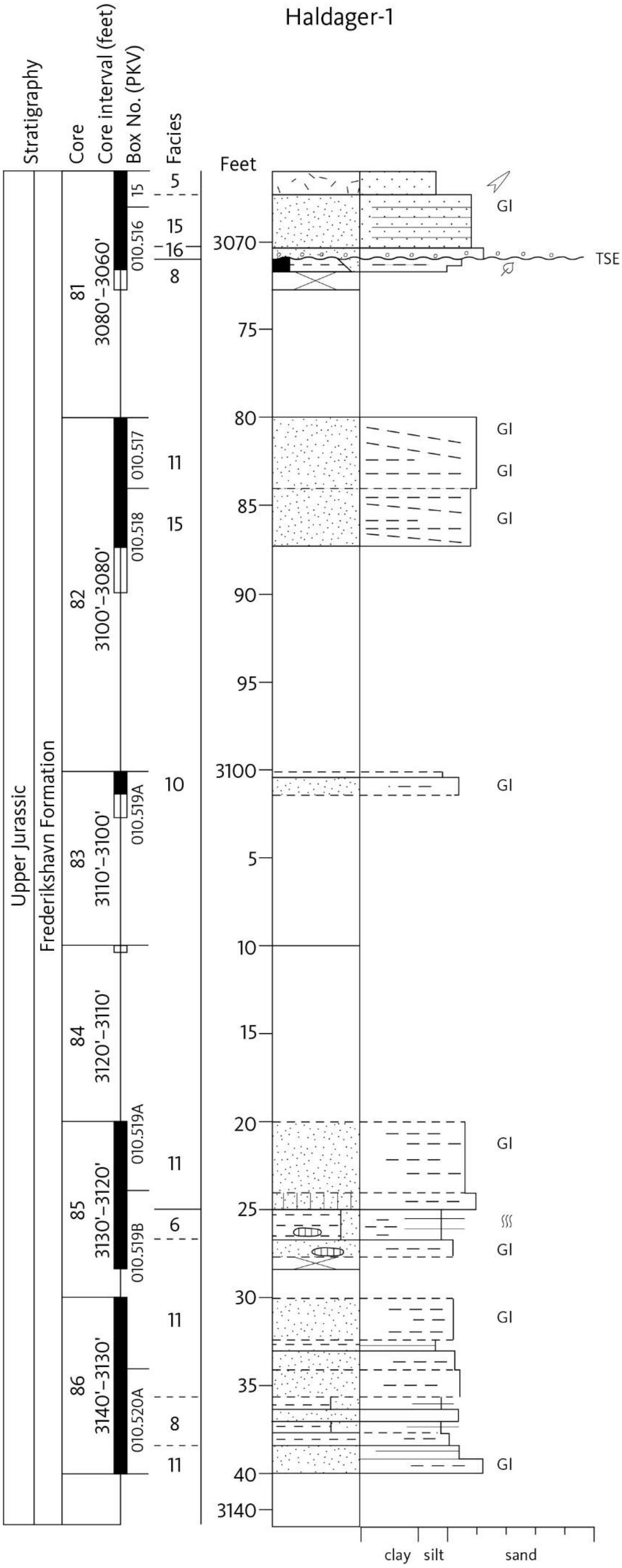


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
64
2842'–2832'
65
2852'–2842'
66
2862'–2852'
67
–2862'
68
2876'–2866'
69
2896'–2876'
70
2915'–2896'
481a2
481b1
481b2
482
483
484
485
486
487
010.488
489
490
491
492
493
494
2832
35
40
55
2850
55
60
65
70
75
80
85
90
95
2900
5
10
15
Nucula sp.
ja
clay
silt
sand

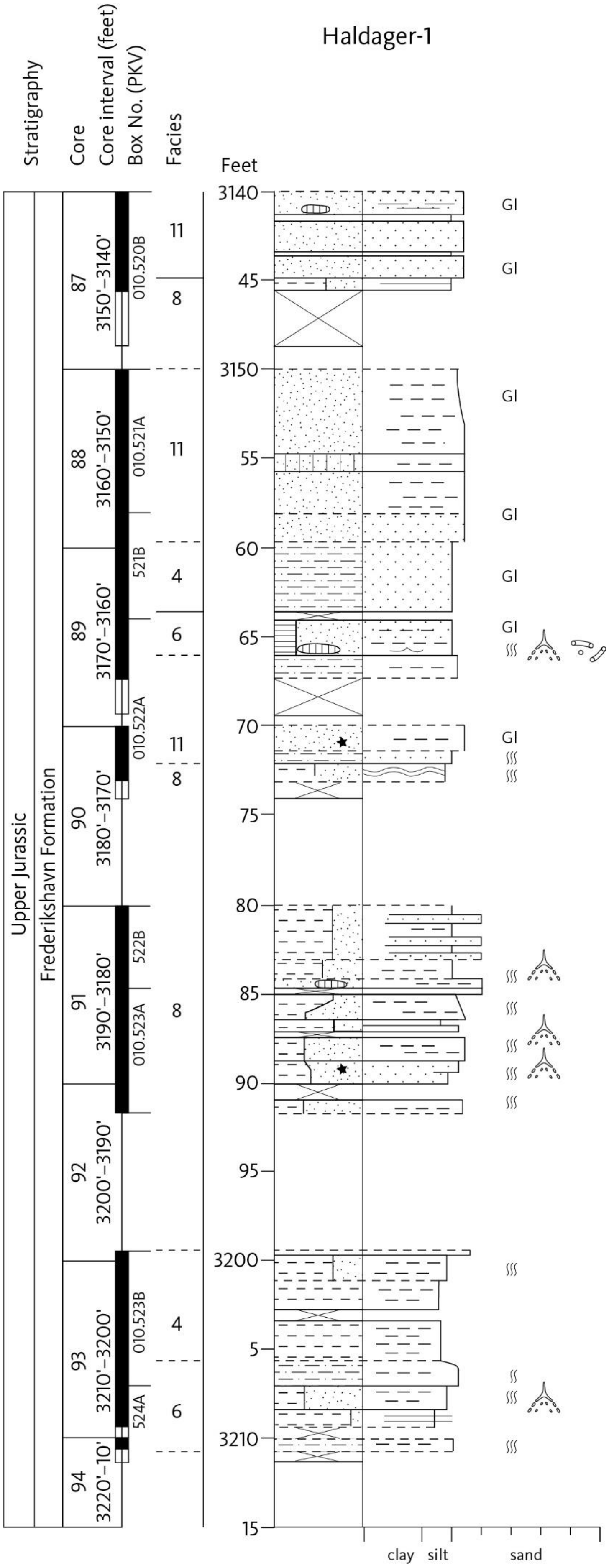

Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Upper Jurassic
Frederikshavn Formation
71
2935'–2915'
72
2949'–2935'
73
2969'–2949'
74
2989'–2969'
495
496
497
498
499
500
501
502
503
504
010.505
4
6
11
15
16
8
15
11
Feet
2915
20
25
30
35
40
45
2950
55
60
65
70
75
80
85
2990
ja
Gl
clay
silt
sand

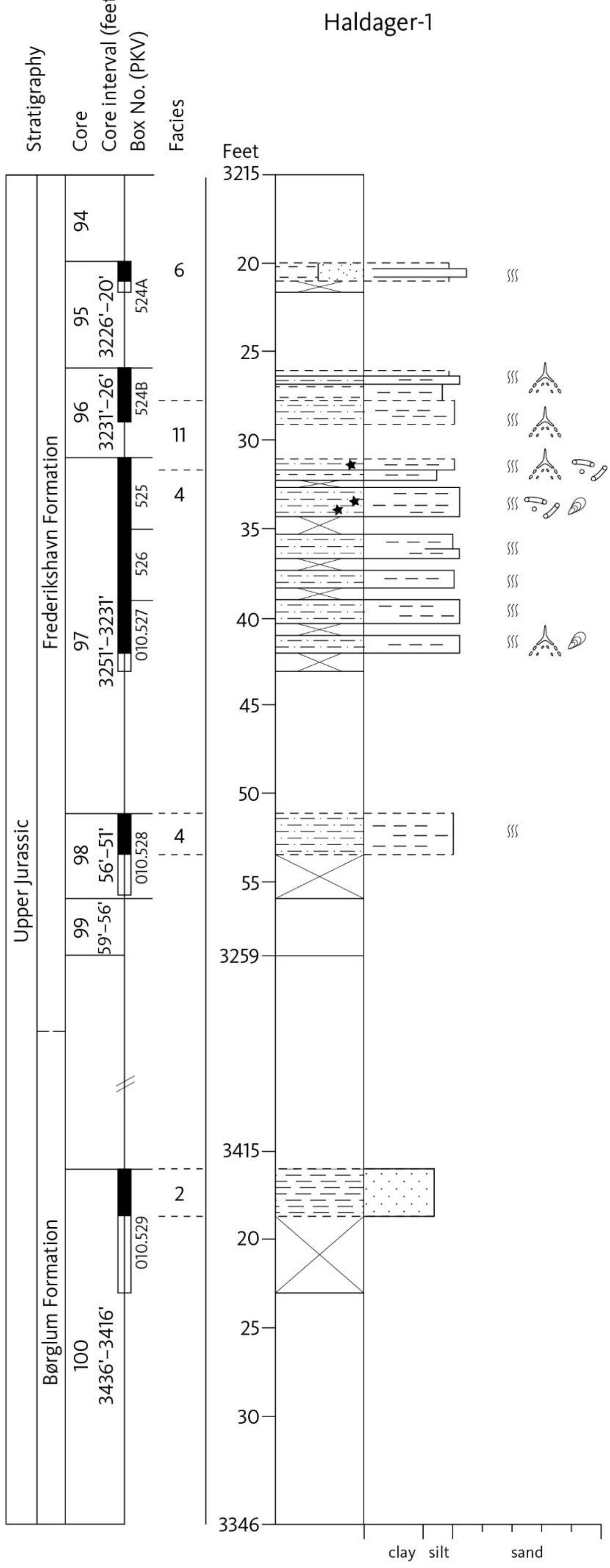


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
75
3009'–2989'
506
507
508
010.509
11
17
6
76
3015'–9'
010.510
18
77
20'–15'
78
3030'–3020'
010.511
11
79
3040'–3030'
010.511
11
80
3060'–3040'
512
010.513
18
81
514
15
4
90
95
3000
5
10
15
20
25
30
35
40
45
50
55
60
3065
Gl ja
Gl ja
Gl ja
Gl
clay
silt
sand

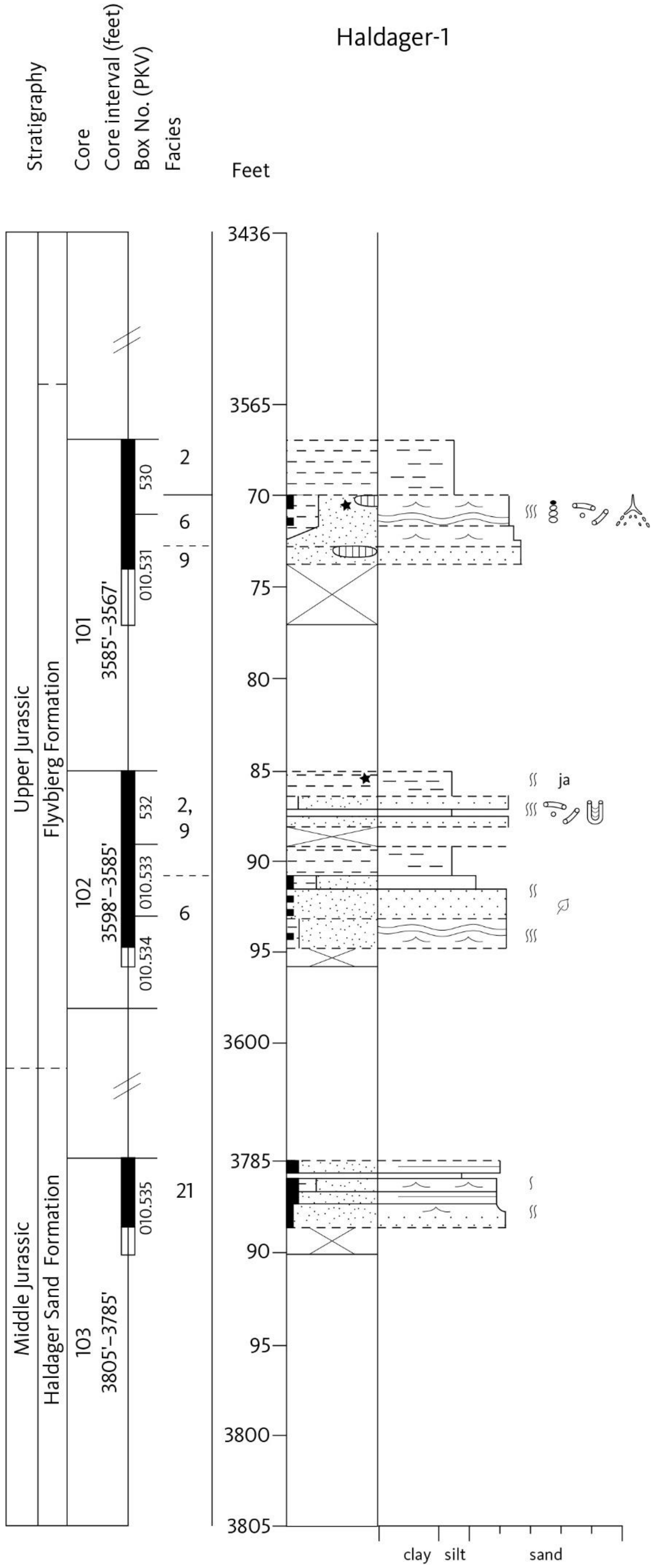


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
81
3080'–3060'
82
3100'–3080'
83
3110'–3100'
84
3120'–3110'
85
3130'–3120'
86
3140'–3130'
010.516
15
010.517
010.518
010.519A
010.519B
010.520A
5
15
16
8
11
15
10
11
6
11
8
11
3070
75
80
85
90
95
3100
5
10
15
20
25
30
35
40
3140
TSE
Gl
clay
silt
sand

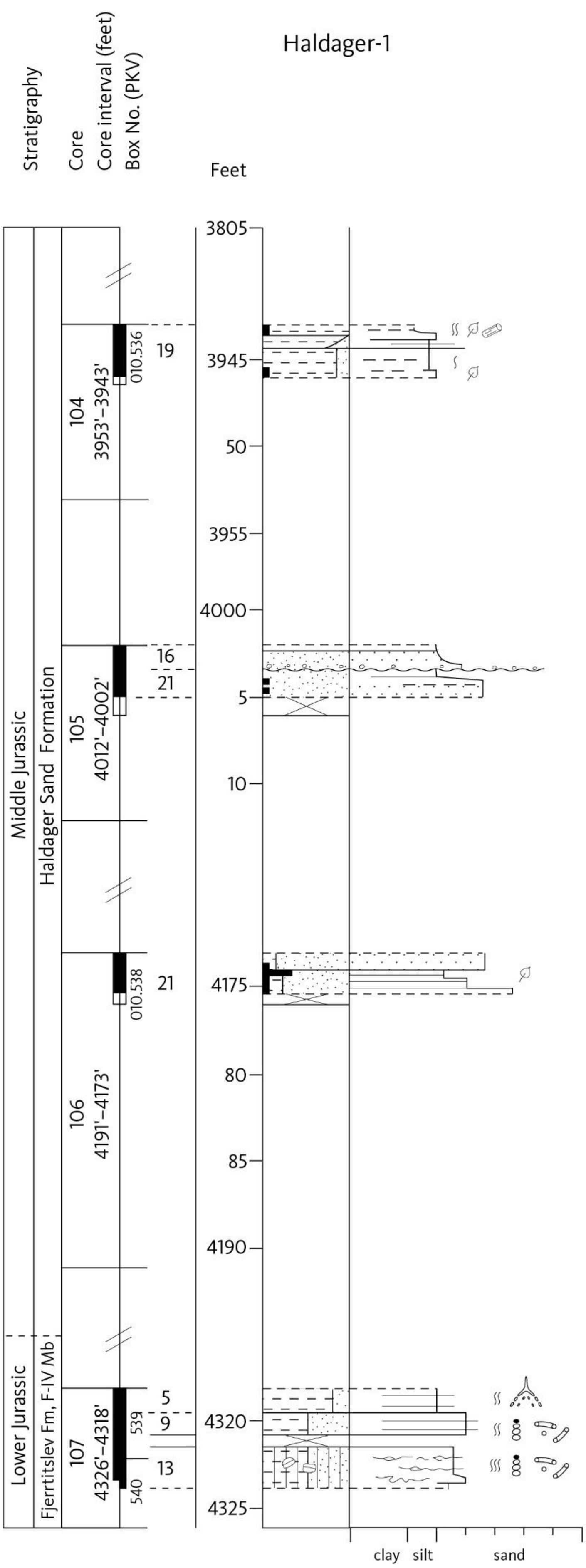

Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
87
3150'–3140'
010.520B
88
3160'–3150'
010.521A
521B
89
3170'–3160'
010.522A
90
3180'–3170'
91
3190'–3180'
522B
010.523A
92
3200'–3190'
93
3210'–3200'
010.523B
524A
94
3220'–10'
11
8
11
4
6
11
8
8
4
6
3140
45
3150
55
60
65
70
75
80
85
90
95
3200
5
3210
15
Gl
Gl
Gl
Gl
Gl
Gl
Gl
Gl
clay
silt
sand

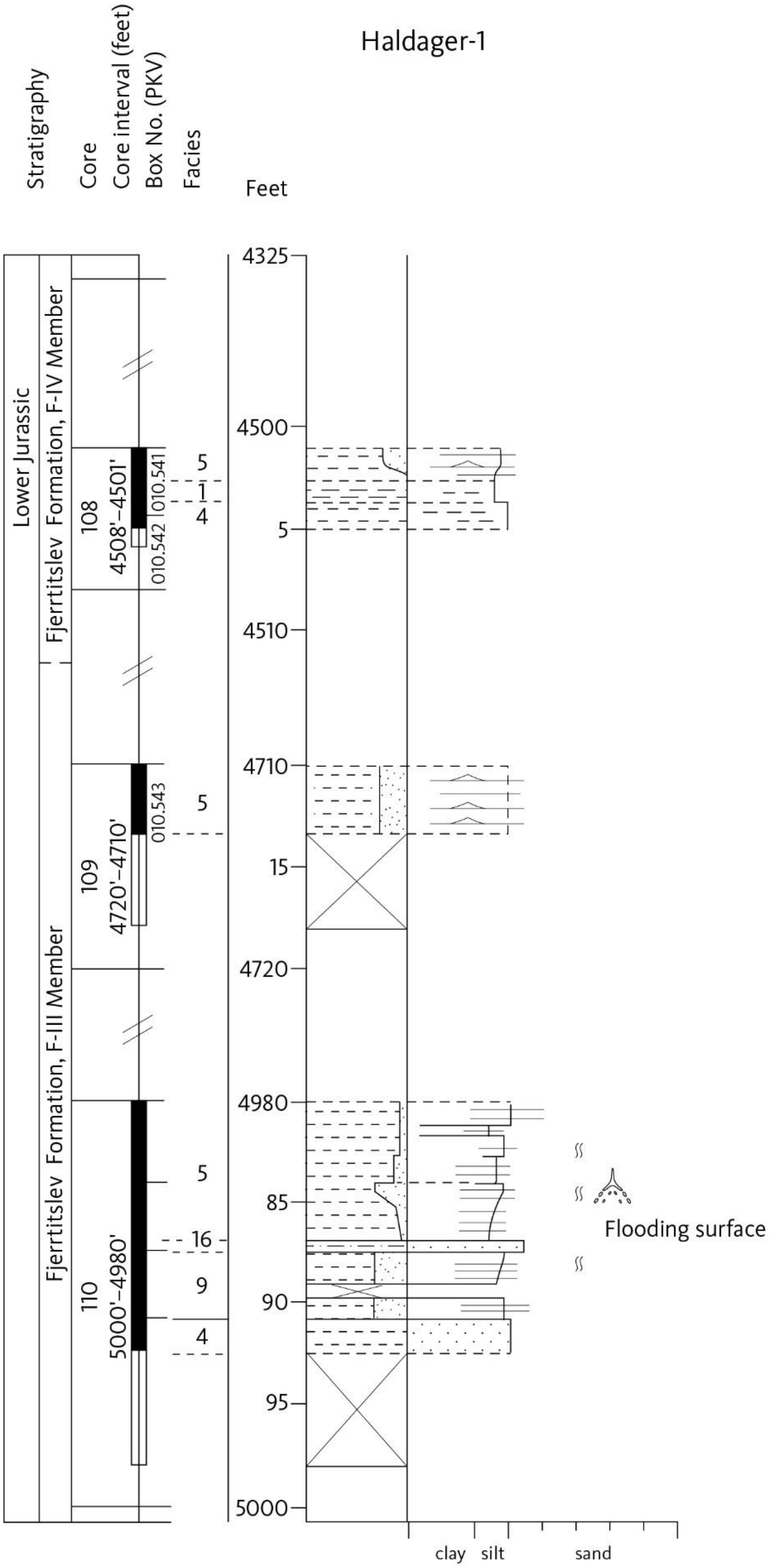


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Frederikshavn Formation
Børglum Formation
94
95
3226'–20'
96
3231'–26'
97
3251'–3231'
98
56'–51'
99
59'–56'
100
3436'–3416'
524A
524B
525
526
010.527
010.528
010.529
6
11
4
4
2
3215
20
25
30
35
40
45
50
55
3259
3415
20
25
30
3346
clay
silt
sand



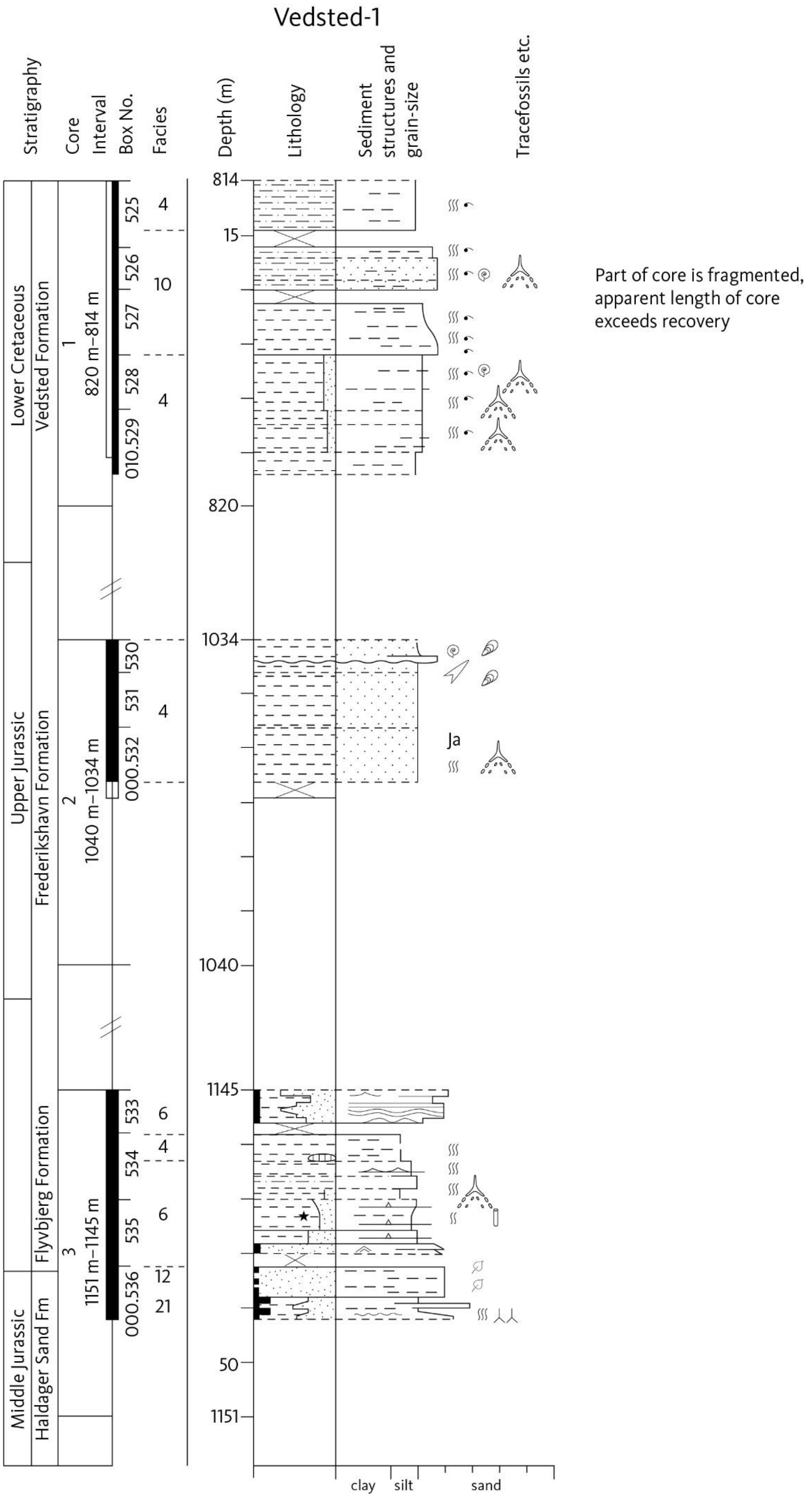
Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Jurassic
Flyvbjerg Formation
Middle Jurassic
Haldager Sand Formation
101
3585'–3567'
102
3598'–3585'
103
3805'–3785'
530
010.531
532
010.533
010.534
010.535
2
6
9
2,
9
6
21
3436
3565
70
75
80
85
90
95
3600
3785
90
95
3800
3805
ja
clay
silt
sand


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Feet
Middle Jurassic
Haldager Sand Formation
Lower Jurassic
Fjerritslev Fm, F-IV Mb
104
3953'–3943'
105
4012'–4002'
106
4191'–4173'
107
4326'–4318'
010.536
010.538
539
540
19
16
21
21
5
9
13
3805
3945
50
3955
4000
5
10
4175
80
85
4190
4320
4325
clay
silt
sand

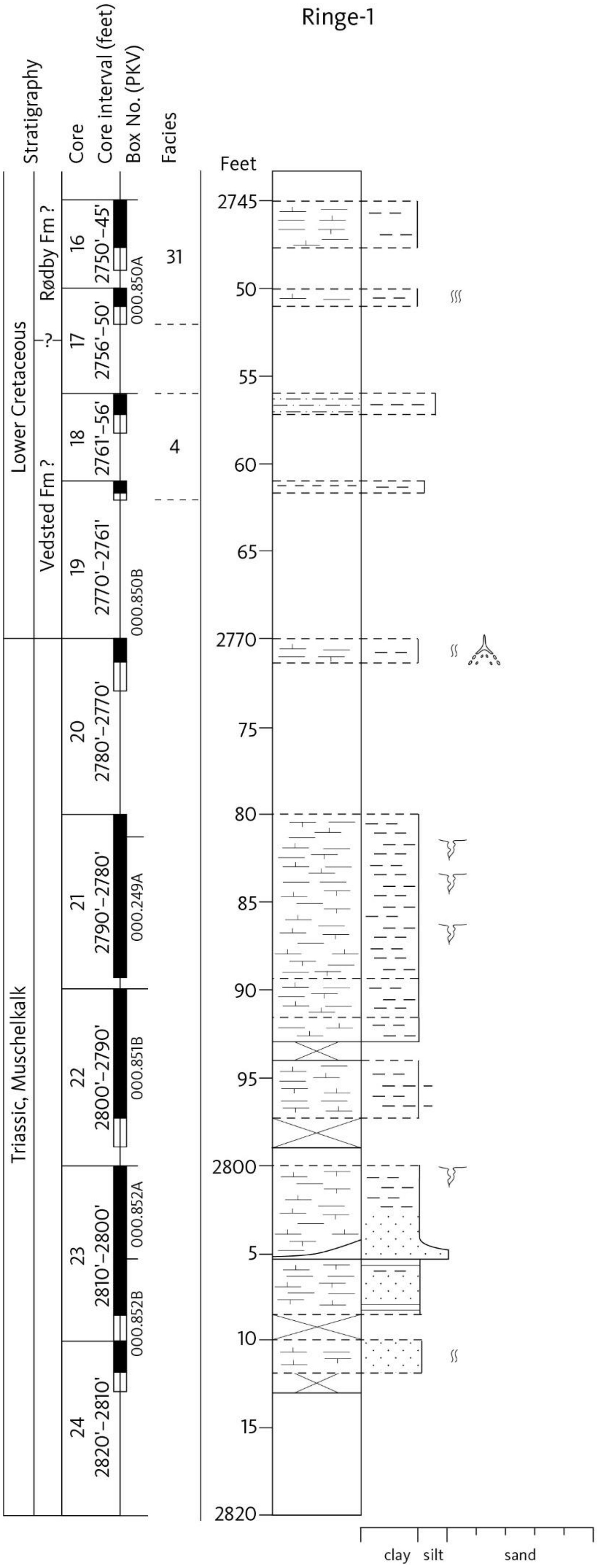


Haldager-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Lower Jurassic
Fjerritslev Formation, F-IV Member
Fjerritslev Formation, F-III Member
108
4508'–4501'
010.541
010.542
109
4720'–4710'
010.543
110
5000'–4980'
5
1
4
5
5
16
9
4
4325
4500
5
4510
4710
15
4720
4980
85
90
95
5000
Flooding surface
clay
silt
sand

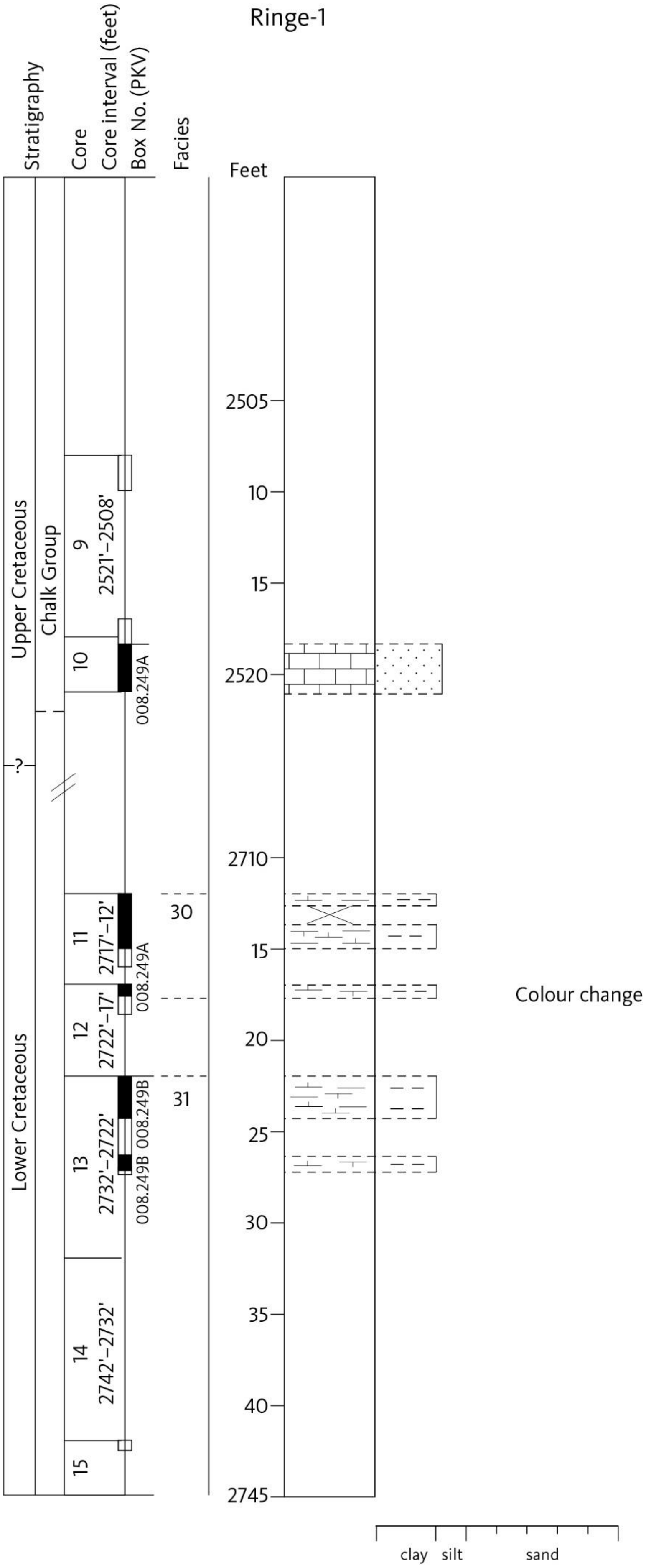
7. Vedsted-1


Vedsted-1
Stratigraphy
Core
Interval
Box No.
Facies
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Vedsted Formation
Upper Jurassic
Frederikshavn Formation
Middle Jurassic
Haldager Sand Fm
Flyvbjerg Formation
1
820 m–814 m
2
1040 m–1034 m
3
1151 m–1145 m
525
526
527
528
010.529
530
531
000.532
533
534
535
000.536
814
15
820
1034
1040
1145
50
1151
Ja
clay
silt
sand
Part of core is fragmented, apparent length of core exceeds recovery

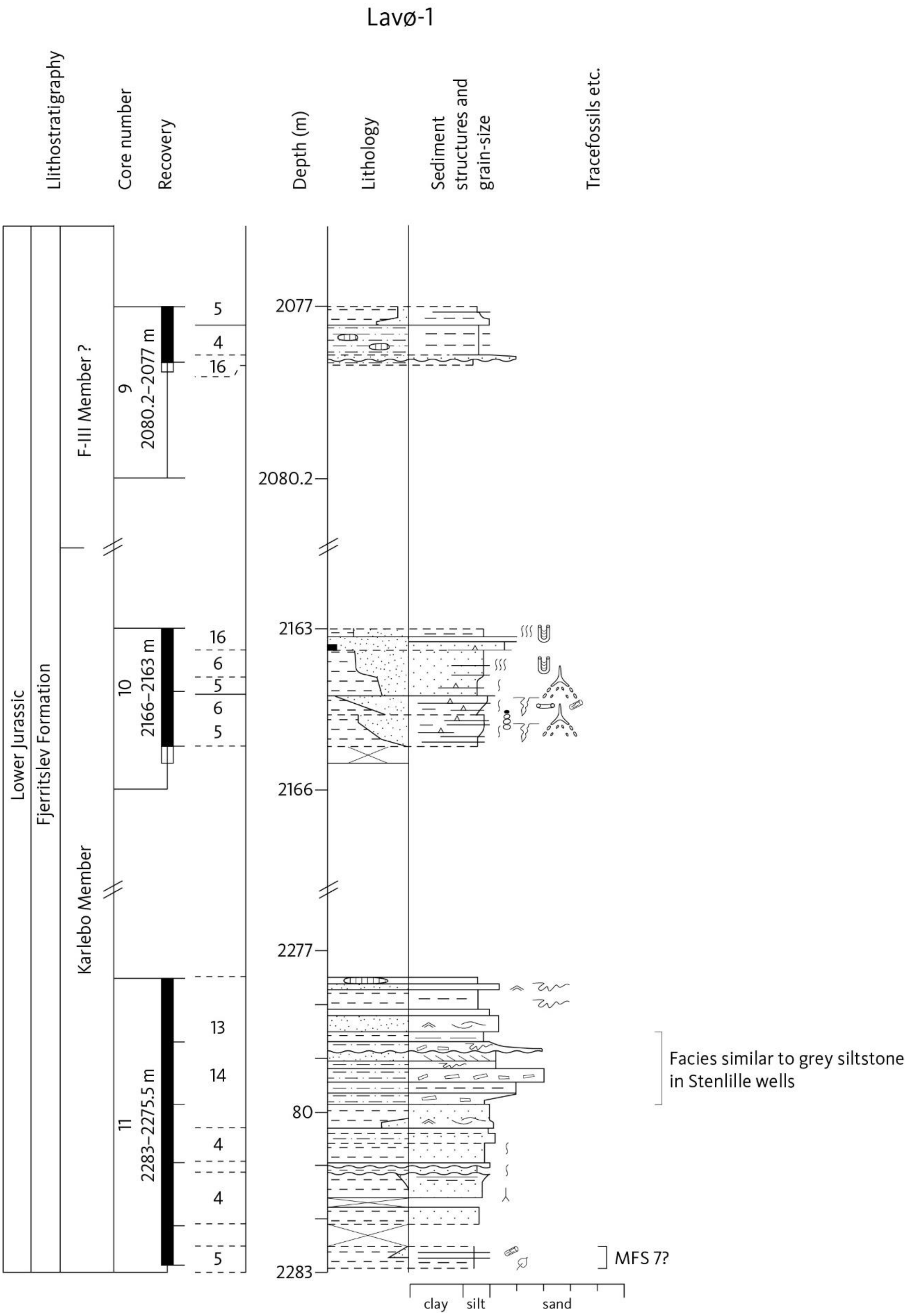
8. Ringe-1



Ringe-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Lower Cretaceous
Rødby Fm ?
Vedsted Fm ?
Triassic, Muschelkalk
16
2750'–45'
17
2756'–50'
18
2761'–56'
19
2770'–2761'
20
2780'–2770'
21
2790'–2780'
22
2800'–2790'
23
2810'–2800'
24
2820'–2810'
000.850A
000.850B
000.249A
000.851B
000.852A
000.852B
31
4
2745
50
55
60
65
2770
75
80
85
90
95
2800
5
10
15
2820
clay
silt
sand

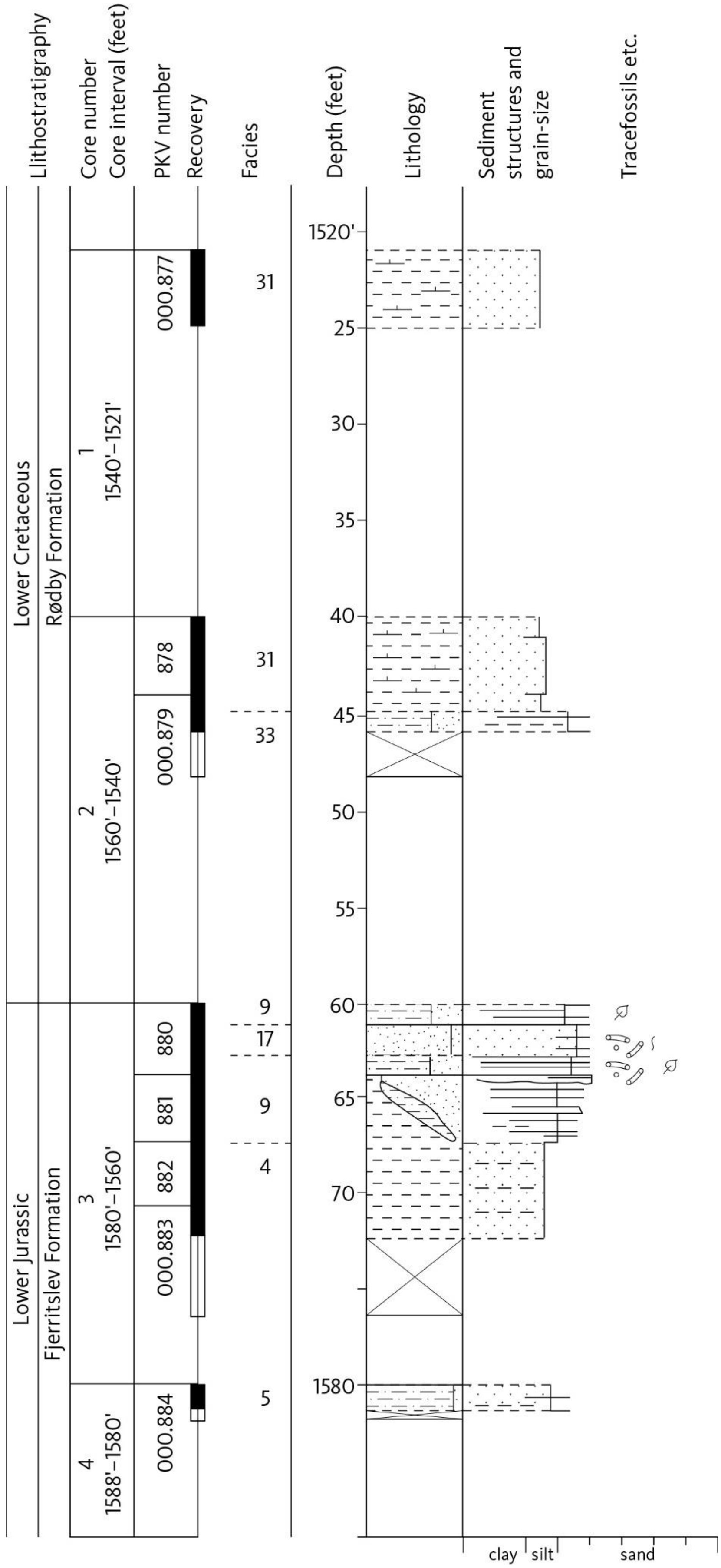

Ringe-1
Stratigraphy
Core
Core interval (feet)
Box No. (PKV)
Facies
Feet
Upper Cretaceous
Chalk Group
Lower Cretaceous
9
2521'–2508'
10
008.249A
11
2717'–12'
008.249A
12
2722'–17'
13
2732'–2722'
008.249B
008.249B
14
2742'–2732'
15
30
31
2505
10
15
2520
2710
15
20
25
30
35
40
2745
Colour change
clay
silt
sand

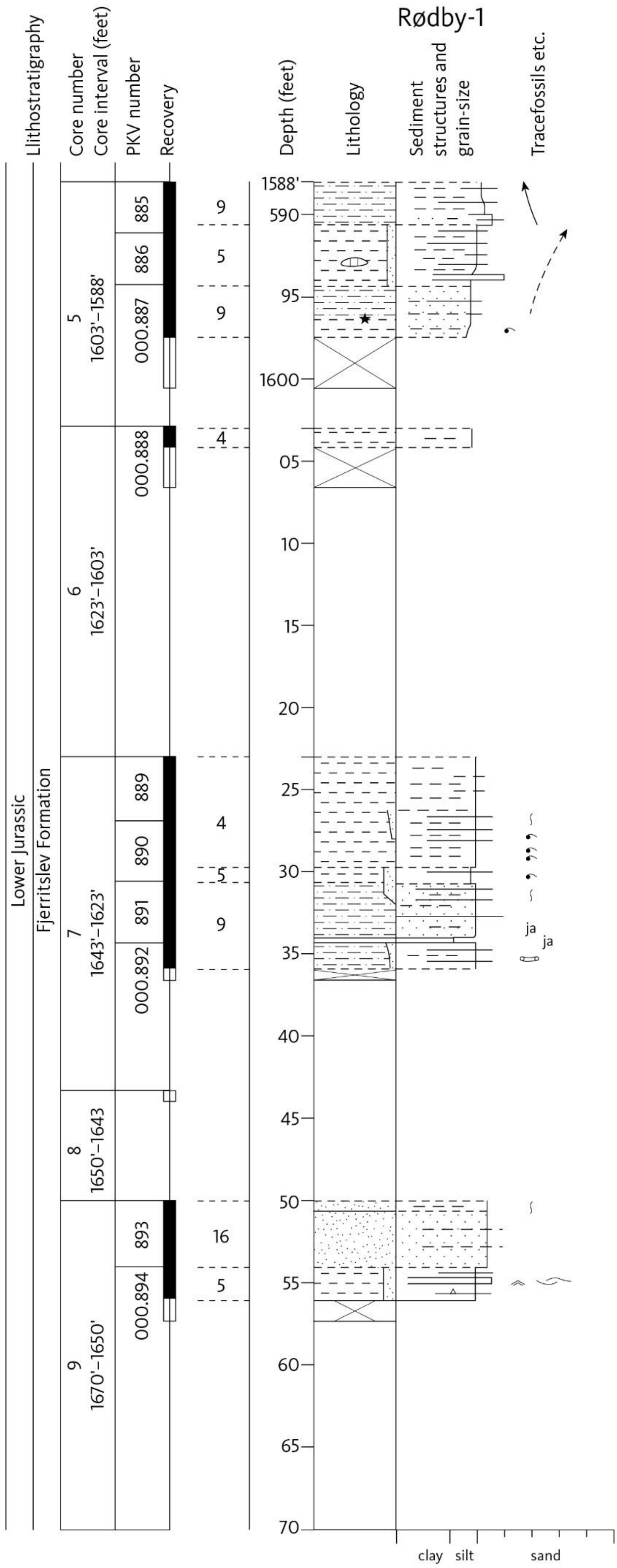
9. Lavø-1

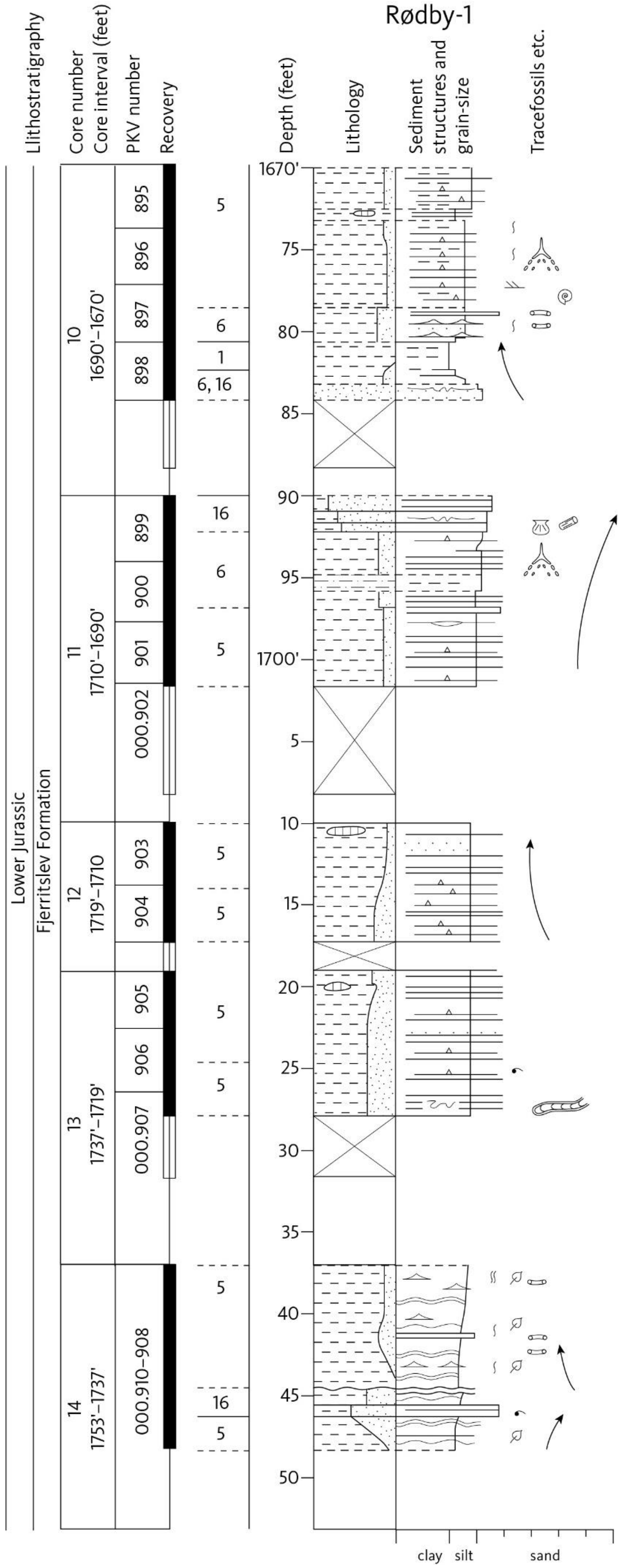

Lavø-1
Lithostratigraphy
Core number
Recovery
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-III Member ?
Karlebo Member
9
2080.2–2077 m
10
2166–2163 m
11
2283–2275.5 m
2077
2080.2
2163
2166
2277
80
2283
Facies similar to grey siltstone in Stenlille wells
MFS 7?
clay
silt
sand

10. Rødby-1

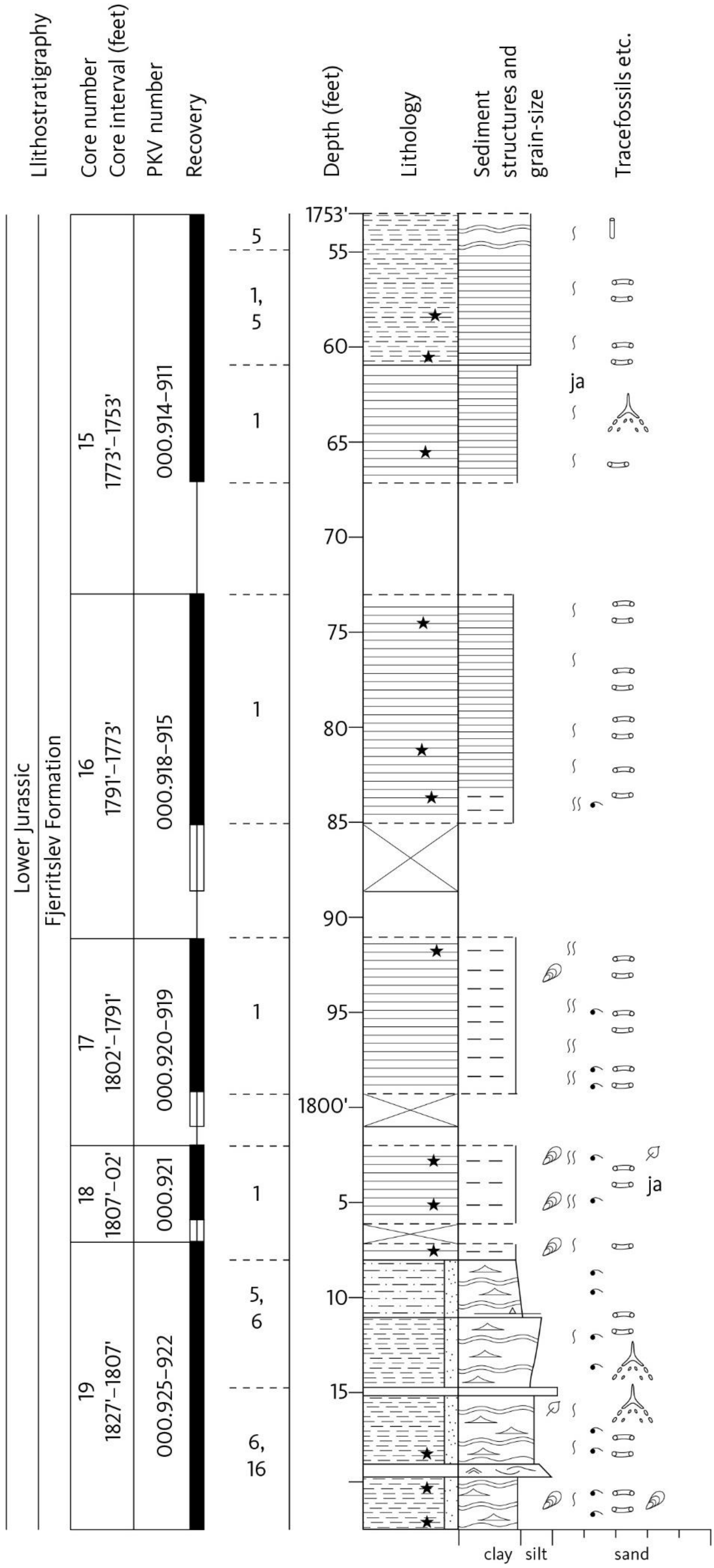
Rødby-1


Llithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Cretaceous
Rødby Formation
Lower Jurassic
Fjerritslev Formation
1
1540'–1521'
2
1560'–1540'
3
1580'–1560'
4
1588'–1580'
000.877
878
000.879
880
881
882
000.883
000.884
31
31
33
9
17
9
4
5
1520'
25
30
35
40
45
50
55
60
65
70
1580
clay
silt
sand

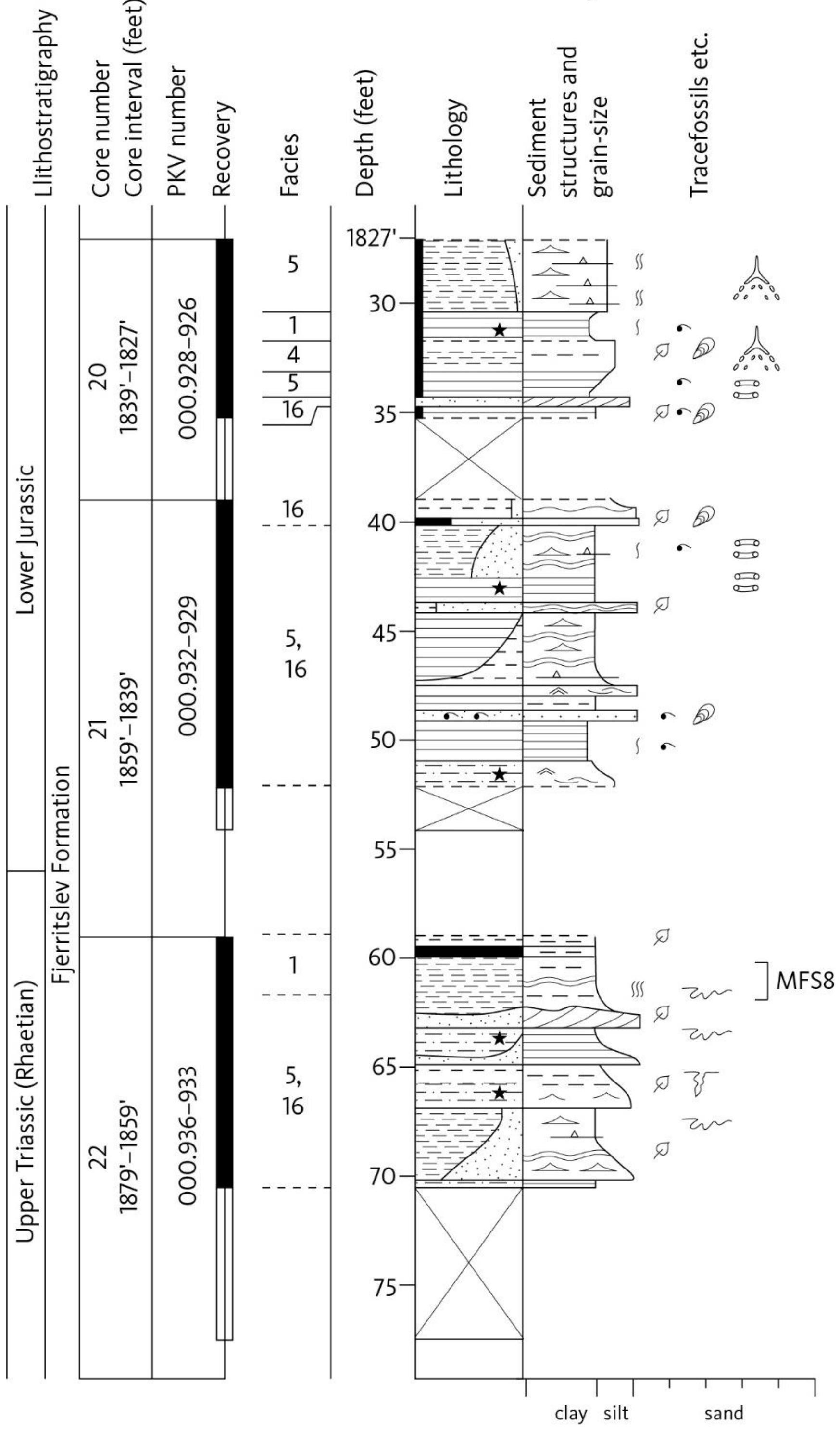

Rødby-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
5
1603'–1588'
6
1623'–1603'
7
1643'–1623'
8
1650'–1643
9
1670'–1650'
885
886
000.887
000.888
889
890
891
000.892
893
000.894
1588'
590
95
1600
05
10
15
20
25
30
35
40
45
50
55
60
65
70
ja
clay
silt
sand

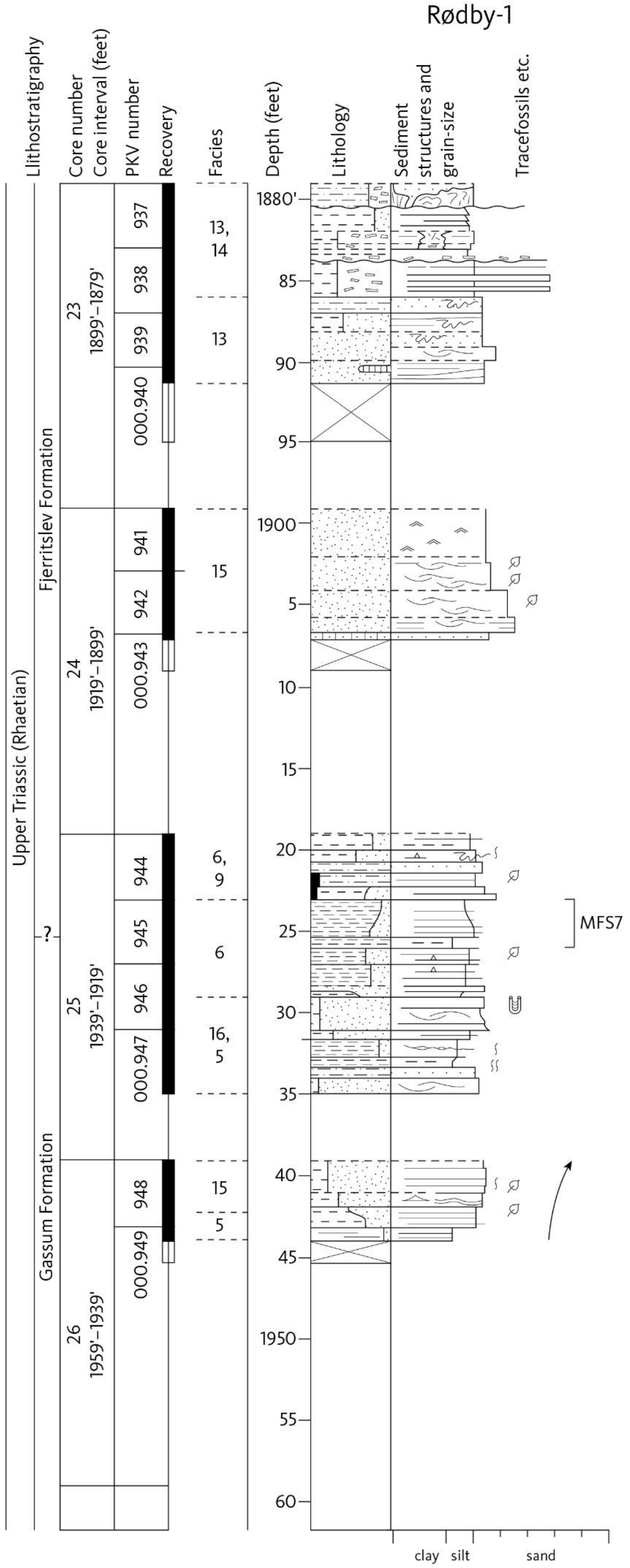

Rødby-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
10
1690'–1670'
11
1710'–1690'
12
1719'–1710
13
1737'–1719'
14
1753'–1737'
895
896
897
898
899
900
901
000.902
903
904
905
906
000.907
000.910–908
5
6
1
6, 16
16
1670'
75
80
85
90
95
1700'
5
10
15
20
25
30
35
40
45
50
clay
silt
sand

Rødby-1

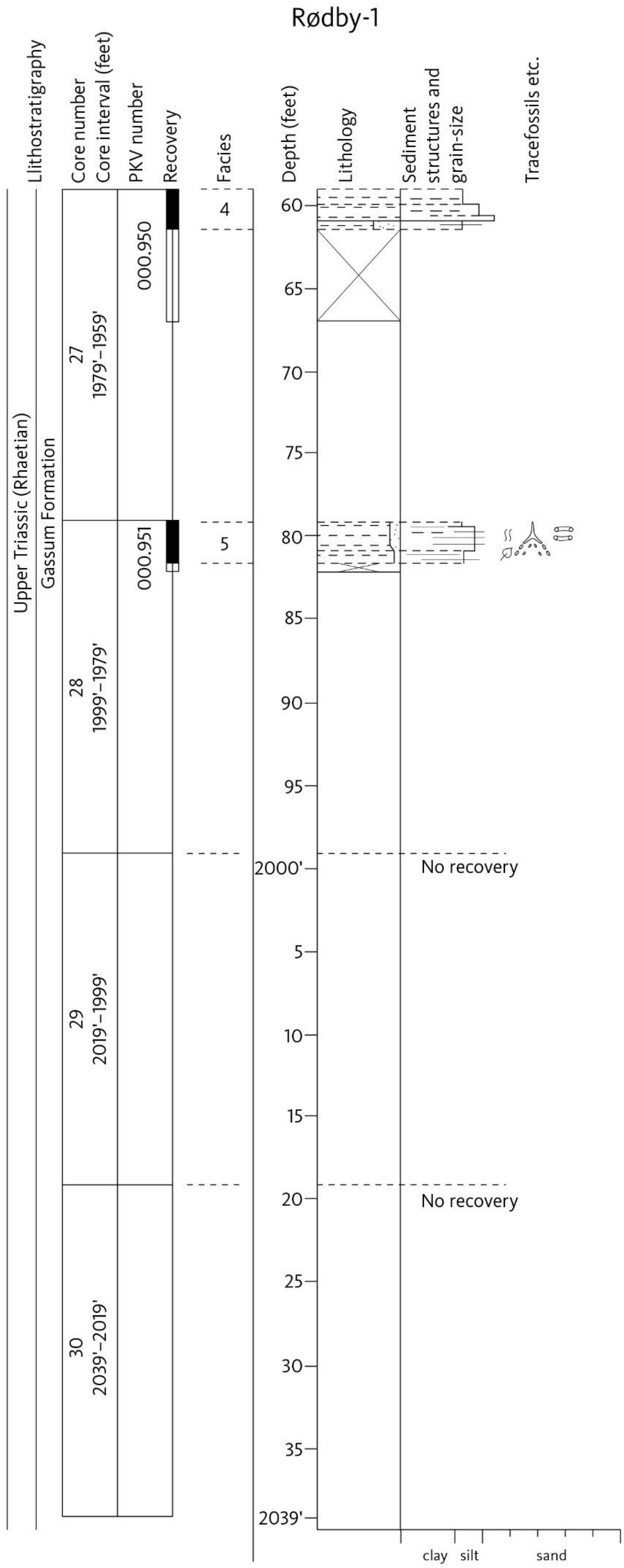

Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
15
1773'–1753'
000.914–911
16
1791'–1773'
000.918–915
17
1802'–1791'
000.920–919
18
1807'–02'
000.921
19
1827'–1807'
000.925–922
5
1, 5
1
1
1
1
5, 6
6, 16
1753'
55
60
65
70
75
80
85
90
95
1800'
5
10
15
ja
ja
clay
silt
sand

Rødby-1


Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Upper Triassic (Rhaetian)
Fjerritslev Formation
20
1839'–1827'
000.928–926
21
1859'–1839'
000.932–929
22
1879'–1859'
000.936–933
5
1
4
5
16
16
5, 16
1
5, 16
1827'
30
35
40
45
50
55
60
65
70
75
MFS8
clay
silt
sand

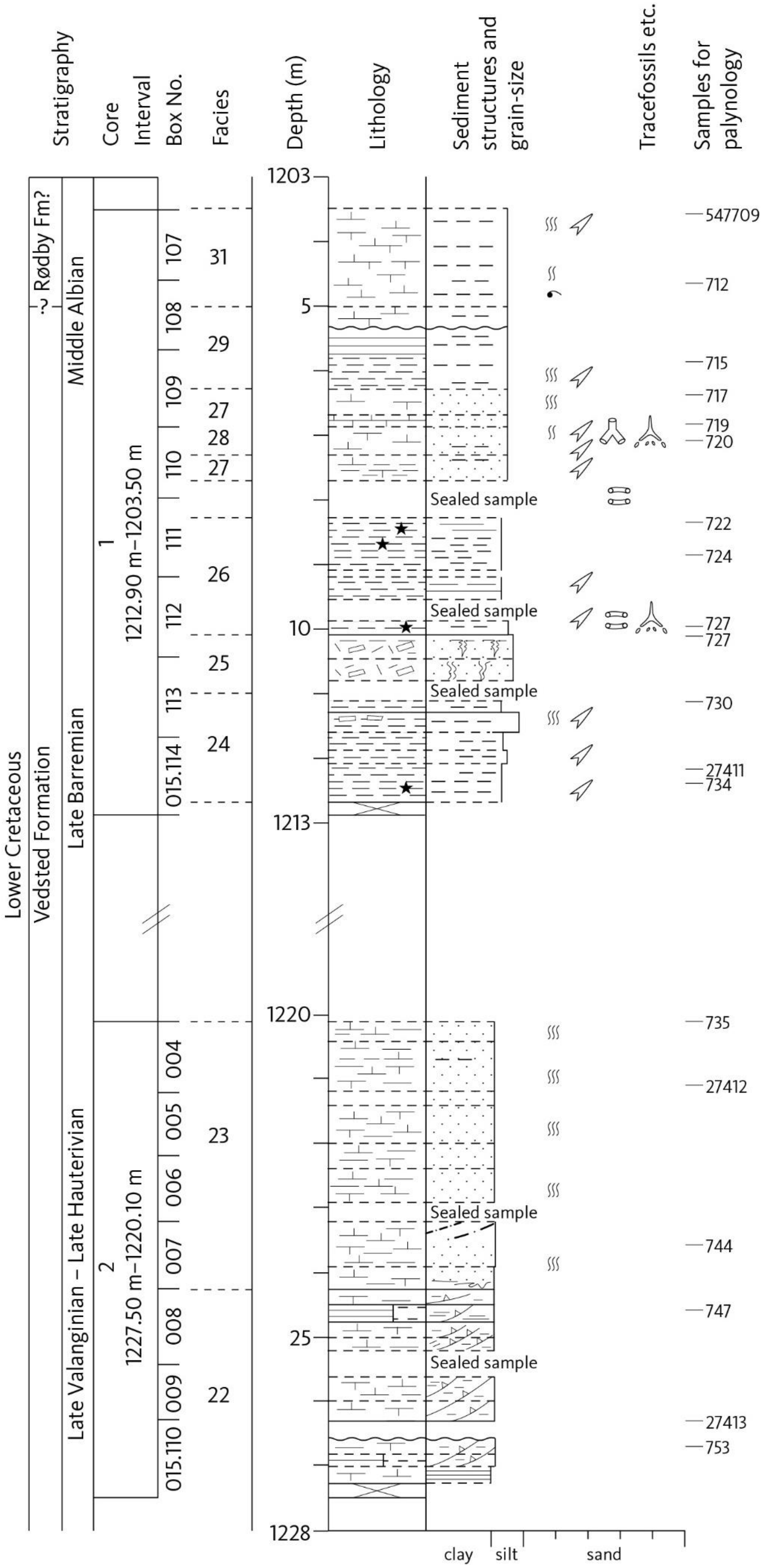


Rødby-1
Llithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Triassic (Rhaetian)
Fjerritslev Formation
Gassum Formation
?
23
1899'–1879'
24
1919'–1899'
25
1939'–1919'
26
1959'–1939'
937
938
939
000.940
941
942
000.943
944
945
946
000.947
948
000.949
13, 14
13
15
6, 9
6
16, 5
15
5
1880'
85
90
95
1900
5
10
15
20
25
30
35
40
45
1950
55
60
MFS7
clay
silt
sand

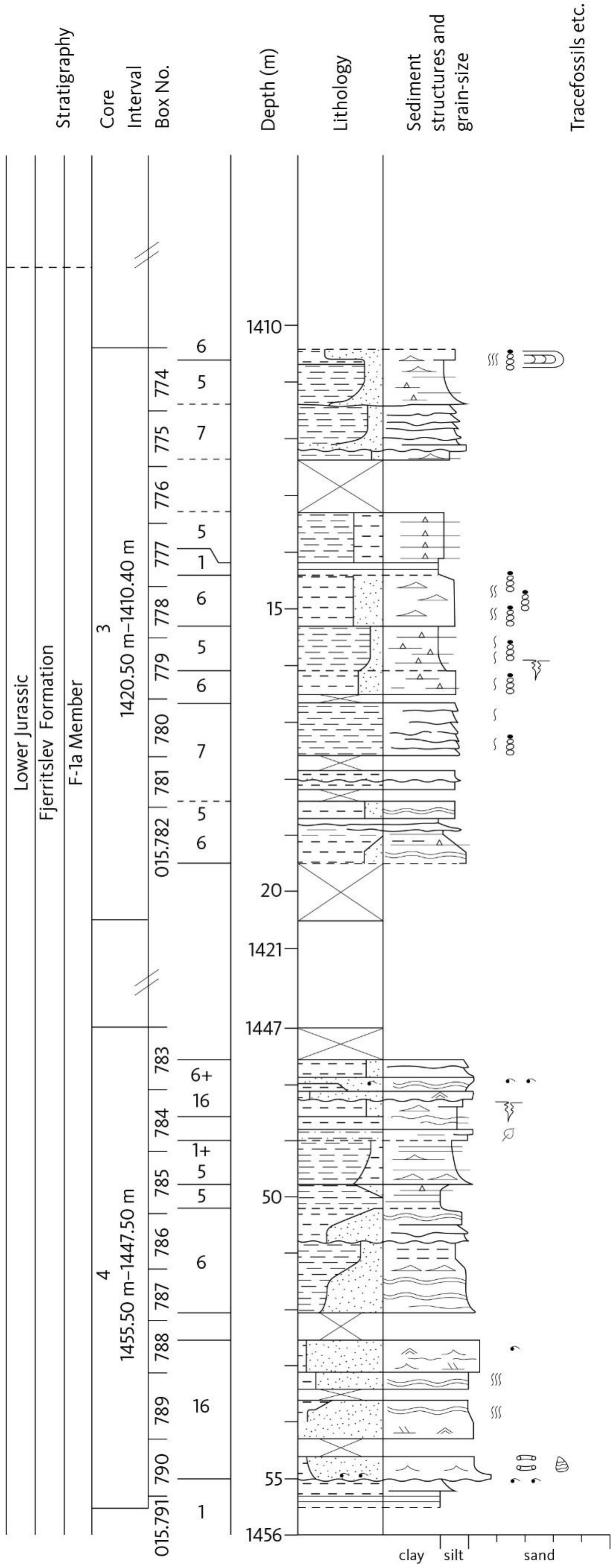

Rødby-1
Lithostratigraphy
Core number
Core interval (feet)
PKV number
Recovery
Facies
Depth (feet)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Triassic (Rhaetian)
Gassum Formation
27
1979'–1959'
28
1999'–1979'
29
2019'–1999'
30
2039'–2019'
000.950
000.951
4
5
No recovery
No recovery
2000'
2039'
clay
silt
sand

11. Stenlille-1

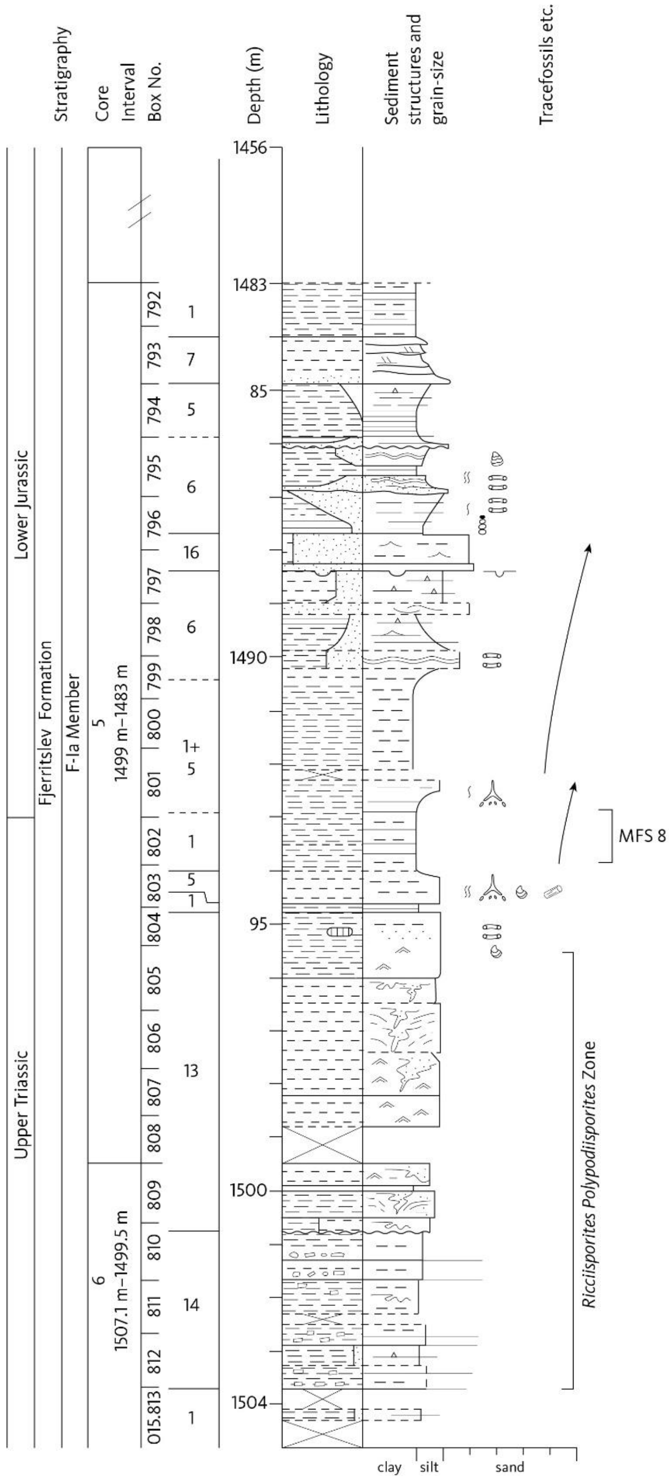
Stenlille-1


Stratigraphy
Core
Interval
Box No.
Facies
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Samples for palynology
Lower Cretaceous
Vedsted Formation
-? Rødby Fm?
Middle Albian
Late Barremian
Late Valanginian – Late Hauterivian
1
1212.90 m–1203.50 m
2
1227.50 m–1220.10 m
107
108
109
110
111
112
113
015.114
004
005
006
007
008
009
015.110
31
29
27
28
27
26
25
24
23
22
1203
5
10
1213
1220
25
1228
Sealed sample
Sealed sample
Sealed sample
Sealed sample
Sealed sample
547709
712
715
717
719
720
722
724
727
727
730
27411
734
735
27412
744
747
27413
753
clay
silt
sand

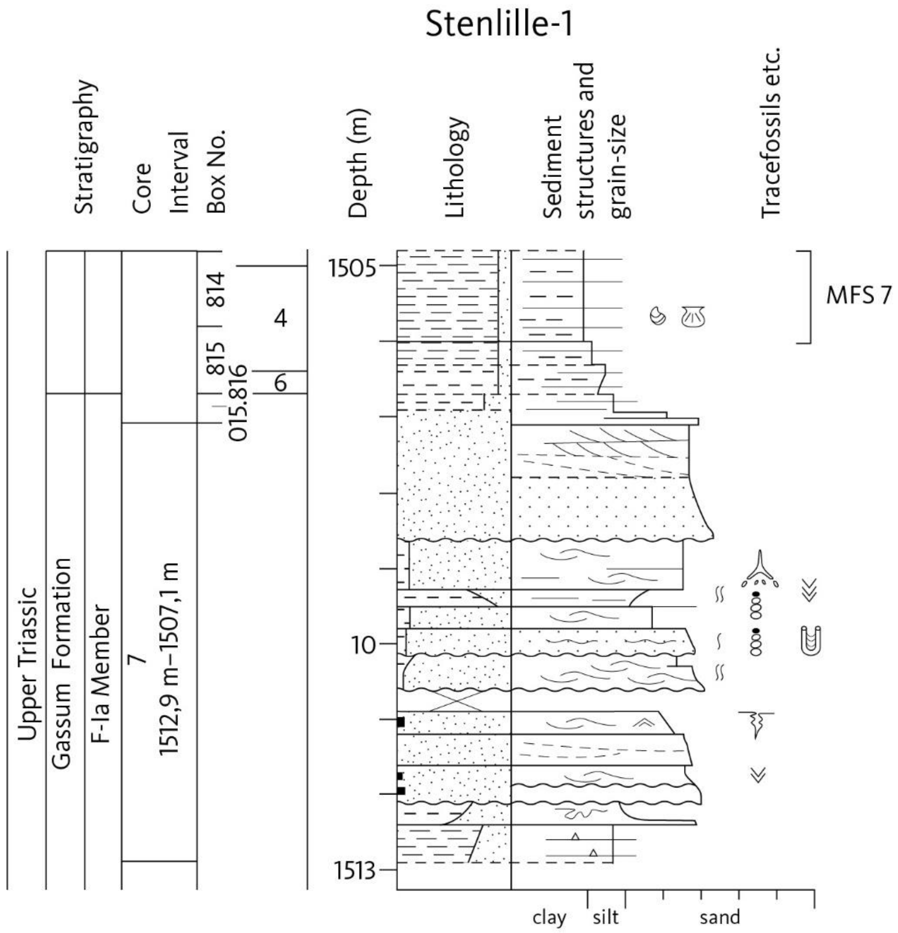
Stenlille-1


Stratigraphy
Core
Interval
Box No.
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Fjerritslev Formation
F-1a Member
3
1420.50 m–1410.40 m
4
1455.50 m–1447.50 m
774
775
776
777
778
779
780
781
015.782
783
784
785
786
787
788
789
790
015.791
1410
15
20
1421
1447
50
55
1456
clay
silt
sand

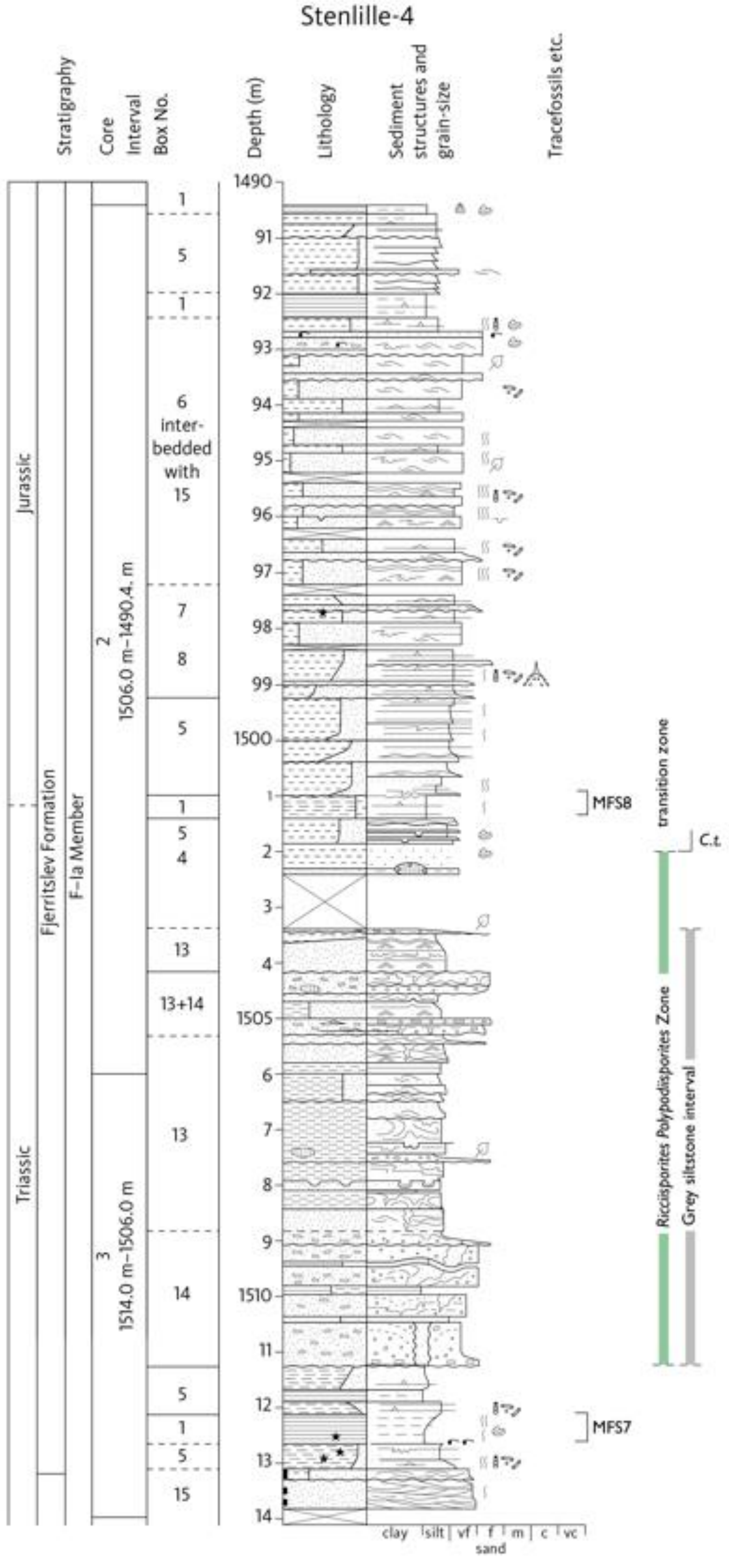
Stenlille-1



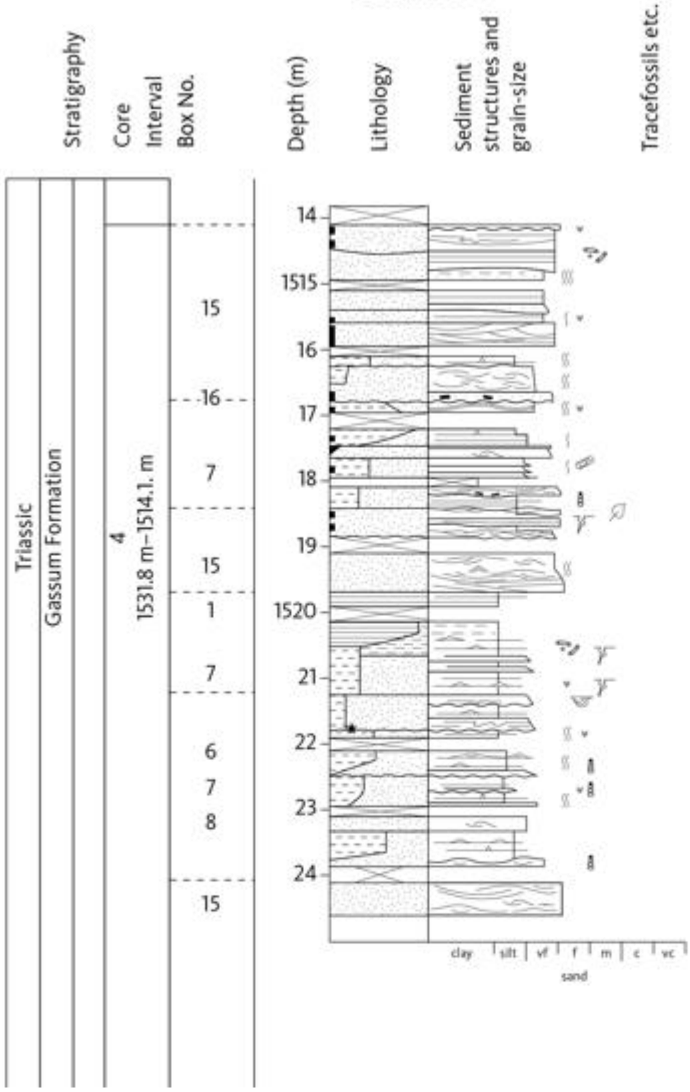
Stratigraphy
Core
Interval
Box No.
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Lower Jurassic
Upper Triassic
Fjerritslev Formation
F-Ia Member
5
1499 m–1483 m
6
1507.1 m–1499.5 m
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
015.813
1
7
5
6
16
6
1+
5
1
5
1
13
14
1
1456
1483
85
1490
95
1500
1504
MFS 8
Ricciisporites Polypodiisporites Zone
clay
silt
sand


Stenlille-1
Stratigraphy
Core
Interval
Box No.
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Upper Triassic
Gassum Formation
F-Ia Member
7
1512,9 m–1507,1 m
814
815
015.816
4
6
1505
10
1513
MFS 7
clay
silt
sand

12. Stenlille-4


Stenlille-4
Stratigraphy
Core
Interval
Box No.
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Jurassic
Triassic
Fjerritslev Formation
F–Ia Member
2
1506.0 m–1490.4 m
3
1514.0 m–1506.0 m
6 inter-bedded with 15
13+14
1490
1500
1505
1510
MFS8
MFS7
transition zone
C.t.
Ricciisporites Polypodiisporites Zone
Grey siltstone interval
clay
silt
vf
f
m
c
vc
sand

Stenlille-4



Stratigraphy
Core
Interval
Box No.
Depth (m)
Lithology
Sediment structures and grain-size
Tracefossils etc.
Triassic
Gassum Formation
4
1531.8 m–1514.1. m
15
16
7
15
1
7
6
7
8
15
14
1515
16
17
18
19
1520
21
22
23
24
clay
silt
vf
f
m
c
vc
sand

13. LEGENDE

Lithology

- Clay
- Mud
- Silt
- Sandy siltstone
  Muddy sandstone
- Heterolithic mudstone
- Heterolithic sandstone
- Sandstone
- Carbonaceous mupdstone
- Mud-clast conglomerate
- Calcareous mudstone
- Marl
- Limestone
- Cemented bed
- Concretion
- ★ Pyrite
- Gl Glauconite
- Ja Jarosite

Sedimentary structures

- Lamination
- Graded beds
- Weak lamination
- Structureless
- Streaks of coarse-grained silt
- Streaks of very fine-grained sand
- Cross-lamination
- Wave-generated cross-lamination
- Hummocky cross-stratification
- Cross-bedding
- Lenticular bedding
- Wavy bedding
- Flaser bedding
- Soft-sediment deformation
- Synaresis cracks

Miscellaneous

- Present-day core length
- Original recovery

Biota and trace fossils

- Rootlets
- Plant remains, mostly comminuted plant debris
- Coalified wood
- Shell fragment
- Bivalve
- Belemnite
- Ammonite
- Bioturbation
- *Planolites* isp.
- *Thalassinoides* isp.
- *Chondrites* isp.
- *Rhizocorallium* isp.
- *Skolithos* isp.
- *Diplocraterion* isp.
- *Cylindrichnus*
- *Ophiomorpha nodosa* isp.
- *Ophiomorpha irregulaire* isp.
- *Teichichnus* isp.

Appendix B: Facies description and interpretations

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1. Core description and facies analysis

The sedimentological logs measured on available core material from the Jurassic and Lower Cretaceous sections constitute Appendix A. An overview of wells, depths and core numbers logged, as well as the sedimentary facies are presented in the Tables in Appendix A. The facies descriptions below refer to sedimentological logs, and the facies interpretations are indicated on the sedimentological logs. The lateral and vertical distribution of facies within each formation is discussed in the main report. Representative pictures of the sedimentary facies are found in the main report Section 5.

1.1 The Jurassic to lowermost Cretaceous siliciclastic depositional system

In the silisiclastic dominated Jurassic to lower part of Lower Cretaceous a total of 21 sedimentary facies have been defined in the siliciclastic deposits of the Jurassic and Lower Cretaceous formations including the mudstone dominated Fjerritslev, Flyvbjerg, Børglum, Frederikshavn, Vedsted, Rødby, and Haldager Formations. The facies are shown, schematically in Figure 1. The facies are described below and interpreted with reference to four depositional complexes based on the depositional model in Figure 2, based on Pemberton et al. (2012).

2. The offshore complex (facies 1 – 10)

2.1 Facies 1: Black clayey mudstone

Description. The black, clayey mudstone of facies 1 often contains small nodules of pyrite, visible to the naked eye. The mudstone is weakly laminated or may appear homogeneous. Trace fossils are rarely seen, and bivalves, if present, are mostly epifaunal (Pedersen 1986). The black colour indicates a relatively high content of organic matter. In the examined cores, the black mudstone often occurs as 1−3 m thick units but is up to 15 m thick in Rødby-1 (cores 15−18). Facies 1 forms thin units at maximum flooding surfaces (Stenlille-1, core 6, MFS 7).

Occurrence. Facies 1 occurs in the Fjerritslev Formation in most of the studied wells, and it is cored in Stenlille-1 (cores 5-6); Stenlille-4 (cores 2-3); Rødby-1 (cores 15-18, 20, 22); Fjerritslev-2 (cores 8-9); Frederikshavn-1 (cores 142, 148, 151); Haldager-1 (core 108); all shown in Appendix A. Petrophysical logs suggest that facies 1 is common in the F-Ib and F-III members of the Fjerritslev Formation, although there is only limited core material of good quality to support this interpretation (Michelsen 1989b).

Interpretation. Facies 1 is interpreted as deposited by mud carried in suspension, and deposited below storm wave base, in a shelf environment (Fig. 2). The black colour, the pyrite, and the epifaunal bivalves suggest a dysoxic environment.

2.2 Facies 2: Weakly laminated grey mudstone

Description. Grey clayey mudstone, weakly laminated, or structureless constitute facies 2 (Fig. 1). Small pyrite concretions are present locally or may have weathered to pale yellow spots of jarosite. Shell fragments occur locally, distinct trace fossils are not preserved. In few places the clayey mudstone contains coalified plant debris. Facies 2 occurs as 1−10 m thick units in the Flyvbjerg and Børglum Formations and dominates the 110 m thick interval (cores 12−51) of the Vedsted Formation in Frederikshavn-1. The core quality is often moderate to poor, as the mudstone splits into small fragments as it dries. Facies 24 and 26 are subfacies of facies 2. They occur in the upper part of the Vedsted Formation and are described below in connection with the underlying and overlying facies.

Occurrence. Facies 2 occurs in the

- Vedsted Formation: Børglum−1 (core 3); Frederikshavn-1 (cores 12−22, 24−45,47, 48, 49−51); Haldager-1 (cores 14, 17, 19, 26−27, 33−34);
- Flyvbjerg and Børglum Formations: Haldager-1 (cores 100–102), Flyvbjerg-1 (core3)
- Fjerritslev Formation: Frederikshavn-1 (core 144−145, 147).

Interpretation. The grey clayey mudstone of facies 2 was deposited from mud carried in suspension at low energy conditions, in a marine environment. The lack of event beds suggests deposition well below storm wave base. The grey colour and the small amount of pyrite suggest deposition in an open marine environment probably an inner shelf environment (Fig. 2).

2.3 Facies 3: Bioturbated, fossiliferous mudstone

Description. Facies 3 is a fossiliferous, medium grey mudstone, locally muddy siltstone. The facies is rich in fossils, especially bivalves including oysters, but also belemnites and ammonites. *Turritella*-like gastropods occur locally (Sorgenfrei & Buch 1964, plates 7–8). In some cores the shell fragments cannot be identified to fossil groups. Facies 3 occurs as 1−5 m thick units in the examined cores. The main difference between facies 3 and facies 4 is the very rich fauna in facies 3.

Occurrence. Facies 3 occurs in the Børglum Formation in the wells Fjerritslev-1 (core1), Børglum-1 (core 8), and Frederikshavn-1 (core 108).

Interpretation. The grey mudstone of facies 3 was deposited from mud carried in suspension at low energy conditions. The abundant marine fossils demonstrate a fully marine environment. The fine grain-size indicates deposition below storm wave-base, and the facies may represent a lower offshore or inner shelf depositional environment (Fig. 2).

2.4 Facies 4: Grey silty mudstone to grey siltstone

Description. Facies 4 comprises pale to medium grey, greenish grey and brownish grey silty mudstone to siltstone. The siltstone is locally micaceous and may contain small amounts of very fine-grained sand. The siltstone may be calcareous. The relative proportion of clay and silt-sized particles is difficult to estimate, and a lithological subdivision is not possible. Facies 4 is therefore a commonly occurring facies. Visible pyrite is rare. Spots of FeOOH and jarosite occur locally, pyritic burrows are rare. Local occurrences of brown or yellowish siltstone are suggested to reflect oxidation of pyrite. Burrows may have a pale-yellow colour (jarosite), which suggests that they originally were pyritic. The pale to medium-grey colours suggest that the mudstone has low contents of organic matter. Locally, the muddy siltstone and the siltstone is fossiliferous, many shell fragments appear to originate from bivalves. Small shell fragments may be present in the siltstone.

The silty mudstone is weakly laminated to structureless, bioturbated to mottled, but distinct trace fossils are rare. The muddy siltstone has rarely any sedimentary structures. Lamination is not recognized, sand-or silt-streaks were obliterated by bioturbation if they ever formed. The siltstone may be bioturbated, but burrows are indistinct. Burrows in the micaceous siltstone are enhanced by small differences in colour, which suggests that this lithology locally was heterolithic. Trace fossils of the *Cruziana* ichnofacies occur locally and include *Chondrites* isp., *Teichichnus rectus, Rhizocorallium isp.. S*ome siltstone beds have dense burrows, probably *Chondrites* isp*.*. Rare occurrences of *Diplocraterion isp.* indicates higher energy conditions may have existed locally.

Most of the cores have not been slabbed, and several are now fragmented. Much of the core material is, however, of a moderate quality. Few cores are slabbed, many cores are fragmented, or mixed with dry drilling mud. Facies 4 occurs typically as 1−3 m thick beds in most formations, but the facies 4 is up to 33 m thick in the Vedsted Formation. It is also thick in the Frederikshavn Formation, although interbedded with thin sandier facies.

Occurrence. Facies 4 occurs in nearly all the studied wells. It occurs as several meters thick units in all members of the Fjerritslev Formation. Facies 4 occurs in the:

- Vedsted Formation: Haldager-1 (cores 10−11, 13–24, 30—33, 35−36); Børglum-1 (cores 1−4), Frederikshavn-1 (cores 48, 52–59); Vedsted-1 (core 1).
- Frederikshavn Formation, here facies 4 is interbedded with sandier facies: Flyvbjerg-1 (core 2); Haldager-1 (cores 37, 42, 45–46, 64–71, 89, 93, 97–98); Frederikshavn-1 (cores 62, 78, 81−82, 86, 105−106); Vedsted-1 (core 2).
- Børglum Formation: Frederikshavn-1 (core 107); Fjerritslev-1 (core 1).
- Flyvbjerg Formation: Børglum-1 (cores 9–10); Flyvbjerg-1 (core 3); Frederikshavn-1 (cores 109–119); Vedsted-1 (core 3).
- Fjerritslev Formation: Børglum-1 (cores 14–15); Flyvbjerg-1 (core 4); Frederikshavn-1 (cores 140, 149–52, 155, 165); Haldager-1 (cores 108, 110); Lavø-1 (cores 9,11); Rødby-1 (cores 3, 6−7, 20, 27); Stenlille-1 (core 6); Stenlille-4 (core 2).

Interpretation. Facies 4 is interpreted as a marine deposit on basis of the fossils and shell fragments, and the occasional occurrence of pyrite and jarosite. The greyish colours suggest low to moderate contents of organic matter. These observations indicate deposition in an open, low-energy marine lower offshore environment. The clay- and silt-sized particles were probably carried in suspension or as dilute storm generated density currents, in which the grain-size varied little. Facies 4 represents deposition at slightly higher energy than facies 2. The lack of sedimentary structures is probably mainly due to bioturbation. A mottled texture may be difficult to recognize, especially in cores of moderate to poor quality. The grain size (clay, silt and locally very fine-grained sand) and the strong bioturbation indicate a depositional environment with a benthic fauna and little physical reworking i.e. deposition below fair-weather wave base.

The fragmented core material may partly explain the few recognized trace fossils. *Chondrites* isp. is easy to recognize in small samples and furthermore has the advantage of being a deep tier burrow, which is less likely to be obliterated by younger burrows. Fresh cores reveal more details of bioturbation or sedimentary structures (Birkelund & Pedersen 1980: their figs 3–4). Facies 4 is interpreted as deposited in a lower offshore environment.

2.5 Facies 5: Silt-streaked mudstone

Description. This heterolithic facies is dominated by mudstone and contains a small proportion (10–20 % by volume, estimated visually) of coarse silt or very fine-grained sand. The mudstone is dark grey to black and may be homogeneous, weakly laminated or laminated on a mm- to sub-mm scale. The coarse silt and very fine-grained sand form laminae, which range from thin (0.3–0.5 mm) streaks of uniform thickness to thick (3–6 mm) streaks, many of which are slightly lenticular in cross-section. The streaks typically have a sharp lower boundary, whereas the upper boundary may be either sharp or gradational. The streaks may be devoid of trace fossils or may be burrowed (Figs 1, 2). Trace fossils include *Chondrites* isp., *Teichichnus* isp., and *Rhizocorallium* isp., all part of the *Cruziana* ichnofacies (Fig. 2). There is a gradual transition between facies 5 and either facies 1 or facies 6. Facies 5 form 1−35 m thick units, most of them are 1−3 m thick.

Occurrence. Facies 5 is fairly common in the Fjerritslev Formation: Børglum-1 (cores 14−15); Frederikshavn-1 (cores 139, 142, 145–146); Haldager-1 (cores 107–110); Fjerritslev-1 (core 2); Fjerritslev- 2 (cores 10, 12); Lavø (cores 9–15); Stenlille-1 (cores 3–5); Stenlille-4 (cores 2–3); Rødby-1 (cores 4–15; 19–22).
Facies 5 occurs is rare in the Vedsted Formation: Haldager-1 (core 35).

Interpretation. Facies 5 is dominated by mud carried in suspension and deposited below storm wave base. This was interrupted by deposition of silt or very fine-grained sand, which was probably transported as distal storm sand layers and reworked by storm-generated currents or waves (Pedersen, 1985). The silt-streaked mudstone (facies 5) represents a lower offshore environment with higher energy than the black clayey mudstone (facies 1) (Figs. 1, 2). The moderate to low degree of bioturbation may indicate either a sparse benthic fauna, a relatively high rate of deposition, or repeated erosion and redeposition.

2.6 Facies 6: Heterolithic mudstone

Description. Facies 6 is a heterolithic mudstone with approximately equal amounts of mudstone and very fine-grained sandstone. The mudstone is dark grey to grey and may contain more silt than the mudstones of facies 1 and 6. The facies locally contain comminuted plant debris. Pyrite is rarely observed. The very fine-grained sandstone may include some coarse silt or some fine-grained sand. The sand forms streaks, laminae or lenses, which may show wave-generated ripple structures such as cross-lamination or small-scale hummocky cross-stratification. The laminae or lenses of sand have sharp bases and graded tops. Few trace fossils are observed and occasionally identified as *Teichichnus* isp., *Planolites* isp., and *Chondrites* isp.. There is a gradual transition between facies 6 and facies 5 or facies 8. Facies 6 occurs as 1−3 m thick beds.

Occurrence. Facies 6 is a rare facies in most wells, and is only common in Rødby-1. Facies 6 occurs in the:

- The Frederikshavn Formation: Børglum-1 (core 7); Frederikshavn-1 (cores 73, 104); Haldager-1 (cores 64–65, 68−69, 72, 75, 85, 89, 93, 95). Flyvbjerg-1 (core2)
- The Børglum Formation: Flyvbjerg-1 (core 2).
- The Flyvbjerg Formation: Flyvbjerg-1 (core 3); Haldager-1 (cores 101–102); Vedsted-1 (core 3).
- Fjerritslev Formation: Frederikshavn-1 (cores 144–146); Børglum-1 (core 13); Flyvbjerg-1 (core 4); Fjerritslev-2 (cores 11, 12); Lavø-1 (core 10); Stenlille-1 (cores 3–6); Stenlille-4 (cores 2, 4); Rødby-1 (cores 10−11, 19, 25).

Interpretation. The trace fossils suggest a marine environment. The heterolithic alternation between thin beds of sandstone and mudstone indicate a depositional environment characterized by local high-energy conditions, probably related to storm activity. This may correspond to the proximal lower offshore to lower shoreface environments (Fig. 2). The thin streaks or laminae of silt- to very fine-grained sand suggest episodic deposition from storm-generated sediment gravity flows. The sand content indicates that facies 6 was deposited in a higher-energy environment compared to facies 5, and the wave-generated structures indicate water depths above storm wave-base. The absence of trace fossils at some levels, and the abundance of trace fossils at other levels, may reflect variations in the rate of deposition. Facies 6 is interpreted as deposited in an upper offshore environment (Fig.2).

2.7 Facies 7: Mudstone to siltstone with graded siltstone beds

Description. Facies 7 is characterized by graded beds, typically 10–50 mm thick, with erosive bases often with a distinct relief. The grain-size ranges from coarse silt, locally with very fine-grained sand, at the base of the beds to mud at the top. Generally, the beds contain only few trace fossils, but the top of the beds may be bioturbated. The coarse silt may form lenses with small-scale HCS-structures at the base of the beds. Laminae of facies 7 may show a gradual transition towards facies 5 (silt-streaked mudstone). The mudstone with graded siltstone beds may have a gradual transition to muddy siltstone with graded beds. Gradual transitions between 8 and facies 16 (storm sand layers) have not been recognized. Facies 7 occur as 1−3 m thick units.

Occurrence. Facies 7 has only been recognized in Stenlille-1 (cores 3, 5) and Stenlille-4 (cores 2, 4).

Interpretation. The graded siltstone beds were deposited from a waning sedimentary gravity flow, possibly a high density current, where the largest particles settled most rapidly. The erosive boundaries suggest a turbulent current. The presence of small-scale HCS-structures indicates deposition at depths above storm wave-base, in an upper offshore environment (Fig. 2).

2.8 Facies 8: Heterolithic sandstone

Description. Facies 8 comprises heterolithic sandstones. They may contain some comminuted plant debris. The mudstone component may be a silty mudstone ranging into siltstone. The sandstone beds range from few cm thick layers with wave-generated bedforms or cross-lamination separated by mudstone to fine-grained sandstones with flaser bedding or thin mudstone layers. Locally facies 8 is strongly bioturbated, and in places the trace fossil *Chondrites* isp. is recognized. In some of the cores the very fine-grained sandstone is friable to loose. In other cores the sand is weakly cemented. The sandstone beds are thicker and more coarse-grained than in facies 6. Gradual transitions exist between the two facies. Locally, small upward coarsening successions show gradual transition from facies 6 to facies 8. The quality of the core material ranges from moderate to poor, partly because the sandstones are friable and may disintegrate to loose sand, while many mudstones fall apart as small fragments. Facies 8 form 1−10 m thick units.

Occurrence. Facies 8 is a common facies in the Frederikshavn Formation: Børglum-1 (core 4); Frederikshavn-1 (cores 66–69, 73–75, 77, and 81) and Haldager-1 (cores 74, 81, 86–87, and 90–91). It also occurs in the Gassum Formation.

Interpretation. Facies 8 represents a range of depositional conditions. The mudstone-dominated parts of facies 8 is interpreted as deposited in an environment characterized by low-energy conditions allowing settling and deposition of mud with episodic deposition of sand during higher-energy conditions, probably storms. The water depth was probably between fair-weather and storm wave-base in an upper offshore fully marine environment (Fig. 2). Facies 8 also includes heterolithic fine-grained sandstones with mudstone drapes, which may form in distal lower shoreface environments or in tidal flats.

2.9 Facies 9: Siltstone to very fine-grained sandstone

Description. Grey siltstone, sandy siltstone, or very fine-grained sandstone characterizes facies 9. Small amounts of clay may occur as a matrix in the silt- and sandstone, which form 20–30 cm thick beds interbedded with finer-grained lithologies. There are gradual transitions between these lithologies. Pyrite is rarely visible. The siltstone is weakly laminated, locally with thin sand-streaks, and frequently blurred by bioturbation. Locally burrows referred to *Chondrites* isp., *Planolites* isp., and possibly to *Diplocraterion* isp. occur. Facies 9 may mostly form 1−2 m thick units and is fairly common in the Fjerritslev Formation.

Occurrence. Facies 9 occurs in the:

- Frederikshavn Formation: Haldager-1 (cores 45, 63)
- Flyvbjerg Formation: Frederikshavn-1 (core 118); Flyvbjerg-1 (core 3); Haldager-1 (cores 101–102).
- Fjerritslev Formation: Flyvbjerg-1 (cores 5−6); Fjerritslev-1 (core 2); Frederikshavn-1 (cores 141, 143, 150); Haldager-1 (cores 107, 110); Rødby-1 (cores 3, 5, 7, 25).

Interpretation. Facies 9 is dominated by particles carried in suspension or as dilute storm generated density currents in which the grain-size varied little. The very fine- to fine-grained sandstone is interpreted as deposited during high-energy events, possibly related to storms. A small proportion of clay or mud increases the matrix strength of the sediment gravity flow and slow the sorting during transport and settling. Later bioturbation may have obliterated the depositional structures, and a mottled texture may be difficult to recognize, especially in cores of moderate to poor quality. The water depth is suggested to have been between fair-weather and storm wave-base, and deposition is interpreted to have occurred in an upper offshore to distal lower shoreface environment.

2.10 Facies 10: Greenish grey, sandy siltstone

Description. The siltstone is grey, locally olive grey or greenish-grey and contains some very fine-grained sand. The siltstone probably contains a small amount of glauconite. Shell fragments are common and often very small. The sandy siltstone locally has spots of jarosite or contains pyritic burrows. Generally, the sandy siltstone is mottled, distinct trace fossils have not been recognized. Facies 10 forms 1–10 m thick units.

Occurrence. Facies 10 is common in the Vedsted Formation and occurs locally in the Frederikshavn Formation. Facies 10 is also present in Lavø-1, core 6, in Cenomanian sandstone.
Vedsted Formation: Børglum-1 (cores 1−2, 4); Frederikshavn-1 (cores 46, 87); Haldager-1 (cores 8−9, 11, 22 25, 28−31); Vedsted-1 (core 1).
Frederikshavn Formation: Haldager-1 (cores 58, 83).
Fjerritslev Formation: Frederikshavn-1 (core 163).

Interpretation. The greenish grey sandy siltstone is interpreted as marine on basis of the shell fragments and the occasional occurrence of glauconite, pyrite or jarosite. The mottled structure suggests that the sandy siltstone may have been heterolithic or may have been deposited from sediment gravity flows as series of weakly graded silty beds. The dominance of silt, and the presence of a little very fine-grained sand suggests a depositional environment with some energy. The water depth was probably close to fair-weather wave-base suggesting deposition in an open, low-energy marine environment, probably upper offshore to distal lower shoreface environment (Fig. 2).

3. The lower to middle shoreface complex (facies 11 – 18)

3.1 Facies 11: Very fine- to fine-grained, structureless sandstone

Description. Very fine-grained to fine-grained sandstone, locally with some silt. The colour ranges from pale grey to greenish, locally dark green, depending on the amount of glauconitic. The sandstone is moderately sorted to well-sorted. It may be consolidated or weakly cemented, and forms units, which are 1–3 m thick. Elsewhere the sandstone is friable, and locally micaceous. Indistinct sedimentary structures indicate that the sandstone in some places originally was interbedded with silt- or mudstone, although the sandstone now mostly is bioturbated, mottled or structureless.

The sandstone locally contains pyrite precipitated either along burrows or as nodules up to 0.5 cm in diameter, now oxidized. The sandstone locally contains pieces of coalified wood and comminuted plant debris. Locally the sandstone is very friable, and the core material consists of loose sand and a few fragments of sandstone. Locally, the sandstone is fossiliferous, bivalves are locally preserved as shells or impressions, but unidentified shell fragments are most common.

The sandstone appears to be structureless, partly because it is well sorted. Locally, faint bioturbation is seen, distinct burrows are rare but include locally *Chondrites* isp., *Planolites* isp. and *Teichichnus* isp. (Børglum-1, core 6). Gradual transitions exist between lower offshore and lower shoreface facies (facies 4, 10 and 12). Facies 11 forms 1−10 m thick units.

Occurrence. Facies 11 is common in the

- Vedsted Formation: Børglum-1 (cores 2, 4); Haldager-1 (cores 22−23, 25, 28, 30, 33); Frederikshavn-1 (cores 23, 46).
- Frederikshavn Formation: Børglum-1 (cores 5–7); Flyvbjerg-1 (cores 1–2); Frederikshavn-1 (cores 59–61,63–64, 77, 79−80, 83, 86), and Haldager-1 (cores 39, 43–44, 47, 56–57, 68–70, 73–74,78–79, 82, 85–88, 90, 96).

Interpretation. The moderately good sorting suggests that the sandstone of facies 11 was reworked mainly by waves and deposited close to fair-weather wave-base, in an environment where most silt and clay were winnowed and carried off in suspension. Distinct trace fossils are rare, which may be due to the uniform grain-size or mottling by a fauna at, or immediately below, the sea floor. Facies 11 is interpreted as deposited in a lower shoreface environment (Fig. 2).

3.2 Facies 12: Fine-grained carbonaceous sandstone

Description. This facies is a fine-grained, well-sorted sandstone, with concentrations of mud, silt, and comminuted plant debris on some bedding planes. The structures range from indistinct lamination to flaser-bedding, and the degree of bioturbation varies. The sandstone is locally micaceous. It differs from other fine-grained sandstone facies by its content of coalified plant debris.

Occurrence. Facies 12 occurs in Haldager Sand Formation in Vedsted-1 (core 3), where it is less than 1 m thick and overlies facies 21.

Interpretation. The good sorting indicates a depositional environment with rather continuous winnowing above fair-weather wave-base, interpreted as a lower shoreface environment in proximity to vegetated subaerial environments (Fig. 2).

3.3 Facies 13: Cross-laminated sandy siltstone to very fine-grained sandstone with soft-sediment deformation structures

Description. Grey sandy siltstone to very fine-grained sandstone has wave-ripple cross-lamination as the typical primary sedimentary structures. The absence of burrows in the siltstone is striking. Post-depositional soft-sediment deformation structures are characteristic of facies 13 and include water-escape structures, fluidized, homogeneous beds, and load-structures. Facies 13 also includes thin layers of clayey mudstone. Adjacent to beds with soft sediment deformation structures the mudstone may be disrupted. Injection of thin clay-clast conglomerates is seen. Facies 13 forms 1−6 m thick intervals.

Occurrence. Facies 13 is restricted to the “grey siltstone unit” in the basal part of the Fjerritslev Formation in Lavø-1, Stenlille-1 and Rødby-1. The grey siltstone unit corresponds closely to the *Riciisporites Polypodiisporites* Zone (Lindström et al. 2012) of latest Rhaetian in age, and the unit was deposited during the End-Triassic mass extinction (Pedersen 1985, Lindström et al. 2012, 2015, 2017, 2019). Facies 13 has not been recorded wells from northern Jylland where deposition of sandstones of the Gassum Formation continued during the Hettangian and Early Sinemurian. Facies 13 occurs in the Fjerritslev Formation in Lavø-1 (core 11); Stenlille-1 (cores 5–6); Stenlille-4 (cores 2–3); Rødby-1 (cores 23) and in other wells in the North German Basin (Lindström et al. 2012). The “grey siltstone unit” is overlain by silt-streaked mudstone (Facies 5).

Interpretation. The presence of mudstone beds within the wave-ripple cross-laminated sandy siltstone shows that the siltstone was deposited at water depths at or slightly above fair-weather wave-base in a lower shoreface environment. This indicates a rapid shallowing at the base of the grey siltstone unit from the clayey mudstone below. The absence of burrows in the siltstone suggests a high sedimentation rate. In the top of the unit an equally rapid deepening is suggested by the abrupt transition from the grey siltstone unit to facies 5 and facies 1 (including MFS 8). The abundant soft sediment deformation structures are interpreted as caused by earth-quake activity related to the initial break-up of the South Atlantic and the initial volcanic activity in the Central Atlantic Magmatic Province (CAMP; Lindström et al. 2015).

3.4 Facies 14: Mud-clast conglomerates

Description. Sub-angular, olive grey–olive green mud-clasts, only a few mm across and fairly uniform in size, form thin mud-clast conglomerates, typically 1–5 cm thick. The mud-clast conglomerates of facies 14 are most prominent in the basal part of the “grey siltstone unit”, but they do also occur in connection with water-escape structures in facies 13. Facies 14 forms up to 2 m thick units.

Occurrence. Facies 14 is a characteristic facies in the grey siltstone unit (see Facies 13). Mud-clast conglomerates occur in Stenlille-1 (core 6), Stenlille-4 (cores 2−3) and Lavø-1 (core 11) Rødby-1 (core 23).

Interpretation. The mud-clasts may have formed as rip-up clasts of consolidated mudstone. The mud-clasts which occur in connection with water escape structures probably formed *in situ*. The mud must have been somewhat consolidated prior to the transport as clasts.

3.5 Facies 15: Very fine- to fine-grained, often glauconitic sandstone with parallel lamination or cross-lamination

Description. Very fine- to fine-grained, frequently glauconitic sandstone, which commonly is micaceous. The sandstone is well sorted and friable. The colour ranges from pale grey to green. The sandstone often occurs as fragments and the identification of sedimentary structures is uncertain. The sandstone is dominated by physical structures such as parallel bedding, with 0.5–2 cm thick beds, which may show faint normal grading. Locally the sandstones show low angle cross-bedding. Parallel lamination and wave-generated cross-laminations occurs in a few places (Frederikshavn-1, cores 70–71) and sometimes of the sand is indistinctly laminated or nearly structureless. Burrows occur locally. In Børglum-1, core 5, indistinct burrows are outlined by jarosite. Shell fragments are uncommon in the sandstones of facies 15. Facies 15 forms 1−10 m thick units.

Occurrence. Facies 15 occurs only rarely in the:

- Frederikshavn Formation: Børglum-1 (core 5); Frederikshavn-1 (cores 70–72); Haldager-1 (cores 74, 80–82).
- Fjerritslev Formation: Stenlille-4 (core 2 (interbedded with facies 6)).
- Gassum Formation: Stenlille-4 (cores 3−4), and Rødby-1 (core 26).

Interpretation. The fine-grained, well-sorted, glauconitic sandstones is interpreted as deposited in a marine environment. The presence of wave-generated sedimentary structures indicates relatively high-energy depositional conditions, probably a proximal lower shoreface to middle shoreface environment (Fig. 2).

3.6 Facies 16: Storm sand layers, including coquinas

Description. Fine-grained or very fine-grained, well-sorted sand forms distinct, solitary beds, from 3 cm to more than 10 cm thick, with sharp bases, which locally are clearly erosive. The thin beds may be structureless. The thicker beds are normal graded and frequently show hummocky cross-stratification and locally wave-ripple cross-lamination. The sandstone may contain comminuted plant debris. Coquinas, composed mainly of fragments of bivalve shells, occur locally. They are rarely more than 2 cm thick. A single example of a pebble lag at the base of a sandstone bed has been noted in the Haldager Formation.

Occurrence. Facies 16 occurs in the Fjerritslev Formation: Haldager-1 (core 110); Rødby-1 (cores 9, 10–11, 14, 20–22, 25); Stenlille-1 (core 4–5); Lavø-1 (core 9). In Stenlille-4 (cores 2–4) the storm sand layers are thin, and although shown on the log, they are not annotated. Facies 16 occurs also in:

- The Haldager Sand Formation: Haldager-1 (core 105).
- The Frederikshavn Formation (Haldager-1 (core 74).

Interpretation. The sandstone beds are interpreted as deposited from storm-generated sediment gravity flows. The wave-generated structures (HCS and wave ripples) indicate deposition at depths above storm wave-base, in a distal lower shoreface environment (Fig. 2).

3.7 Facies 17: Bioturbated, fine-grained sandstone

Description. Fine-grained, well-sorted, often friable, locally micaceous, sandstone constitutes facies 17. The facies also includes very well sorted, very fine-grained to medium-grained sandstones. The sandstone may be grey, olive grey, greenish grey or pale green depending on the content of glauconite. The sandstone may be slightly calcareous. Sedimentary structures are difficult to identify due to the low degree of cementation in the sandstone and the high degree of bioturbation. In some cores the sandstone appears to be structureless, but faint remnants of mud drapes and flaser structures suggest that the sandstone originally was heterolithic, at least locally. The sandstone is often strongly bioturbated. Indistinct burrows are locally enhanced by jarosite. The tracefossils *Chondrites* isp., *Planolites* isp., and *Teichichnus* isp., *Rhizocorallium* isp., *Ophiomorpha nodosa, O. irregulaire, Thalassinoides* isp., occur locally in the Vedsted or Frederikshavn Formations. Shell fragments occur locally. In places, the sandstone is cemented by siderite. The glauconitic sandstone contains a small proportion of mud and comminuted plant debris (Haldager-1, core8). Facies 17 forms 1−5 m thick units.

Occurrence. Facies 17 is rare in the measured cores. It is possible that this facies has low recovery, partly due to the friable nature of the sand. Facies 17 occurs in:

- The Vedsted Formation: Frederikshavn-1 (core 11), Haldager-1 (cores 8, 12), Lavø-1 (core 8). In the Frederikshavn-1 well, facies 17 separates mudstones (facies 2I in the upper part of the Vedsted Formation from dark grey mudstones (facies 32) in the Rødby Formation. Glauconitic sandstones occur in the Vedsted Formation in Frederikshavn-1, and facies 17 is therefore referred to the Vedsted Formation. yy

- The Frederikshavn Formation: Frederikshavn-1 (cores 60, 76, 84–85); Børglum-1 (core 6); Haldager-1 (core 75).
- The Haldager Sand Formation: Frederikshavn-1 (cores 137–38).
- The Fjerritslev Formation: Frederikshavn-1 (cores 153−58, 162−164); Fjerritslev-1 (core 2); Rødby-1 (core 3).

Interpretation. The sandstone is interpreted as a marine shoreface deposit. The rich trace fossil assemblage dominated by vertical burrows suggests a fairly steady, but low rate of sand accumulation. The good core quality in the Vedsted Formation suggests a weak cementation of the sandstone. The lack of sedimentary structures in the fairly well-sorted, fine-grained sandstone may suggest an early phase of intense bioturbation later overprinted, locally, by burrows interpreted as *Ophiomorpha nodosa*. Spreiten may represent oblique sections in *Teichichnus* isp. or *Rhizocorallium* isp. The sandstones of facies 17 are interpreted as marine shoreface deposits (proximal lower shoreface to middle shoreface) deposited at depths around above fair-weather wave-base (Fig. 2).

3.8 Facies 18: Fine-to medium-grained cross-bedded sandstone

Description. The fine- to medium-grained, friable sandstone is very well-sorted and olive grey or pale grey to green depending on the amount of glauconite. Indistinct cross-bedding or parallel bedding has been observed in high quality cores, whereas structures are difficult to characterize in fragmented cores with a small diameter. Facies 18 forms 1−5 m thick units.

Occurrence. Facies 18 is recognized in the Frederikshavn Formation: Frederikshavn-1 (cores 86–87); Haldager-1 (cores 76, 80). It is possible that the friable sandstone has low recovery.
Interpretation. Facies 18 is interpreted as marine on basis of the glauconite and the good sorting. The cross-bedding or parallel bedding indicates moderately high energy. The sandstone may represent deposition in a middle shoreface environment (Fig. 2).

4. The upper shoreface – foreshore – backshore complex (facies 19 – 21)

4.1 Facies 19: Weakly laminated, carbonaceous clayey mudstone

Description. Greyish black mudstone with poorly preserved shells and a fairly high content of coalified plant debris of terrestrial origin constitute facies 19. This facies is distinguished from facies 1–2 based on its high content of coalified plant debris. The mudstone shows indistinct lamination, but locally the lamination is enhanced by thin streaks of silt or very fine-grained sand. Soft sediment deformation structures may occur. Locally burrows with a diameter of 1 mm show some resemblance to *Chondrites* isp. Facies 19 is interbedded with facies 20.

Occurrence. Facies 19 is restricted to the Haldager Sand Formation. It occurs in Børglum-1 (core 12) and Haldager-1 (core 104). The Haldager Sand Formation was generally excluded from this study. The few occurrences of facies 19−21 are therefore not representative of the formation.

Interpretation. The mudstone represents deposition in a low-energy environment. The abundance of terrigenous plant material and the association with facies 20 and 21, suggests that the deposition may have occurred in a protected environment as a bay or lagoon, rather than a deep-water marine environment (Fig. 2).

4.2 Facies 20: Sand-streaked mudstone

Description. Grey, structureless, silty mudstone forms 5−15 mm thick laminae interbedded with 1–2 mm thick streaks of very fine-grained micaceous sand. Terrestrial plant material occurs. The degree of bioturbation is generally low, but some intervals are heavily bioturbated. Shell fragments occur locally and may be concentrated at certain bedding planes. In core 12 the sand-streaked mudstone is interbedded with facies 19.

Occurrence. Facies 20 is restricted to the Haldager Sand Formation in Børglum-1 (cores 11–12).

Interpretation. The sand-streaked mudstone represents deposition at depths below fair-weather wave-base. The sand-streaks indicate deposition from occasional events of slightly higher-energy conditions, possibly linked to storms, or to brief phases of increased fluvial run-off. Wave-generated sedimentary structures such as HCS are, however, not identified in the relatively limited core material. The presence of terrestrial plant debris and the association with shoreface and lagoonal deposits (facies 19 and 21) may suggest deposition in a lagoon. This interpretation is supported by the occurrence in the non-marine Haldager Sand Formation (Fig. 2).

4.3 Facies 21: Heterolithic, very fine-grained carbonaceous sandstone

Description. Fine-grained to very fine-grained sandstone, locally micaceous, is interbedded with siltstone with a relatively high content of coalified plant debris. The facies also includes laminated sandstone with laminae enriched in coalified plant debris. The laminated facies may also consist of alternation between sandy laminae with plant debris and silty laminae. Elsewhere the plant debris may drape ripples and form flaser-like structures. The sandstone may contain rootlets and is, locally, bioturbated.

Occurrence. Facies 21 occurs in:

- the Vedsted Formation: Haldager-1 (core 12).
- the Haldager Sand Formation: Haldager-1 (cores 103 and 105−106); Vedsted-1 (core 3) Facies 21 is rare in the measured cores, partly because cores from the Haldager Sand Formation generally were not included in the study.

Interpretation. The high amount of comminuted plant debris indicates the sediments were supplied from a terrestrial environment such as a floodplain or -delta plain. Facies 21 is interpreted as deposited in a low energy environment, possibly a lagoon. The rootlets suggest a very shallow water depth (Fig. 2).

5. The Lower Cretaceous siliciclastic and mixed carbonate-siliciclastic depositional systems (facies 22-33)

The Upper part of the Vedsted Formation and the overlying Rødby Formation represent a mixed siliciclastic-calcareous depositional system, and the interpretation of facies 22–33 is made with reference to the depositional model presented by Ineson (1993) and Ineson et al. 1997 (Fig. 3). Facies 22–26 occur in the Vedsted Formation, facies 27–29 occur in either the Vedsted or the Rødby Formation, facies 30–34 occur in the Rødby Formation. Facies 22-33 are described on core material mainly from Stenlille-1, Frederikshavn-1, Lavø-1, and Ringe-1.

5.1 Facies 22: Grey-green laminated calcareous mudstone

Description. Greenish grey mudstone with parallel laminae, which range in thickness from few mm to 1–2 cm characterize facies 22. The laminae are not disturbed by bioturbation. Pyritic concretions or yellow stains of jarosite are not observed. A few beds, dominated by silt with small amounts of very fine-grained sand, show sedimentary structures which resemble small-scale hummocky cross-stratification. The laminated mudstone is cut by numerous small-scale faults.

Occurrence: The Vedsted Formation: Stenlille-1, core 2, 1227.25–1224.25 m.

Interpretation. The dominance of mud indicate deposition mainly from suspension fall-out in a low-energy environment below fair-weather wave-base. The coarser layers of silt and very fine sand are tentatively interpreted as distal storm deposits. The lack of burrows show that a benthic fauna was absent. The pale colour indicates that very little organic matter was preserved. The lack of both TOC and pyrite suggests that the depositional environment was not anoxic to dysoxic. The absence of a benthic fauna might relate to either brackish-, or hyper-saline conditions, which might occur in a lagoon. It is tentatively suggested that the laminated mudstone was deposited in a lagoon at depths below wave-base. The small-scale faults are post-depositional tectonic structures, probably generated by movements of the Stenlille salt diapir.

5.2 Facies 23: Grey-green structureless calcareous mudstone

Description. Structureless, homogeneous greenish grey calcareous mudstone, without concretions and without fissility, and thus different from facies 2. Trace fossils are rare; macrofossils are rare in core 2, but fairly abundant in core 1, small-scale faulting is only seen locally. The boundary to facies 22, below, is sharp but does not indicate a hiatus.

Occurrence: The Vedsted Formation: Stenlille-1, core 2, 1224.25–1220.10 m.

Interpretation. The grain-size dominated by mud indicates deposition from suspension fall-out. The absence of both physical sedimentary structures and trace fossils suggest that the sediment was either (1) deposited from mudflows, (2) fluidized after deposition or (3) mottled by an infauna while the mud was still a “soup-ground” (Bromley 1996), in which burrows were not preserved. Neither erosive boundaries or intraformational clasts, suggestive of deposition from mudflows, nor fluidization structures have been recognized, and it is therefore suggested that the structureless mudstone facies may be a result of early bioturbation. Facies 22 and 23 are similar in colour and grain-size. There is not yet any evidence to show that they represent two widely different depositional environments. It is therefore suggested that facies 23 also represents deposition at low energy conditions in a lagoon

5.3 Facies 24: Grey silty mudstone, weakly laminated or structureless

Description. Grey mudstone, silty, weakly laminated to structureless, locally with concretions of pyrite (3 x 15 mm). Belemnites are fairly common, locally accumulated on bedding surfaces. Facies 24 is a subfacies of facies 2.

Occurrence: The Vedsted Formation: Stenlille-1, core 1, 1212.65–1211.00 m.

Interpretation. The mudstone is deposited in a low-energy environment around storm wave-base. The lack of physical sedimentary structures suggests a burrowing benthic fauna. The scarcity of distinct trace fossils suggests that the burrowing fauna inhabited a soft substrate. The belemnites show that the depositional environment was marine, possibly a lower offshore environment.

5.4 Facies 25: Grey muddy siltstone

Description. Brownish-grey muddy siltstone possibly with some very fine-grained sand constitute facies 25. The siltstone has an indistinct bedding, which is cut by vertical structures, c. 1 cm in dimeter, with a structureless fill. The boundary to the overlying dark grey mudstone (facies 26) is sharp.

Occurrence: The Vedsted Formation: Stenlille-1, core 1, 1211.00–1210.05 m.

Interpretation. Mudstones with belemnites occur both below and above facies 25 and indicate that facies 25 also was a marine deposit. The depositional environment may possibly have been a marine upper offshore to distal lower shoreface environment. The vertical structures may have formed during fluidization of the silty mudstone. Such structures may be generated by seismic shocks. Facies 25 occurs only once in the cored section, which may suggest that the fluidization was the result of a single event.

5.5 Facies 26: Medium grey, weakly laminated mudstone

Description. Medium grey mudstone, with indistinct bedding and pyrite concretions up to 2–5 cm in diameter. The mudstone may also be weakly laminated and include homogeneous layers. Belemnites occur locally, in low numbers. Trace fossils include *Chondrites* isp. and *Planolites* isp. Facies 26 is a subfacies of facies 2.

Occurrence: The Vedsted Formation: Stenlille-1, core 1, 1210.05–1208.30 m. Facies 2 occurs in the Vedsted, Børglum, Flyvbjerg and Fjerritslev Formations.

Interpretation. The belemnites and the medium grey mudstone with large pyrite concretions indicate that this mudstone was deposited in a marine environment close to storm wave base. The weak lamination and the trace fossils indicate an environment with a sparse benthic fauna. The mudstone of facies 26 is interpreted as deposited in a marine, offshore environment.

5.6 Facies 27: Pale olive marl

Description and occurrence. Pale olive marl, mottled, locally with indistinct thin drapes of mudstone constitutes facies 27. The carbonate content has not been analysed. The marl has large burrows (possibly *Thalassinoides* isp.), which locally are re-occupied by *Chondrites* isp..

Occurrence: Facies 27 has only been observed in the upper part of the Vedsted Formation in Stenlille-1 (core 1, 1207.05–1206.25 m). Within this depth interval the marl is interbedded with the mudstone of facies 26 and the white limestone of facies 28. Marl of facies 27 is common in Late Hauterivian to Barremian strata in Vinding-1.

Interpretation. The marl appears to represent a transitional facies between the grey-green mudstone (facies 23) and the white limestone (facies 28). According to the depositional model pelagic limestone was deposited in the deeper part of the basin during a sea-level low-stand or at the shelf during sea-level high stands.

5.7 Facies 28: White, fine-grained limestone

Description and occurrence. White, homogeneous limestone, without macrofossils, trace fossils or sedimentary structures. The limestone appears to be slightly coarser than the limestone of facies 30. Facies 28 is restricted to a single bed, only 17 cm thick, in Stenlille-1, core 1, 1206.72–1206.89 m. Recent unpublished studies of the Vinding-1 well in the Danish Basin have shown the occurrence of a similar limestone in the Lower Aptian interbedded with red marl. The chalk in Vinding-1 is dominated by the remains of pelagic nannofossils.

Interpretation. Facies 28 is interpreted as a relatively deep-water marine deposit. A similar facies has been described from Vinding-1, where it represents open marine conditions in a well oxygenated sea-floor probably in the deeper part of the basin (Lauridsen et al. in prep.). Facies 28 may represent deposition in a lower offshore to shelf environment.

5.8 Facies 29: Variegated calcareous mudstone

Description. Grey, yellowish green and red calcareous mudstone with weak lamination constitutes facies 29. The weak lamination is enhanced by the variations in colour (Fig. 43). Burrows are indistinct, one belemnite and a single bivalve shell are seen in the core (Fig. 43). In Stenlille-1 facies 29 represent the transition between the upper part of the Vedsted Formation (facies 22−28) and the Rødby Formation (facies 31).

Occurrence: Facies 29 occur in the upper part of the Vedsted Formation in Stenlille-1 (core 1, 1205 m–1206.25 m).

Interpretation: The fine grain-size, the few macrofossils and the indistinct lamination suggest a marine, low-energy depositional environment, possibly a lower offshore environment with a burrowing fauna. The colour variations are not explained at present but appear to mark a transition to the overlying red mudstones referred to the Rødby Formation.

5.9 Facies 30: Pale green or pale pink marl

Description. Facies 30 is characterized by marl, which range from pale grey to pale green (Frederikshavn-1) or to pale pink (Ringe-1). The marl may be interbedded with thin layers of white limestone. Thin clayey drapes locally indicate a weak lamination, elsewhere the marl is structureless. Macrofossils have not been observed in the sparse core material. Facies 30 occurs directly below white limestone in Ringe-1 and Frederikshavn-1. It seems likely that facies 30 represents a transition from underlying clay-dominated facies of the Lower Cretaceous to the Upper Cretaceous Chalk Group. Facies 30 is tentatively referred to the Rødby Formation.

Occurrence. Facies 30 occurs in Ringe-1 (cores 11–12) and in Frederikshavn-1 (cores 3–9), in strata of ?Upper Cretaceous age, which tentatively are referred to the Rødby Formation.

Interpretation. The pale grey, green or pink marl is interpreted as deposited in a low-energy marine environment. Palaeontological data are sparse, but both the underlying Vedsted Formation and the overlying Chalk Group are fully marine. The mix of pelagic chalk and siliciclastic clay suggests deposition in a lower offshore to shelf environment (Fig. 3).

5.10 Facies 31: Red calcareous mudstone

Description. Red, structureless calcareous mudstone without fissility constitute facies 31. Indistinct burrows are seen locally. In places the mudstone is cemented. A few belemnites occur in the uppermost part of core 1 in (Stenlille-1). The carbonate content of the calcareous mudstone has not yet been measured.

Occurrence: Facies 31 occurs in the Rødby Formation: Rødby-1 (cores 1–2, 1521'–1560'); Stenlille-1 (core 1, 1205–1203.50 m); Ringe-1, cores 13–17 (2722'–2756'). Red marl is common in the Aptian of Vinding-1.

Interpretation. The belemnites indicate a marine depositional environment. The lack of sedimentary structures suggests that the sediment was bioturbated before compaction, in which case burrows would have a poor preservation potential. The red colour may be due to an increase in hematite. It is interpreted as a decrease in clastic influx as a result of continuous transgression and a change to more oxygen-rich conditions at the sea-floor (Jensen et al. 1986). Red mudstones occur also in the uppermost Lower Cretaceous cores in Rødby-1, Ringe-1, Harte-2 and Vinding-1. The depositional environment is interpreted as a marine, low-energy, lower offshore environment.

5.11 Facies 32: Grey clayey mudstone

Description. Grey calcareous mudstone or clayey mudstone, with shell fragments. The mudstone includes thin streaks of silt. Locally the mudstone is interbedded with 2–4 cm thick layers of silt. The thickest of these may show low-angle cross-lamination, which resembles miniature hummocky cross-stratification. Facies 32 comprises lithologies, which also occur in facies 2, 4 and 6 (Fig. 2) and may be considered a subfacies of these facies. It is described here as a part of the Rødby Formation.

Pale to dark grey mudstone with thin siltstone beds characterize the basal part of the Rødby Formation in Frederikshavn-1 and Rødby-1. The mudstone is weakly laminated and range in colour from pale olive grey to black. The mudstone contains silt-streaks, and locally streaks of very fine-grained sand. Shell fragments occur in the mudstone but are rare or absent in the dark grey to black clayey mudstone. Pyrite has not been noted.

Occurrence. Facies 32 occurs in the Rødby Formation: Frederikshavn-1 (cores 5–11) and Rødby-1 (core 2).

Interpretation. The dominance of silt-and clay-sized particles, and the shell fragments, indicate a marine environment with water depths well below fair-weather wave-base. The thin streaks and beds of silt are interpreted as deposited from storm-generated currents and deposited at depths around storm wave-base. The dark grey mudstone (Frederikshavn-1, cores 10− 11) suggests a weakly oxic environment where some of the organic matter was preserved. The lack of visible pyrite suggests that the environment was not dysoxic. Facies 32 is thus interpreted as a marine, lower offshore deposit.

5.12 Facies 33: Green glauconitic sandstone

Description. The sandstone is well-sorted, fine- to medium-grained, and thoroughly bioturbated. The colour ranges from dark bluish-green (Lavø-1, core 7) to green (Lavø-1, core 8. The difference in colour may reflect either a higher content of glauconite or different chemical compositions of the glauconite. In cores of good quality, it is possible to recognize a diverse trace fossil assemblage, which includes *Planolites* isp., *Chondrites* isp., *Teichichnus* isp. (few examples of *T. rectus*), *Asterosoma* isp., probably *Cylindrichnus* isp, different types of *Ophiomorpha* isp. (*Ophiomorpha nodosa*, and possibly *Ophiomorpha irregulaire*), and large burrows, which might be *Thalassinoides* isp. Possibly *Rosselia* isp. and *Diplocraterion* isp. occur locally.

Occurrence. Facies 33 is restricted to cores 7–8 in Lavø-1. Similar sandstones have not been encountered in any other of the measured cores. The ages of the sandstones of cores 7−8 are not known. The overlying core 6 is Cenomanian, and cores 9–11 are Lower Jurassic. Sorgenfrei & Buch (1964) reported the occurrence of green, glauconitic sandstone from the Albian in the Lavø-1 well.

Speculation: In Rødby-1, the Lower Cretaceous Rødby Formation directly overlies the Lower Jurassic Fjerritslev Formation. This suggests that deposition of the Rødby Formation reflects a late Early Cretaceous transgression in the eastern part of the Danish onshore area. The same might be the case in Lavø–1, where all of the Middle and Upper Jurassic and most of the Lower Cretaceous is not present. The green, glauconitic sandstones of facies 33 may possibly be correlated with facies 17 at the boundary between the Vedsted and Rødby Formations in Frederikshavn–1. Glauconitic sandstone also occurs in the Upper Cretaceous succession at Arnager on Bornholm (Kennedy et al. 1981, Ravn 1925). Finally, glauconitic sandstones (facies 11, 17, 18) occur in the Frederikshavn Formation in Frederikshavn-1 (cores 60–62) and in Haldager-1 (several levels from core 90 to core 42), but this correlation is considered less likely.

Interpretation. The presence of trace fossils of both the *Cruziana* and *Skolithos* ichnofacies in facies 33 suggests a marine, lower shoreface depositional environment. The well-sorted sandstone suggests deposition around fair-weather wave-base, where clay- and silt-sized particles would rarely settle. The dominance of biogenic structures suggests a slow sediment accumulation rate, and little wave-reworking of the sea-floor. It is concluded that facies 33 probably was deposited in a marine, lower shoreface environment (Fig. 2, 3).

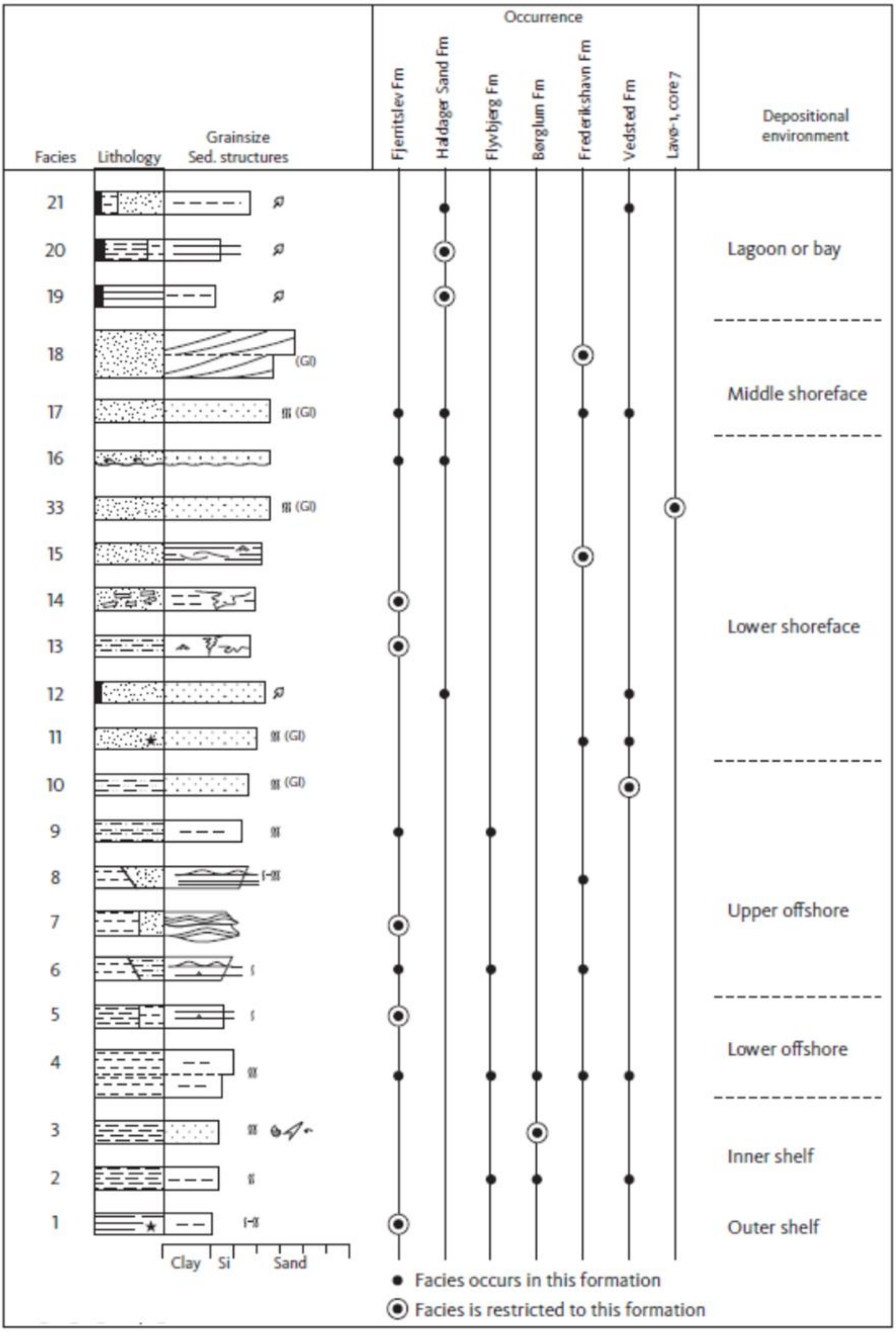

***Figure 1**. Facies identified and described in cores form the Jurassic and Lower Cretaceous sections.*

***Figur 1.** Facies der er identificeret og beskrevet i kerner fra Jura og Nedre Kridt*

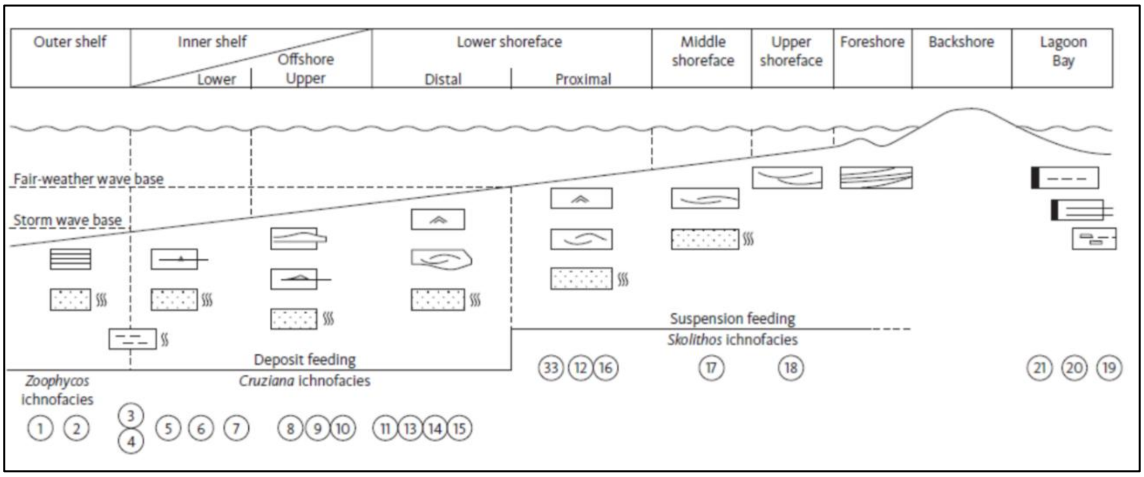

Figure 2. *Facies model showing interpreted depositional environments for the defined facies*
Figur 2. *Faciesmodel der viser tolkede aflejringsmiljøer for de definerede facies*

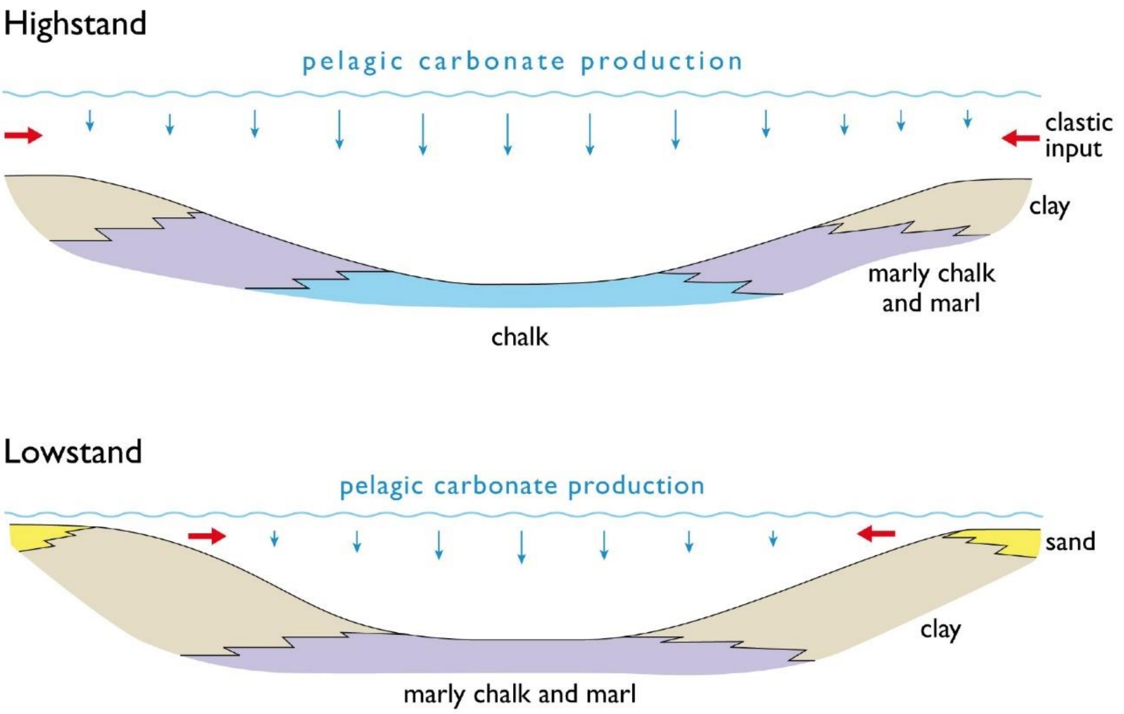

Figure 3*. Model for the deposition of mixed siliciclastic-carbonate facies based on Ineson (1993) and Ineson et al. (1997).*

Figur 3. *Model for aflejring af siliciklastiske–karbonatrige facies baseret på Ineson (1993) og Ineson et al. (1997).*

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