DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Sedimentology and sequence stratigraphy of Middle Jurassic deposits

## Danish and Norwegian Central Graben

Jan Andsbjerg

Ph.D. Thesis, University of Copenhagen, Geological Institute

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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## Forord

Afhandlingen er resultatet af et Ph.D. studie udført ved Geologisk Institut, Københavns Universitet under vejledning af Professor, Dr. Scient. Finn Surlyk. Studiet blev i hovedsagen finansieret af Danmarks Geologiske Undersøgelse (DGU) senere Danmarks og Grønlands Geologiske Undersøgelse (GEUS). DGU/GEUS stillede arbejdsplads, teknisk bistand og faciliteter til rådighed. Dele af studiet indgik i et projekt "Jura sekvensstratigrafi i Den danske Central Grav" (EFP-92, ENS nr. 1313/92-0002) finansieret af GEUS, EFP-midler samt bidrag fra Mærsk Olie og Gas A/S og Norsk Hydro senere Amerada Hess A/S. I forhold til den oprindelige opgave-beskrivelse er der i projektforløbet foretaget enkelte ændringer og justeringer. Udviklingen af de Jurassiske rift-bassiner i Central Graven kunne ses at have stor betydning for forståelsen af Mellem Jura aflejringerne, en sekvensstratigrafisk analyse af Jura bassinudviklingen i Den danske Central Grav blev derfor inddraget i opgaven På grund af mangel på relevante, tilgængelige boringsdata i den sydlige del af Den norske Central Grav blev kun området nærmest den danske sektor inddraget i opstillingen af en sekvensstratigrafisk model for Mellem Jura. Seismisk tolkning kom ikke til at ingå i projektet; derimod blev tolkede seismiske profiler i et vist omfang anvendt i det geologiske tolkningsarbejde. Sammenligningen med publicerede modeller fra andre områder blev begrænset til det sydlige og centrale Nordsø område. Mellem Jura blotningerne i Yorkshire blev besøgt i projektforløbet men feltstudier blev ikke direkte inddraget i arbejdet. Afhandlingen omhandler primært den geologiske udvikling i Mellem Jura i Den Danske Central Grav med hovedvægten på stratigrafi og sedimentationshistorie. Et væsentligt supplement til hovedtemaet er en kortlægning af bassinets udvikling gennem hele Jura Perioden med hovedvægten på hoved-riftfasen fra sen Mellem - Øvre Jura. Ud over forord, dansk sammendrag, takkeord og indholdsfortegnelse er afhandlingen bygget op som artikler; fire manuskripter der alle forventes udgivet og en allerede udgivet artikel. To af artikelmanuskripterne er under review med henblik på udgivelse i en kommende GEUS udgivelse " The Jurassic of Denmark and Greenland", en artikel er ugivet i Sedimentary Geology mens to manuskripter endnu ikke er afsendt til udgivelse.

## Dansk sammendrag

Central Graven udgør den sydlige gren af Nordsø Rift Systemet. Riften var aktiv i dette område både i Trias og i sen Mellem Jura - Sen Jura. Af den ca. 500 km lange Central Grav ligger ca. 150 km i den danske del af Nordsøen. I den danske sektor består Central Graven af NNV-SSØ orienterede halvgrave, og et underordnet N-S orienterede segment i den sydlige del af området. Hovedforkastningen i Den danske Central Grav er Coffee Soil Forkastningen, der udgør gravens østlige rand. Søgne Bassinet, Tail End Graven, Salt Dome Provinsen og muligvis Feda Graven blev aktivt indsynkende bassiner i løbet af Mellem Jura. I Øvre Jura blev Feda Graven, Gertrud Graven, Heno Plateauet, Outer Rough Bassinet og Ål Bassinet aktivt indsynkende områder med meget store insynkningshastigheder i Tail End Graven og Feda Graven.

Den sekvensstratigrafiske analyse af Jura successionen, præsenteret i "Jurassic sequence stratigraphy of the Danish Central Graben" af Andsbjerg og Dybkjær (del 1) er baseret på data fra omkring 50 boringer, primært borehuls logs, sedimentologiske kerne logs og biostratigrafiske data. Endvidere blev et antal tolkede regionale seismiske linier anvendt i tolkningen. Opbygningen af en sekvensstratigrafisk ramme er baseret på korrelation af log mønstre kombineret med biostratigrafiske dateringer. Sedimentologisk tolkede kerner er anvendt i de få sandstens-dominerede stratigrafiske niveauer, hvor et godt kernemateriale er til rådighed. Kun kerner fra Mellem Jura aflejringerne er tolket med henblik på dette projekt. Kernetolkninger fra Øvre Jura aflejringer er stillet til rådighed af P.Johannesen og L.H.Nielsen (begge GEUS). I dette studie er det tilstræbt at opnå en sekvensopdeling, hvor alle sekvenser kan følges over størstedelen af det studerede område. Det indebærer at sekvenser af en højere orden der kan genkendes i visse områder på grund af større aflejringshastighed, særlig litologisk kontrast eller ekstraordinært god biostratigrafisk opløsning, ikke er medtaget i dette studie.

Nedre Jura successionen af Hettang - Pliensbach alder er opdelt i fem sekvenser. Fire Mellem Jura sekvenser omfatter intervallet seneste Aalen eller tidligste Bajoc - Callov. I Øvre Jura er 11 sekvenser kortlagt. På basis af sekvensstratigrafiske korrelationer og isopach kort fremstillet for hver enkelt af Øvre Jura sekvenserne kan Den danske Central Gravs historie i Jura Perioden inddeles i syv faser:

(1) Lavmarine og fuldt marine sedimenter blev aflejret i et langsomt indsynkende præ-rift bassin, der strakte sig fra Nordsøen til den Fennoskandiske Grænsezone (Hettang - Pliensbach).

(2) Hævning og erosion i forbindelse med Nordsø-domens udvikling. En større hiatus repræsenterer denne fase i området (Toarc - Aalen).

(3) Terrestriske og marginalt marine sedimenter blev aflejret under en tidlig rift fase (seneste Aalen eller tidligste Bajoc - Callov).

(4) Tidlig Oxford - Tidlig Kimmeridge transgression foregik under rift klimaks. Aflejringsmiljøet skiftede fra kystslette og marginalt marint til fuldt marint. Kombinationen af stor indsynknings-hastighed og en overordnet eustatisk havniveau-stigningen har forhindret større relative havniveau-fald.

(5) I Sen Kimmeridge foregik regression og fornyet transgression under en pause i indsynkningen i forbindelse med en strukturel omorganisering af bassinet. Lavmarine og marginalt marine sedimenter blev aflejret over en regionalt udbredt erosionsflade. Pausen i bassinets indsynkning har betydet at selv mindre havniveau-fald er kommet til udtryk som markante relative havniveau-fald.

(6) Bassinet opdeltes i flere mindre gravsænkninger med høj indsynknings-hastighed under fornyet rift-klimaks. Aflejringen domineredes af fuldt marine muddersten (seneste Sen Kimmeridge - mellem Mellem Volg).

(7) Meget organisk-rige muddersten og turbidit-sandsten blev aflejret i løbet af sen Mellem Volg - Ryazan. Indsynknings-hastigheden var stærkt faldende i hovedbassinet, mens der fortsat var kraftig indsynkning i enkelte subbassiner.

Sedimentologi og høj-opløselig sekvenstratigrafi i Mellem Jura aflejringerne i Søgne Bassinet behandles i "Sedimentology and sequence stratigraphy of the Bryne Formation; Middle Jurassic, Danish Central Graben" (del 2).

Den Mellem Jurassiske Bryne Formation i Søgne Bassinet i den nordlige del af Den danske Central Grav og tilgrænsende norske område består af alluvial slette og kystslette aflejringer overlejret af sammenflettede kystplan og tidalt påvirkede lagune og estuarie aflejringer.

Alluvial slette/kystslette aflejringerne i den nedre del af Bryne Formationen er domineret af lateralt sammenhængende, hovedsageligt opad-finere kanal-sandsten og af enheder af mere fin-kornede flodslette sedimenter der typisk fremviser et finere - grovere opad mønster. Øverst i den nedre del af Bryne Formationen kan de finkornede aflejringer optræde som lakustrine muddersten i den centrale og østlige del af bassinet. Sedimentstrukturer i visse kanalsandsten tyder på periodevis tidal påvirkning af flod-systemet.

De paralisk og lav-marine aflejringer i den øvre del af Bryne Formationen afgrænses nedefter af en markant erosionsflade. Erosionsfladen er bund og sider i en dybt nedskåret dal. Log korrelationer i den nedre del af Bryne Formationen viser at op mod 50 m af den nedre Bryne Formation kan være fjernet erosivt. Over erosionsfladen udgør op til 45 m af stakkede fluviale og estuarine kanal-sandsten dalfyldet i de vestlige proksimale områder, mens sandsten aflejret i mindre tidevandskanaler og heterolitiske tidevandsaflejringer sammen med enkelte større estuarine kanal-sandsten udgør dalfyldet i den østlige mere distale del af området. Over dalfyldet ligger flere meter tykke kulaflejringer. Kullagene kan følges over store områder, også hvor det nedskårne dalsystem ikke er til stede. Over kulenheden er den vestlige del af det sydlige Søgne Bassin domineret af paraliske sedimenter i form af estuarine kanal-sandsten, "bay-head" delta aflejringer, lagune- og finkornede estuarie aflejringer, samt barriere-ø aflejringer. Længere mod øst er den øvre del af formationen domineret af opad-grovende enheder af shelf-, kystplan- og strandaflejringer. De paraliske sedimenter aflejredes fortrinsvis under transgression, mens de opad-grovende marginalt- til lav-marine sediment-enheder progradèrede ud i bassinet under relative havniveau fald.

Successionen, der består af Bryne Formationen og den nederste del af den overliggende Lola Formation er inddelt i 10 sekvenser. I den nedre del af Bryne Formationen er sekvens-grænserne lagt ved basis af udbredte kanal-sandsten, mens maksimum overskyls flader er lagt i finkornede flodslette eller lakustrine sedimenter typisk i infleksions-punktet mellem finere opad og grovere opad enheder. Erosionsfladen der markerer basis af den nedskårne dal er en vigtig sekvens-grænse der kan korreleres over store dele af Den danske Central Grav. I den øvre del af formationen ligger sekvensgrænserne ved basis af estuarie kanaler i de proksimale områder og ved toppen af progradèrende kystplan successioner i de distale områder. Sekvenserne er inddelt i fire system trakte: lavstand, transgressiv, højstand og tvungen regressiv. Tvungen regressiv system trakte kan kun identificeres i de progradèrende kystplan aflejringer i den øverste del af formationen.

I afhandlingen "Incised valleys and reciprocal architecture in coastal plain deposits of a half-graben basin; Middle Jurassic of the Central Graben, Danish North Sea" (del 3) er der gået mere i dybden med problemer der er berørt i del 2. På baggrund af de detaljerede sedimentologiske og sekvenstratigrafiske undersøgelser af den øvre del af Bryne Formationen er dannelsen af den nedskårne dal, dalfyldets aflejringshistorie samt aflejringen af paraliske og lavmarine sedimenter under henholdsvis transgression og regression behandlet mere indgående, og forsøgt sat i relation til eksteme faktorer. Nedskæring af dalen synes at være forårsaget af et markant havniveau-fald. Placeringen af nedskårne dale kan være påvirket af tektonisk styret bassin-topografi. Opfyldningen af dalen foregik under en overordnet havniveau-stigning. Dalfyldets kompleksitet tyder på påvirkning fra højfrekvente havniveau-svingninger. Kul-dannende tørvemoser og sumpe udvikledes da havniveau nåede dalranden og det primære aflejringsområde for fluvialt tilført sediment skubbedes tilbage over den flade kystslette. Kystbarrierer og måske et højt tørvemose-profil forhindrede for en tid at fortsat transgression kunne erstatte de fluvialt tilførte sedimenter med marine. Forkastningsaktivitet ved hovedforkastningen kan have forøget kystslettens hældning og dermed druknet de kystnære tørvemiljøer som start på fornyet transgression. Den forøgede gradient har ført til en koncentration af de transgressive paraliske aflejringer i en relativt snæver zone og samtidig friholdt bassinværts akkomodering til opfyldning under den efterfølgende regression. Det resulterende aflejringsmønster med en kile af proksimalt tykkest transgressive sedimenter adskilt af en transgressiv og en maksimum overskyls flade fra en distalt tykkest kile af regressive sedimenter kaldes reciprok sedimentation eller reciprok arkitektur.

I del 4 " Middle Jurassic palaeogeography of the Danish Central Graben, southem North Sea" inddeles Mellem Jura successionen i Den danske Central Grav på basis af den opstillede sekvensstratigrafiske ramme i seks korrelerbare enheder, og hver af disse enheder repræsenteres med et palæogeografisk kort. Enhed 1 - 3 ( seneste Aalen eller tidlig Bajoc - Bathon) viser et ekspanderende aflejringsområde domineret af alluvial-slette miljøer. Fluviale og lakustrine miljøer udviser stærkt varierende indflydelse. Enhed 5 er domineret af flettede floder i den sydvestlige del af området og nedstrøms af meandrerende floder og estuarie kanaler aflejret under et relativt havniveau-fald og fornyet stigning (seneste Bathon - Tidlig Callov). Enhed 5 og 6 repræsenterer en gradvis nord til syd transgression over en lavtliggende kystslette domineret af laguner, lavvandede søer, mindre distributarie kanaler og sumpe. En sammenligning med Mellem Jura successioner andre steder i regionen antyder at den endelige Callov transgression i Central Graven kan være begyndt i området omkring Søgne Bassinet og derfra have fortsat mod henholdsvis nord og syd. Transgressionen kan enten være kommet gennem det dybe trug i Sorgenfrei - Tornquist Zonen eller gennem de nordligste subbassiner i det Norsk - danske Bassin.

I artiklen "Organic facies development within Middle Jurassic coal seams, Danish Central Graben, and evidence for relative sea-level control on peat accumulation in a coastal plain environment" af H.I. Petersen og J.Andsbjerg (Sedimentary Geology 106, 1996: 259-277) relateres kullagene i den øvre del af Bryne Formationen i West Lulu-2 boringen til relative havniveau-ændringer. Det tørvedannende miljø er tolket i 5 kullag ved hjælp af konventionel kulfacies analyse. Det tørvedannende miljø er relateret til aflejringsmiljø som tolket sedimentologisk ved kernestudier. Specifik kul sammensætning er dernæst relateret til ændringer i grundvandsstand tolket som en følge relative havniveau-ændringer. Kullagene forefindes i transgressive system trakte i to sekvenser A og B. Kullag dannet under hurtig relativ havniveau-stigning viser typisk en petrografisk sammensætning der er karakteristisk for en situation med permanent højt grundvandsniveau. Kul dannet under langsomt stigende havniveau har typisk en "tør" sammensætning. Det højeste pyrit-indhold er observeret i de "våde" kul. Kullagene er et terrestrisk udtryk for en marin overskylsflade (flooding surface). Et enkelt kullag er associeret med en maksimum overskylsflade der repræsenterer tidspunktet hurtigst dannelse af ny akkomodering. Den endelige sekvenstratigrafiske model var ikke færdiggjort under arbejdet med denne artikel, og tilstedeværelsen af Cal-1B sekvensgrænsen i B- sekvensen blev ikke registreret. Med den endelige model er B-sekvensen blevet opdelt i sekvenserne Cal-1A og Cal-1B. Kullagenes position i transgressive system trakte står ved magt. De højestliggende kullag i successionen er associeret med maksimum overskylsfladen i sekvens Cal-1B.

## Tak

GEUS (oprindeligt DGU) takkes for at det var muligt at gennemføre projektet og for støtten undervejs. Finn Surlyk, Geologisk Institut ved Københavns Universitet takkes for vejledning, diskussioner, kritisk læsning af flere af manuskripterne samt for at have organiseret de uformelle Jura-kollokvier der har været en tilbagevendende kilde til inspiration. Stefan Hultberg (DGU) takkes for tildeling af den nødvendige arbejdstid og for sin store opbakning af projektet. Flemming G. Christiansen takkes for at den nødvendige arbejdstid har kunnet anvendes til at afslutte opgaven. Mange kollegaer på GEUS har ydet hjælp op støtte gennem diskussioner, konkrete forslag, kritisk gennemlæsning af manuskripter, og levering af informationer; især tak til Karen Dybkjær, Torsten Hoelstad, Jon Ineson, Peter Johannessen, Eva Koppelhus, Jens Jørgen Møller, Lars Henrik Nielsen, Henrik I. Petersen, Niels Poulsen og Erik S. Rasmussen. En særlig varm tak til Karen Dybkjær for et godt samarbejde i forbindelse med arbejdet på en sekvenstratigrafi for Jura successionen i Den danske Central Grav. Heinke Andersen takkes for assistance med manuskripterne, og Eva Melskens, Gitte Nicolajsen, Stefan Sølberg, Lis Duegård, Annabeth Andersen, Benny Schark, Peter Moors og Henrik K. Petersen takkes for hjælp med figurer og fotos. Bjørn H. Christensen og Karsten Holm takkes for hjælp med kernehåndtering.

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Organic facies development within Middle Jurassic coal seams, Danish Central Graben, and evidence for relative sea-level control on peat accumulation in a coastal plain environment.

by Henrik I. Petersen and Jan Andsbjerg.

The principal work of Jan Andsbjerg has been:

- the description of the geological setting of the study area

- description and sedimentological interpretation of cores

- correlation of wells and establishment of sequence stratigraphic framework

- participation in discussion and interpretation of controls on peat formation and of the significance of coal beds in the sequence stratigraphic framework in close cooperation with Henrik I. Petersen

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**STATEMENT ON AUTHORSHIP**

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Jurassic sequence stratigraphy of the Danish Central Graben

by Jan Andsbjerg and Karen Dybkjær.

The principal work of Jan Andsbjerg has been:

- lithological and sequence stratigraphic interpretation of well logs, well to well correlations based on well logs, and establishment of sequence stratigraphic model in cooperation with Karen Dybkjær after integration of palynological results

- construction of palaeogeographic and isopach maps

- construction of relative sea-level curve

- interpretation of Jurassic basin history in cooperation with Karen Dybkjær who provided biostratigraphic datings

- writing the sections introduction, regional geology, sequence stratigraphic subdivision and basin history, lithology prediction, basin asymmetry of the rift climax stage reflected in depositional patterns, and conclusion.

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## Part 1

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# Jurassic sequence stratigraphy of the Danish Central Graben

Jan Andsbjerg and Karen Dybkjær

# Contents

# Abstract

A sequence stratigraphic framework is established for the Jurassic of the Danish Central Graben based primarily on petrophysical log data, core sedimentology and biostratigraphic data from about 50 wells. Regional seismic lines are used to assist in the correlation of some wells and in the construction of isopach maps.

In the Lower Jurassic (Hettangian-Pliensbachian) succession five sequences have been identified. The Middle Jurassic is subdivided into four sequences that together span the latest Aalenian or earliest Bajocian to the Callovian. In the Upper Jurassic, better well coverage permits greater stratigraphic resolution, and 11 sequences are identified and mapped.

On the basis of the sequence stratigraphic correlation and the construction of isopach maps for individual sequences, the basin history of the Danish Central Graben in the Jurassic can be subdivided into seven discrete phases:

(1) Shallow marine and offshore sediments were deposited in a pre-rift basin extending from the North Sea to the Fennoscandian Border Zone (Hettangian-Pliensbachian).

(2) Uplift and erosion took place in association with the Toarcian-Aalenian North Sea doming event. A major hiatus represents this phase in the study area.

(3) Terrestrial and marginal marine sediments were deposited during a rift initiation stage (latest Aalenian or earliest Bajocian-Late Callovian)

(4) Early Oxfordian-Early Kimmeridgian transgression took place during rift climax. The sedimentary environment changed from coastal plain and marginal marine to fully marine.

(5) Regression and renewed transgression took place in the Late Kimmeridgian in association with a cessation of subsidence during a structural rearrangement. Shallow to marginal marine sandstones were deposited above an erosion surface of regional extent.

(6) Deep water mudstones were deposited in a composite graben with high subsidence rates during rift climax (latest Late Kimmeridgian-middle Middle Volgian)

(7) Deposition of organic-rich mudstones and turbidite sandstones took place during the late Middle Volgian-Ryazanian. The main basin became more shallow and symmetric and experienced a decreasing rate of subsidence.

A relative sea-level curve is constructed for the Middle-Late Jurassic. It shows good similarity to earlier published, eustatic (global) and relative (North Atlantic area) sea-level curves in the Oxfordian-Early Kimmeridgian, but differs in the Late Kimmeridgian-Middle Volgian interval probably due to the high rate of subsidence in the study area.

# Introduction

The Jurassic deposits in the Danish Central Graben are of particular interest in relation to hydrocarbon exploration, as they comprise units of reservoir sandstones as well as oil- and gas producing source rocks (figs 1, 2). Hydrocarbon discoveries have been made in both Middle and Upper Jurassic sandstones, and a Middle Jurassic reservoir, the Harald Field, is now entering the production phase. The distribution of both reservoirs and source rocks reflects the complex tectonic evolution of the area and a depositional history strongly influenced by relative sea-level changes.

Data from a large number of wells in the study area have been released in recent years contributing important new information to this study. The aim of the study is to produce a complete and fully updated sequence stratigraphic model for the Jurassic deposits of the Danish Central Graben. The application of sequence stratigraphy has makes it possible to construct a genetically-based model of much higher resolution than previous models.

# Regional geology

The Central Graben forms the southern part of the North Sea rift system. Active rifting took place in this area both in the Triassic and in the late Middle Jurassic-Late Jurassic time (Ziegler, 1990; Roberts et al. 1990).

The 500 km long Central Graben, approximately 150 km of which are situated in the Danish North Sea sector, consists of a NNW-SSE trending complex of half-grabens, and a minor N-S trending segment to the south extending into the German and Dutch sectors. The main bounding fault in the Danish sector is the Coffee Soil Fault, which forms the eastern margin of the Danish Central Graben (fig. 2).

The Early Jurassic was characterized by a slow relative sea-level rise and deposition of marine mud of the Fjerritslev Formation, probably over most of the Danish area (fig. 3)(Larsen, 1966; Michelsen, 1978, 1989; Michelsen et al., 1987; Pedersen, 1986).
In latest Early Jurassic-earliest Middle Jurassic time the whole area was uplifted and most of the Lower Jurassic section was removed by erosion (Hallam and Sellwood, 1976; Ziegler, 1982, 1990; Underhill and Partington, 1993). The uplift occurred in response to the development of a rift dome extending 700 in a north-south direction and 1000 km east-west across the central North Sea (Ziegler, 1990; Underhill and Partington, 1993). Domal uplift was accompanied by the development of a volcanic complex at the triple junction between the Viking Graben, Central Graben and Moray Firth Graben (Ziegler, 1990). Sedimentation was resumed in the Danish part of the Central Graben during the Middle Jurassic with deposition of the sandstone dominated Bryne Formation and Central Graben Group, that are restricted to the Søgne Basin, Tail End Graben and Salt Dome Province(NAM and RGD,1980; Vollset and Doré,1984; Jensen et al.,1986). The first marine transgression in the Danish Central Graben occurred during the Callovian-Oxfordian, probably reflecting the onset of domal collapse combined with eustatic sea-level rise (Ziegler, 1990; Underhill and Partington, 1993).

During Late Jurassic time the Feda Graben, Heno Plateau and Gertrud Graben became actively subsiding depositional basins, and the depositional area was later extended to the Outer Rough and Ål Basins (fig. 2).

Deep-water conditions were established in the Central Graben during the Oxfordian-Kimmeridgian, when the marine mudstones of the Lola Formation were deposited. During the Late Kimmeridgian shallow marine sandstones of the Heno Formation were deposited on plateau areas. Transgression culminated during the Volgian with deposition of the deep marine mudstones of the Farsund Formation (Vollset and Doré,1984; Jensen et al.,1986). The Early Cretaceous saw a change to more passive thermal subsidence (Roberts et al., 1990).

Basin development in the Central Graben was, in addition to the influence of rift tectonics, also strongly influenced by the presence of mobile Zechstein salt. Salt movements had a profound influence on the development of depocentres in the Søgne Basin, Tail End Graben and the Salt Dome Province (Korstgård et al., 1993; Sundsbø and Megson, 1993).

# Stratigraphic methods

The stratigraphic analysis is based on data from about 50 wells, i.e. all released wells that penetrate Jurassic deposits in the Danish Central Graben, and a few wells from the Norwegian North Sea sector located near the boundary (fig.2). Well-logs, including gamma ray, sonic, neutron/density and resistivity logs, sedimentological core logs, lithology logs, and biostratigraphic data were used in the study. Furthermore, a number of interpreted regional seismic lines were included to support the generation of isopach maps.

## Biostratigraphy

The biostratigraphic data used in the present study are confined to palynological data, because in most wells information from other groups of microfossils are too scarce to be useful for detailed correlation. The biostratigraphic correlations are based on events rather than recognition of chronozones. The events used in our study are mainly last occurrence datums (=first downhole appearance) of dinoflagellate cyst species (tab. 1 a-c).

The biostratigraphic information utilized in the study includes published data (Birkelund et al. 1983, Hoelstad 1986, Poulsen 1986, 1991, Heilmann-Clausen 1987, Johannessen et al., 1996), unpublished reports of the Geological Survey of Denmark and Greenland (GEUS), and of industrial service companies and the results of new analyses made specific for this study.

Due to poor core coverage generally restricted to sandy successions of relatively few wells, most data were derived from cuttings samples. Although sample quality in the Lower Jurassic succession was variable, it was possible to establish a palyno-stratigraphic framework based on a small number of events and stratigraphically diagnostic palyno-assemblages (tab. 1a; appendix 1). A detailed palynostratigraphical subdivision of the Middle Jurassic succession is precluded due to the sparse occurrence of age-diagnostic palynomorphs (tab. 1b). A few recordings though, made it possible to give an approximate age of the sequences and major events in the Middle Jurassic. In the Upper Jurassic the large sediment thicknesses, the somewhat better data quality, the favourable environment, and the higher diversity of dinoflagellate cyst species probably all contributed to a higher biostratigraphic resolution (tab. 1c).

## Sequence stratigraphy

The sequence stratigraphic terminology applied is that introduced by the EXXON group (e.g. Posamentier et al. 1988; Posamentier and Vail 1988; Van Wagoner et al. 1988, 1990).

Sequences are subdivided into the lowstand, transgressive and highstand systems tracts. A four-fold subdivision with a forced regressive systems tract like the one suggested by Hunt and Tucker (1992) is not attempted due to the scale of the study.

Construction of the sequence stratigraphic framework is based on correlation of well log patterns, combined with biostratigraphic datings. The most conspicuous log-patterns, supported by the most important biostratigraphic events, are used to produce a coarse grid, within which more detailed correlations were made. Most commonly the gamma ray logs are used for high-resolution correlations, but in some organic-rich mudstone units resistivity-logs are the primary tool for this work. Distinct sonic-log markers are occasionally used for correlations. Maximum flooding surfaces (MFS) are considered the most reliable correlation surfaces in successions dominated by marine mudstones, whereas sequence boundaries (SB), and occassionally flooding surfaces (FS), are of primary importance in silty and sandy units. Both SB and MFS-types of key surfaces can normally be traced through most of the basin. In sections dominated by marine mudstones and siltstones the SB is usually picked at the inflection point between an upward coarsening and an upward fining unit or at the sharp base of a relatively coarse-grained bed occupying the position of the inflection point.

Well logs are a primary tool for the identification of lithologies, sedimentary facies and sedimentary successions, and thus for the identification of key-surfaces and systems tracts. The cored units have been the subject of more detailed sedimentological facies analysis and palynofacies investigations (Hoelstad 1986; Johannessen and Andsbjerg 1993; Johannessen et al. 1996; Andsbjerg this volume; Ineson et al. this volume; Johannessen this volume); these results have been used to support the sequence stratigraphic subdivision.

The Lower Jurassic succession shows laterally consistent log patterns and where a unit has not been removed by erosion correlation of key surfaces is possible over wide areas.

In the Middle Jurassic, only two or three key surfaces can be correlated from one sub-basin to another. A more detailed, four-fold sequence subdivision of the Middle Jurassic deposits within the Søgne Basin is presented by Andsbjerg (this volume).

The laterally uniform log patterns of most of the Upper Jurassic succession allow detailed well correlations. Besides the gamma ray log, the resistivity logs prove very efficient for high-resolution correlations in the Lower Volgian succession of the southern Feda Graben and northernmost Heno Plateau. Most key surfaces in the Upper Jurassic succession are picked in marine mudstones and siltstones. Of these key surfaces only one sequence boundary showes any sign of significant erosion. Most other sequence boundaries may represent type 2 sequence boundaries (Van Wagoner et al. 1988).

Unusually high organic contents in the Upper Volgian-Ryazanian mudstones of the Hot Unit (Jensen et al., 1986) probably influences log responses and impede sequence stratigraphic interpretation (see further Ineson et al., this volume). In the uppermost sequence of this study, Ryaz-1, a maximum flooding surface is not identified. It might have been picked at the highest gamma-ray peak in accordance with conventional sequence stratigraphic concepts, but in this case all of the Hot Unit may form part of the transgressive systems tract as suggested for this type of deposits by Posamentier and James (1993). The top of the Farsund Formation marks the top of the studied succession. In those wells where the upper part of the Farsund Formation is preserved it is dated as Late Ryazanian.

# Sequence stratigraphic subdivision and basin history

The Jurassic succession in the Danish Central Graben is subdivided into 20 sequences. A definition of each sequence appears in appendix 1. The names of the sequences refer largely to their age, e.g. Hett-1 (Hettangian).

The identified sequences are of approximately the same order of thickness. Due to variations in subsidence rates the duration of the sequences recognised in the Lower and Middle Jurassic is somewhat longer than for the Upper Jurassic sequences. All sequences, however, probably correspond to 3rd order sequences as defined by Vail et al.(1977) and Van Wagoner et al.(1990).

The evolution of the Danish Central Graben can be considered in terms of seven depositional phases on the basis of the subdivision of the Jurassic deposits into sequences and systems tracts. The significant influence of tectonics on depositional patterns in rift-settings suggests that these depositional phases show a relationship with rift stages in the studied basins (e.g. Surlyk and Clemmensen, 1983; Rosendahl, 1987; Gabrielsen et al., 1990; Prosser, 1993 and Nøttvedt et al., 1995). Other factors such as eustasy, regional tectonics and climate had also an influence on deposition, and the depositional phases described below do not exhibit a one to one relationship with the tectonic episodes.

The nomenclature and subdivision of rifting phases introduced by Prosser (1993) and adapted by Nøttvedt et al.(1995) are used in the attempt to relate the depositional phases of the present study to rifting stages. The proto-rift stage is characterised by flexural subsidence and interrupted by domal uplift; the rift initiation stage associated with fault block compartmentalisation and weak tilting; the rift climax stage with maximum rate of fault displacement and strong tilting; the early post-rift stage, activity at main faults ceases and rate of regional subsidence decreases.

In the present study several pulses of active faulting are observed to have taken place between the late Middle Jurassic rift initiation stage and the late Late Jurassic - early Early Cretaceous early post-rift stage. We have followed Surlyk (1978, 1989) and Blair and Bilodeau (1988) in correlating overall upward fining successions with periods of active tectonic subsidence, and large-scale upward coarsening successions with periods of relative tectonic quiescence.

## Phase 1. Pre-rift shallow marine deposition (Hettangian - Pliensbachian. Sequences Hett-1 to Pliens-2)

The Early Jurassic was a tectonically quiescent period between phases of active rifting in Triassic and in Middle and Late Jurassic time (Cartwright, 1991; Nøttvedt et al., 1995). A eustatic rise in sea-level during the Early Jurassic was proposed by Hallam (1981) and Haq et al. (1988), compatible with observations from the Danish Basin (Michelsen, 1978; 1989; Pedersen, 1986; Dybkjær, 1988; 1991). Uniform lithologies, dominated by shelf mudstones indicate that marine conditions existed across a major North Sea Basin and extended into the Danish Basin (Michelsen, 1978, 1982, 1989; Michelsen et al., 1987; Pedersen, 1985; Nielsen, this volume).

The Lower Jurassic marine mudstones within the study area have only been found in the Salt Dome Province. They were probably deposited over a wider area, but were removed by erosion during the regional uplift phase (phase 2) at the Early-Middle Jurassic transition (Andersen et al., 1982; Gowers and Sæbøe, 1985; Underhill and Partington, 1993). The extent of Lower Jurassic deposits into these areas is unknown due to the lack of wells penetrating the base of the Middle Jurassic in the deepest parts of the Tail End Graben and Søgne Basin.

Five transgressive-regressive cycles, corresponding to the sequences Hett-1 - Pliens-2 are identified in the Lower Jurassic succession (e.g. Edna-1 and Deep Gorm-1, fig. 4). Individual sequences show a remarkably lateral consistency in thickness (fig. 4), indicating a uniform subsidence history in the study area during most of the Early Jurassic.

## Phase 2. Uplift and erosion in the proto-rift phase (latest Pliensbachian - Aalenian)

A major unconformity separates Lower Jurassic deposits from the overlying Middle and Upper Jurassic deposits over much of the North Sea area. It has been suggested, that the formation of this unconformity was caused by domal uplift in the Toarcian to Aalenian, centred at the triple junction between the Viking Graben, the Moray Firth Basin and the Central Graben (Hallam and Sellwood, 1976; Ziegler, 1982; Underhill and Partington, 1993). The unconformity is an example of a proto-rift unconformity, described by Nøttvedt et al. (1995) as being typical of rift systems with thermally-induced domal uplift before or at the onset of active stretching.

As a result of the regional uplift most of the Lower Jurassic deposits were removed by erosion. In the southern part of the Danish Central Graben, where Lower Jurassic deposits are preserved, differential erosion of the upper part of the succession may be due to local salt tectonics. Regional erosion caused a larger part of the succession to be removed over the top of the salt structures. The full Lower Jurassic succession shows thickness variations from about 60 m in U-1 to about 260 m in Edna-1 (fig. 4).

Reworked Lower Jurassic palynomorphs recorded from the Upper Kimmeridgian sandstones of the Heno Formation in the northern part of the Danish Central Graben (Gwen-2) (Johannessen et al. 1996) supports the assumption that Lower Jurassic deposits were significantly more extensive prior to mid-Jurassic erosion.

## Phase 3. Terrestrial and marginal marine deposition during the rift initiation stage (latest Aalenian or earliest Bajocian-Late Callovian. Sequences Aalen-1 - Cal-1)

Deposition of terrestrial sediments was resumed in the Danish Central Graben during the latest Aalenian or earliest Bajocian after the regional uplift and possible incipient collapse of the domal structure. Subsequent Middle Jurassic deposits rest unconformably on pre-Jurassic and Lower Jurassic sediments (fig. 4).

The initiation of syn-rift subsidence during this phase is shown by seismic evidence, which demonstrates an asymmetric distribution of the sediment package in the Søgne Basin and the Tail End Graben (Møller, 1986, his fig. 5; Cartwright, 1987; Korstgård et al., 1993, their figs 39, 40). The asymmetric distribution of sedimentary facies and thickness variations of sequences in the Søgne Basin suggests that this took place during the Bajocian (Andsbjerg, this volume). Salt-tectonics also influenced sediment distribution and location of local depocentres in both the Søgne Basin, the Tail End Graben and the Salt Dome Province (Mogensen et al., 1992; Korstgård et al., 1993).

Middle Jurassic deposits are preserved in the Søgne Basin, Tail End Graben and Salt Dome Province with a depocentre located to the east near the Coffee Soil Fault (figs 4,5). Sand and mudstones of sequences Aalen-1 - Bat-1 were deposited in a fluvially dominated environment with large and small rivers and large areas dominated by overbank deposits during the early part of the Middle Jurassic (latest Aalenian or earliest Bajocian - Late Bathonian)(fig. 6A). Deeper parts of the basins were periodically inundated by lakes. Lacustrine conditions in central parts of the basins normally corresponds to wet floodplain conditions in marginal locations.

The occasional presence of rare marine palynomorphs and tidal indicators such as flaser bedding and double mud-drapes suggest that deposition took place in a coastal plain setting. However, during this period, fully marine conditions are only reported from the Dutch part of the Central Graben (van Adrichem Boogaert and Kouwe, 1993). A coastline must therefore have been located in the southern part of the Danish or in the German Central Graben. The regional transport direction in the Danish Central Graben was probably towards the coastline in the south, parallel to the basin axis.

Within the Middle Jurassic succession several levels of well developed, erosionally-based channels, prograding deltas and splays, and lacustrine and floodplain mudstone units form correlatable units over a wide area comprising the Søgne Basin and the Tail End Graben. This suggests a common, external control on base level, such as rift tectonics, eustatic sea-level change, climate change or a combination of these.

In the Søgne Basin, northern Tail End Graben, and possibly in the Salt Dome Province, the deposits of the Aalen-1 to Bat-1 sequences are cut by a significant erosion surface, the basal sequence boundary of Cal-1 (see fig. 5). The development of this surface was caused by a major fall in relative sea-level. At the time of formation of this surface the regional slope had changed from a southward to a northward dip (Andsbjerg, this volume). The erosional surface, which is commonly developed at the base of extensive fluvial or estuarine channel-sandstones, is the bounding surface of an incised valley. The valley fill is dated to the latest Late Bathonian-Early Callovian. In the Søgne Basin, the channel-sands were initially deposited in straight or sinuous rivers, which show an increase in tidal influence with time. In the Salt Dome Province, channel-sandstones occur as stacked or single, either as upward fining units typical of sinuous channel fills or showing blocky gamma ray patterns that may indicate deposition in a straight or braided river (see fig. 4, U-1 and John Flank-1)(Koch, 1983). The incised valley fill of the Søgne Basin is capped by a coal bed, up to 3 m thick.

Later in the Callovian, a low-energy coastal plain or delta plain characterised by small distributary channels, lagoons and coal swamps, was established in the southern part of the study area (Koch, 1983). Contemporaneously a barrier coast separated tidal lagoons at the margins of the Søgne Basin and northern Tail End Graben from a wave-dominated marine bay in the central and eastern parts of these basins (fig. 6B).

## Phase 4. Transgression and first pulse of the rift climax stage (Early Oxfordian to Early Kimmeridgian. Sequences Cal-1 - Kimm-1)

In the Tail End Graben subsidence along the Coffee Soil Fault began to accelerate in the Early Oxfordian resulting in a very asymmetric distribution of the Oxfordian to Lower Kimmeridgian sediment package and in very large thicknesses of sediments in the central and eastern parts of the Tail End Graben (figs 7, 8A). This suggests that the Tail End Graben had entered the rift climax stage. In the Søgne Basin the rate of subsidence did not increase until the Kimmeridgian. During this phase fault-controlled subsidence in the Danish Central Graben mainly occurred along north-south trending faults (Møller & Rasmussen, this volume).

The Early Oxfordian-Early Kimmeridgian succession is strongly influenced by an overall transgressive development, that changed the depositional environment from paralic to fully marine. The transgression was caused by a combination of the increased subsidence rate and a eustatic rise in sea-level documented both from the North Sea rift system and elsewhere (e.g. Hallam, 1978, 1988; Haq et al., 1988; Surlyk, 1990).

Fully marine conditions were established in the Søgne Basin in latest Callovian-earliest Oxfordian time (Cal-1 TST) with the introduction of the shelf mudstones of the Lola Formation. A coastal plain environment probably still dominated parts of the Salt Dome Province to the south, indicating that the Callovian-Oxfordian transgression entered the Danish Central Graben from the north (figs 6B,C).

During the Early Oxfordian also the Tail End Graben, the south-eastern marginal parts of the Heno Plateau, the Salt Dome Province, and the Rosa Basin were transgressed (Ox-1, Ox-2, figs 6C; 7; 8B,C). The remaining parts of the Heno Plateau and possibly areas farther west were slowly inundated during the Late Oxfordian-Early Kimmeridgian (Kimm-1, figs 9, 10A). Marginal marine sandstones were deposited locally on the southern part of the Heno Plateau during this transgression (e.g. Elly-2, fig. 9), but in most of the basin marine mudstones of the Lola Formation were deposited. A number of minor transgressive-regressive cycles can be discerned within the overall transgressive succession of marine mudstones (e.g. Nora-1, fig. 7). The main basinal part of the study area was thus characterised by an offshore environment during this period. A coast-near shelf environment developed, however, on the Gertrud Plateau and the northern part of the Heno Plateau at the end of this depositional phase (fig. 11A).

## Phase 5. Shallow to deep marine deposits and changing structural patterns (Late Kimmeridgian. Sequences Kimm-2 - Kimm-3)

The basin configuration changed significantly during the late Early Kimmeridgian-Late Kimmeridgian. Fault activity and fault-related subsidence decreased to a stillstand, and at the end of the period a new pattern of dominantly NNW-SSE trending faults was established (Møller and Rasmussen, this volume). This development marked a pause between two rift pulses. At this time the Tail End Graben, including the Søgne Basin and most of the Heno Plateau, comprised one major, half-graben basin with an eastward dipping hanging-wall slope. Passive subsidence took place in the Feda Graben during this phase. The Feda Graben was separated from the Tail End Graben by a transfer zone (fig. 10B).

The cessation in rift-related subsidence at the beginning of this phase probably combined with a regional fall in sea-level caused a significant relative sea-level fall. This sea-level fall caused the development of a distinctly erosional sequence boundary traceable over most of the Danish Central Graben (figs 7 and 9). The sequence boundary (the base Kimm-2 SB) is probably a type 1 sequence boundary (Van Wagoner et al., 1988), which can be seen on seismic sections as an onlap surface (Møller and Rasmussen, this volume).

The succeeding transgression, caused by eustatic or regional sea-level rise and differentiated passive subsidence, gave rise to a gradual flooding of the Heno Plateau, the southern part of the Feda Graben and the Gertrud Plateau area. Two higher-order sea-level cycles can be recognised during this overall transgression. During the first of these the Kimm-2 sequence and during the second the Kimm-3 sequence were deposited. While marginal areas were characterised by deposition of sand in shallow marine to paralic environments, low-energy marine conditions prevailed in the deeper parts of the basin during the Kimm-2 cycle (fig. 11B). Sand was deposited in a high energy shoreface environment on the southern part of the Heno Plateau and in a back-barrier environment on the northern part of the Heno Plateau and in the Gert area (Johannessen et al., 1996; Johannessen, this volume). The flooding of the Heno Plateau area forced the coastline back from its position near the eastern margin of the plateau at the beginning of the transgression to the western margin of the Heno Plateau or possibly farther west at the time of maximum flooding. Subsequently the shallow areas in the western part of the basin were separated from the marine basin to the east by a zone of sand-dominated prograding shoreface. The coastline was re-established in a position at the eastern edge of the Heno Plateau at the end of this cycle (fig. 11C).

At the beginning of Kimm-2 the relatively low accommodation space in the marginal areas, such as the Heno Plateau, the southern Feda Graben and the Søgne Basin, was rapidly filled with deposits of the LST and TST, before maximum flooding was attained (e.g. Gert-2, Falk-1, fig. 9). A relatively thick TST was deposited in the Feda Graben due to a rapidly subsiding basin floor.

After the time of maximum flooding most available accommodation space occurred in the central parts of the Tail End Graben. Here a thick HST was deposited (e.g. G-1, fig. 9). The shallow areas in the western part of the basin probably lacked accommodation space during most of this period.

By the end of the first sea-level cycle (Kimm-2) depocentres were almost completely filled, leading to a rather smooth topography; this resulted from the decreasing rate of subsidence in combination with high sediment input (fig. 10C).

The Kimm-3 sequence is characterised by uniform sediment distribution without major depocentres in the study area except for the Feda Graben. The thickest sediment package outside the Feda Graben is present along the eastern and southern margins of the Heno Plateau and in the central parts of the Salt Dome Province (fig. 10C).

Coarse-grained conglomeratic shoreface deposits were deposited right above the sequence boundary on the Heno Plateau (Johannessen, this volume). These deposits were overlain by backstepping parasequences of shallow marine sand and silt (e.g. Ravn-1, Falk-1, fig. 7). In basinal settings of the Feda Graben a change from coarse to fine-grained shallow-marine deposits took place gradually, whereas an abrupt shift from shallow-marine sandstone to offshore mudstone can be seen in marginal areas of the Feda Graben and on the Gertrud Plateau (fig. 9).

When fully marine conditions were established in the Feda Graben, a very high rate of subsidence in this area impeded the re-establishment of paralic conditions during the highstand part of the cycle. In the Tail End Graben and Søgne Basin the Kimm-3 sequence consists of a thin unit of marine mudstones.

The accommodation space at the beginning of Kimm-3 was limited by an initial sea-level fall and a small rate of subsidence. The small accommodation space available was filled mainly by deposits of the TST in most of the basin (fig. 9). Only in the northeastem part of the area was there sufficient accommodation space for the development of HST-successions (e.g. Cleo-1, Amalie-1, fig. 12). On most of the Heno Plateau and on the southern part of the Gertrud Plateau the small remaining accommodation space was filled with HST deposits followed by exposure and bypass.

## Phase 6. Deep water mudstones in a composite graben; rift pulses and passive subsidence (latest Late Kimmeridgian-middle Middle Volgian. Sequences Kimm-4 - Volg-3)

In this depositional phase the occurrence of rift pulses is reflected by syn-rift successions with fining upward log patterns separated by successions with overall coarsening upward patterns (cf. Surlyk, 1978). A rift pulse in Late Kimmeridgian time is indicated by the assymmetric sediment distribution of the Kimm-4 deposits in the Tail End Graben (fig. 14A). Another pulse in the earliest Early Volgian is reflected by log patterns in the lower part of Volg-1 sequence (e.g. Gert-4, G-1 fig. 9) and seen on seismics in the Tail End Graben (Møller and Rasmussen, this volume). A further rift pulse in the Early Volgian is interpreted from the abrupt change from low to high gamma ray values right below the Volg-2 MFS coinciding with an onlap surface seen on seismic sections from the Tail End Graben (Møller and Rasmussen, this volume).

The Tail End Graben and Heno Plateau acted initially as one major asymmetric basin, with an elongate, northwest-southeast oriented depocentre located in the Tail End Graben. This depocentre was during the Early Volgian extended into the eastern part of the Søgne Basin, where subsidence increased significantly (figs 14 A,B). Also the Feda Graben was an important depocentre. The Outer Rough and Ål Basins had become actively subsiding basins at the time of deposition of the Volg-2 sequence (figs 14C,15). Later during this phase increased fault activity initiated the generation of several minor subbasins, e.g. the Arne-Elin Graben, which became a distinct depocentre in the early Middle Volgian during deposition of the Volg-3 sequence (figs 14C, 16A).

Plateau areas, covered by Heno Formation sandstones were drowned and an upward fining succession of marine siltstones and mudstones of the Farsund Formation was deposited. Thin storm- or gravity-derived sandlayers were occasionally deposited in the Søgne Basin (figs 15,17A).

During the Early Volgian also the Outer Rough and the Ål basins were transgressed, and fully marine conditions were established (figs 15,17B). Shoreface sands were deposited at the western margin of the Outer Rough Basin as documented by data from the British part of the Central Graben (Mackertich, 1996).

## Phase 7. Organic-rich mudstones and basin axis turbidites (late Middle Volgian-Ryazanian. Sequences Volg-4 - Ryaz-1)

The rate of subsidence decreased in the Tail End Graben and the Salt Dome Province during this phase resulting in stratigraphic condensation. According to the time-scale of Haq et al. (1988) the succession deposited during phase 7 represents a period of 5-7 mill years, equal to the time represented by the 2-10 times thicker succession of phase 6.

Fault activity ceased along large segments of the main boundary fault, and this caused the geometry of the Tail End Graben to change from an asymmetric rift to a more symmetric saucer-like shape with a relatively uniform sediment distribution (fig. 16B). These changes probably indicate the beginning of an early post-rift stage for the Tail End Graben. Minor depocentres continued to exist in the northern part of the Tail End Graben and in the Arne-Elin Graben. Subsidence continued in the Feda Graben and in the Outer Rough Basin.

The deposits of phase 7 consist of marine shales of the Farsund Formation. They generally show a gradual increase in gamma ray and TOC values culminating in the Hot Unit in the uppermost part of the Farsund Formation (figs 15, 18) (Jensen et al., 1986; Ineson et al., this volume).

Below the Hot Unit a well developed sequence boundary separates the Volg-4 and Ryaz-1 sequences. This sequence boundary is strongly erosional in most wells on the northern part of the Heno Plateau and along the southern margin of the Feda- and Gertrud Grabens (e.g. Jeppe-1, fig. 15). Above the sequence boundary sandstones are present in a number of wells along the basin axis of the Tail End Graben and Gertrud Graben (figs 17,18). The sandstones occur as turbidite sandstones (Iris-1) and debris flows (Jeppe-1) and may have originated from a number of sources, e.g. the East North Sea Block of the Ringkøbing-Fyn High, the Mandal High and the Gert Ridge (Nielsen, 1985; Ineson et al., this volume). Their occurrence may be related to changed drainage patterns in the hinterland, after subsidence had ceased along large parts of the main boundary fault and to erosion of inverted structures or crests of rotated fault blocks.

The high organic content in the mudstones of the Hot Unit was a result of oxygen deficiency in bottom waters of a stratified water-mass (Tyson et al., 1979). This condition was induced by coincidence of several contributory factors, among others: climatic shift from humid to arid conditions, sea-level fluctuations in combination with a tectonically induced complex topography (Tyson, 1987; Doré, 1991; Hallam et al., 1991). Development of the Hot Unit and the contributing factors is discussed in detail by Ineson et al. (this volume).

# Relative sea-level changes

A relative sea-level curve is constructed for the Middle - Late Jurassic time interval (fig. 19). It is compared with eustatic curves proposed by Haq et al. (1987) and Hallam (1988) (North Sea and global data) and relative sea-level curves of Surlyk (1990) (East Greenland data) (fig. 20). The Lower Jurassic is only penetrated by wells in a minor part of the study area, and no attempt has thus been made to construct a sea-level curve for this part of the succession. Data are lacking from the Toarcian and probably most of the Aalenian due to the hiatus caused by the regional base uppermost Aalenian-lowermost Bajocian unconformity. In the remaining part of the Middle Jurassic succession good biostratigraphic datings become available from the latest Bathonian-Callovian and upwards; construction of a sea-level curve thus has its starting point at this level. Wells from basin-central and intermediate positions were preferably chosen to supply data for construction of the curve.

The relative sea-level changes are interpreted mainly on the basis of lithology changes (e.g. changes in mud content in marine sediments) reflecting bathymetrically related changes in energy level. Lithology changes are interpreted on the basis of well log patterns and seen in cores. Also sedimentary facies and palynofacies, and the extent of marine flooding surfaces have been used.

High organic contents in marine mudstones cause large deflections on the well logs, thus hampering the lithological interpretation. For that reason sea-level interpretations were not attempted in the Hot Unit.

The coastal plain deposits of latest Bathonian-earliest Callovian age were transgressed during the Callovian-earliest Oxfordian in most of the Danish Central Graben. A relative sea-level rise caused a rapid, step-wise transgression that expanded the basin laterally and drowned previous sediment sources. The sea-level rise and transgression continued throughout the Oxfordian and culminated in the Early Kimmeridgian. This development, from the latest Bathonian to the late Early Kimmeridgian, is almost identical to the sea-level curves of Haq et al. (1987, 1988) and Hallam (1978, 1981, 1988) based on North Sea and global data and by Surlyk (1990) for East Greenland. The gradual collapse of the North Sea Dome (Hallam and Sellwood, 1976; Ziegler, 1982; Underhill and Partington, 1993) and the initiation of rifting in the Danish Central Graben may have influenced the transgressive trends during this period. However, the resemblance between the relative sea-level curve of this study and the curves of Haq et al. (1988), Hallam (1988) and Surlyk (1990) may indicate that a common causal factor of super-regional or global extent also influenced sea-level changes during this interval.

The uppermost Lower Kimmeridgian-Upper Kimmeridgian of the Danish Central Graben is characterised by a double lowstand peak. The other sea-level curves are close to their maximum at this level. The lowstand in the Danish Central Graben probably evolved as a result of a sea-level fall during a pause in rift induced subsidence (phase 5).

After the lowstand event the Late Kimmeridgian-late Middle Volgian interval shows an overall rise in relative sea-level, interrupted by a number of minor falls. This overall trend differs from the fall seen in most of the other sea-level curves. The difference is probably a result of the continued high subsidence rate in the Danish Central Graben, which neutralised the effect of the global sea-level fall indicated by the other curves. The minor, relative sea-level falls in the interval may reflect pauses between periods of active subsidence.

# Lithology prediction

An important reason for undertaking a sequence stratigraphic study of a hydrocarbon-producing basin is to improve lithology and reservoir prediction. The predictive potential in syn-rift units is much less than in post-rift units. This is due to the problems for orderly sediment dispersal caused by the creation of tilted fault blocks and sub-basins, the continuous presence of accommodation space on the lower hanging-wall slopes of tilted fault blocks, and by the local supply of sand from erosion of uplifted footwall shoulders. However, in the Middle to Upper Jurassic syn-rift deposits of the Danish Central Graben the sandstone units seem to show a systematic distribution, which may be related to the combination of sea-level changes and periods of little tectonic subsidence.

The Bathonian-Callovian sandstones, that are widely distributed in the Søgne Basin, Tail End Graben and Salt Dome Province, result from a generous supply of sand from the North Sea Dome area and a relatively low and only slowly increasing accommodation space in the rift-initiation stage. The best reservoir sandstones occur in the lowstand and transgressive systems tracts of the Baj-1, Bat-1 and Cal-1 sequences (figs 4,5), where laterally extensive fluvial channel sandstones occur across the basin; and as tidal and shoreface sandstones in the uppermost part of the sandstone unit deposited prior to the final transgression (Cal-1 sequence). The desirable combination of large fluvial and tidal channels and extensive wave-reworked sandstones occur in the deeper parts of the Søgne Basin and the Tail End Graben. In these areas subsidence seem to have been sufficiently fast to create accommodation space for successions of wave-influenced sediments up to 30 metres thick during the final Middle Jurassic transgression (Andsbjerg, this volume).

An overall transgressive development is interpreted for the Late Jurassic. The largest concentration of reservoir sandstones in this succession, the Heno Formation, was deposited during a pause in the otherwise rapid subsidence. The sand is concentrated on the Heno Plateau, Gertrud Plateau and on the southern margin of the Feda Graben. The Heno Plateau constituted an upper hanging-wall slope of a major half-graben, the Tail End Graben; and the Gertrud Plateau probably comprised the transfer zone between the Tail End and Feda Grabens (figs 7,9). Possible source areas for the sandstones were to the north-east, where the Ula and Bryne Formation sandstones were located, and to the west, on the Mid North Sea High (figs 11B,C). Fluvial systems and/or marine current and wave-activity may have facilitated sediment transport to the Gertrud and Heno Plateaus. A similar scenario is envisaged by Howell et al. (1996) for the UK South Central Graben.

The turbidite and debris flow sandstones of the Upper Volgian-Ryazanian constitutes potential reservoirs (fig. 18). The main part of the sands were deposited during depositional phase 7, when subsidence had decreased, and parts of the Danish Central Graben had broken up into fault bounded sub-basins. Inactivity of some Coffee Soil Fault segments (Møller and Rasmussen, this volume) may have increased the drainage area in the marginal hinterland and opened new sediment transport routes, causing an increased sand supply. Sediment dispersal in the receiving basin was still hampered by a topography dominated by tilted fault blocks and many small sub-basins. The most extensive sandstones are present right above the Ryaz-1 basal sequence boundary.

Sandstones have not been encountered in the few wells drilled in the Danish part of the Outer Rough and Ål Basins. However, the presence of Volgian reservoir sandstones of a type similar to the Heno Formation is reported from wells nearby in the UK sector (Mackertich, 1996).

# Basin asymmetry of the rift climax stage reflected in depositional patterns

Correlatable log patterns commonly show a significant variability between closely spaced wells, whereas wells located far apart may show a good similarity of log patterns.

Wells within the same subbasin can in many cases be correlated over relatively long distances parallel to structural strike (e.g. 25 km from Gwen-2 to Ravn-1, for the lower part of the Farsund Formation, fig. 9). Along dip, closely spaced wells such as Ravn-1 and Ravn-2, only 4 km apart, show quite different log patterns in the Farsund Formation, although correlation of the most important key-surfaces is possible (fig. 7). The differences in correlability are caused by the influence on depositional patterns from differential subsidence associated with half-graben development.

# Conclusions

Application of sequence stratigraphic methods has improved both the stratigraphic resolution of the Jurassic deposits in the Danish Central Graben and the understanding of the basin development during the Jurassic Period. This study may hopefully form the basis for further work, both local and regional basin studies and for exploration purposes. It is important that the results of this study are integrated with 3-D seismic data; in particular in areas with poor well coverage. The depositional history of the Danish Central Graben in the Jurassic shows a relationship to contemporaneous rift stages and to relative and eustatic sea-level changes. The basin development in the Jurassic is subdivided into seven depositional phases.

### Phase 1 (Hettangian-Pliensbachian)

During phase 1 pre-rift marine mudstones were deposited in a stable epicontinental sea, that stretched across a major part of the North Sea region. The deposits were removed from large parts of the central North Sea region by subsequent erosion (phase 2).

### Phase 2 (latest Pliensbachian-latest Aalenian or earliest Bajocian)

Phase 2, corresponding to the tectonic proto-rift stage, was characterised by domal uplift and regionally extensive erosion.

### Phase 3 (latest Aalenian or earliest Bajocian-Late Callovian)

The Middle Jurassic sandstones owe their presence to erosion of the North Sea dome, and to slow accommodation-space generation during the rift initiation phase. Subsidence rates increased in the Callovian and Oxfordian at the beginning of the rift climax stage. This resulted in marine flooding and cessation of sand deposition.

### Phase 4 (Early Oxfordian-Early Kimmeridgian)

In the Oxfordian-Early Kimmeridgian the Tail End Graben entered the rift climax stage resulting in the development of a half-graben. Marine mudstones were deposited during this phase.

### Phase 5 (Late Kimmeridgian)

Extensive sand deposition took place in the early Late Kimmeridgian during a halt in subsidence between two rift pulses. Sand was deposited in a large area with low accommodation space, which was created on the hanging-wall plateau. Exposed highs and land areas outside the graben supplied the sand. Due to the decrease in subsidence in the Tail End

Graben input of fine-grained sediment could catch up with accommodation space generation, probably resulting in a flat topography at the end of this phase.

## Phase 6 (latest Late Kimmeridgian-middle Middle Volgian)

During the latest Late Kimmeridgian-middle Middle Volgian renewed rifting caused rapid subsidence in the study area. Several rift pulses occurred during this interval. Due to the high overall rate of subsidence sand-deposition associated with relative sea-level falls did not occur. The Danish Central Graben began to break up into minor subbasins during this phase.

## Phase 7 (late Middle Volgian-Ryazanian)

In the late Middle Volgian-Ryazanian, subsidence decreased in large areas of the basin, which probably had entered an early post-rift phase. Large segments of the Coffee Soil Fault became inactive resulting in a more shallow and symmetric basin. Active subsidence continued in a number of subbasins. The marine shales deposited during this phase were dominated by very organic-rich mudstones at distinct levels. The mudstones are interbedded with turbidite and debris flow sand deposits in some parts of the study area, in particular along the Tail End Graben - Gertrud Graben basin axis and along the eastern margin of the Tail End Graben.

A comparison of the sea-level curve constructed for the Danish Central Graben (fig. 20) and published sea-level curves indicate that deposition in the sometimes very rapidly subsiding rift basin was strongly influenced by tectonics. In the latest Bathonian-late Early Kimmeridgian interval the overall deepening trend is probably influenced both by eustatic rise and by rift-related subsidence. In the remaining part of the Late Jurassic the deepening trend is primarily a result of the high subsidence rate associated with rifting. Most sediments were deposited between rift pulses in accomodation space, that was generated during the rift pulses or by passive subsidence. Only a relatively small part of the sediments were deposited during the rift pulses.

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# Figure captions

**Fig. 1** Location of study area within the Jurassic North Sea rift system

**Fig. 2** Jurassic structural elements in the Danish Central Graben and position of studied wells

**Fig. 3** Jurassic lithostratigraphy of the Danish Central Graben

**Fig. 4** Sequence stratigraphic correlations of the Lower, Middle and lowermost Upper Jurassic in the Salt Dome Province. Lower Jurassic section is truncated by base Middle Jurassic unconformity

**Fig. 5** Sequence stratigraphic correlations of the Middle and lowermost Upper Jurassic in the Søgne Basin and northern Tail End Graben. Unconformity at the base of the Cal-1 sequence truncates underlying sequences

**Fig.6A-C** Palaeogeographic maps representing the Aalenian to Bathonian or earliest Callovian (6A), Early to Middle Callovian (6B), Late Callovian to earliest Oxfordian (6C). The figure illustrates the gradual transition from a terrestrially dominated environment (6A) through a tidally influenced coastal plain (6B)to a fully marine environment (6C). Deposits of the lowermost part of the Middle Jurassic succession may have been present in the western part of the Danish Central Graben, and removed by erosion during hanging wall uplift in association with early half graben subsidence (6A). Due to lack of data the distribution of Middle Jurassic deposits in the Feda Graben is uncertain.

**Fig. 7** Sequence stratigraphic correlations of the Middle Jurassic and Upper Jurassic on the Heno Plateau and in the Tail End Graben. The profile represents the dip-line from the Heno Plateau to the Tail End Graben

**Fig.8A-C** Isopach maps of the Cal-1 (8A), Ox-1 (8B) and Ox-2 (8C) sequences. A progressive transgression can be seen in the Ravn - Elly area on the southeastern part of the Heno Plateau (8A-B)

**Fig. 9** Sequence stratigraphic correlations of the Upper Jurassic from the Feda Graben, across the Heno Plateau, to the southern Tail End Graben. Onlap of the base Jurassic unconformity can be seen on the southern part of the Heno Plateau. The base Kimm-2 sequence boundary exhibits a distinct log break, interpreted as an erosional surface that cuts into underlying marine mudstones in the southern part of the study area. The upper part of the Kimm-3 sequence and possibly the lowermost part of the Kimm-4 sequence onlaps the Kimm-3 flooding surface in the Feda Graben and on the southern Heno Plateau

**Fig.10A-C** Isopach maps of the Kimm-1 (10A), Kimm-2 (10B) and Kimm-3 (10C) sequences. A progressive transgression of the northern Heno Plateau, the Gertrud Plateau and the Feda Graben area takes place from the Late Oxfordian to the earliest Late Kimmeridgian (10A,B). Subsidence of the southern Feda Graben has begun during the latest Early to earliest Late Kimmeridgian. A relatively uniform distribution of sediments with a narrow depocenter along the eastern margin of the Heno Plateau and only a thin section of marine mudstones in the Tail End Graben developed in the Late Kimmeridgian (10C)

**Fig.11A-C** Palaeogeographic maps representing the Late Oxfordian to Early Kimmeridgian (11A), latest Early to earliest Late Kimmeridgian (11B), and Late Kimmeridgian (11C). Transgression continued across the northern Heno Plateau, Gertrud Plateau and Feda Graben areas (see also fig.6C) during the Late Oxfordian-Early Kimmeridgian (11A). After a major regression (SB base Kimm-2) renewed transgression resulted in a change from fully marine to paralic, marginal and shallow marine conditions in the plateau areas (11B,11C).

**Fig. 12** Sequence stratigraphic correlations of the Upper Jurassic in the Tail End Graben. The profile is parallel to the basin axis

**Fig. 13** Sequence stratigraphic correlations of the Upper Jurassic in the Salt Dome Province and the southern Tail End Graben

**Fig.14A-C** Isopach maps of the Kimm-4 (14A), Volg-1 (14B), and Volg-2 (14C) sequences. A depocenter developed in the eastern Søgne Basin during the earliest Early Volgian (14B). The Outer Rough and Ål Basins were transgressed in the Early Volgian (14B-14C)

**Fig. 15** Sequence stratigraphic correlations of the Upper Jurassic in the northern part of the Danish Central Graben. Profile is perpendicular to main structural elements from the Outer Rough Basin in the west to the Søgne Basin in the east. The subbasins were transgressed in a stepwise manner from the east to the west from the Middle Jurassic to the earliest Early Volgian

**Fig.16A-B** Isopach maps of the Volg-3 (16A) and Volg-4 (16B) sequences. Subordinate depocentres developed in the Arne-Elin Graben and in the Outer Rough Basin in the latest Early to middle Middle Volgian (16A). The assymetric half graben geometry of the Tail End Graben became less pronounced during the Middle to Late Volgian (16B)

**Fig.17A-C** Palaeogeographic maps representing the Late Kimmeridgian (17A), earliest Early to Late Volgian (17B), and Late Volgian to Late Ryazanian (17C). A transgression of the Outer Rough and Ål Basins took place in the Early Volgian (17A-17B). Turbidite and submarine fan sandstones were deposited in deep parts of the basin during the Late Volgian to Ryazanian (17C)

**Fig. 18** Sequence stratigraphic correlations of the uppermost Upper Jurassic in the Tail End Graben and Gertrud Graben. Turbidite and fan sandstones are abundant in the Upper Volgian-Ryazanian section

**Fig. 19** Generalized sequence stratigraphic diagram of the Middle and Upper Jurassic succession with a constructed relative sea-level curve for the Late Bathonian to the Middle Volgian. Inset shows the Kimmeridgian Heno Formation sandstones

**Fig. 20** Diagrammatic comparison of constructed relative sea-level curve with sea-level curves of Haq et al.(1987), Hallam (1988) and Surlyk (1990). Figure modified after Surlyk (1990)

**Fig. 21** Sequence definitions of sequences Hett-1 to Pliens-2

**Fig. 22** Sequence definitions of sequences Aalen-1 to Cal-1

**Fig. 23** Sequence definitions of sequences Ox-1 to Kimm-1

**Fig. 24** Sequence definitions of sequences Kimm-2 and Kimm-3

**Fig. 25** Sequence definitions of sequences Kimm-4 to Volg-3

**Fig. 26** Sequence definitions of sequences Volg-4 to Ryaz-1

**Table 1a-c** Bioevents used for dating the sequences defined in the present study. The tie to boreal standard chrons are according to Riding and Thomas (1992), where nothing else is indicated. Otherwise to:

1)Fenton and Riding (1987)
2)Dybkjær (1991)
3)Poulsen (1991)
4)Costa and Davey (1992)
5)Poulsen (1992)
6)Poulsen and Riding (1992)

tie to boreal standard chrons uncertain
occur sporadically up to Anguiformis

## Appendix 1

## Sequence definition

Introductory remarks

Examples of typical log patterns for all the sequences defined in this study are presented in figs 21-26. The expression of sequence boundaries, lithologies and thicknesses of systems tracts, and approximate ages of the sequences are described below.
Lithologies in the sequence descriptions have been interpreted primarily on the basis of gamma ray-logs, supported by other log types and by core data when available. In the sandstone intervals increasing gamma ray values are interpreted as upward fining, and decreasing values as upward coarsening sections. In the mudstone successions changing gamma ray values are interpreted as reflecting changes in clay content. Here increasing gamma ray values are interpreted as increasing clay contents and decreasing gamma ray values as decreasing clay contents. Thin carbonate beds are represented by low-value gamma ray spikes. Mudstone intervals with exeptionally high gamma ray values are interpreted as having an uncommonly high organic content.
Based on the assumed connection between gamma ray values and lithologies as mentioned above, upward increasing gamma ray patterns are generally interpreted as TST-units and upward decreasing gamma ray patterns as HST-units. The MFS is picked at the inflection point between the increasing gamma ray patterns of the TST-unit below and decreasing gamma ray patterns of the HST-unit above.

Hett-1 sequence

The Hett-1 sequence is present only in the Deep Gorm-1, the U-1, and the M-8 wells, and consists of marine mudstones. The lower sequence boundary is located at the change from the low gamma-ray values of the underlying Triassic deposits to the high gamma-ray values, characteristic for the mudstones of the Hett-1 sequence (figs 4, 21). The transition may be abrupt or gradational. The TST is represented by a 7-10 m thick mudstone unit in U-1 and M-8. The HST is an 8-20 m thick mudstone unit. Stratigraphically usefull bioevents have not been recorded from this unit. However, the sequence is thought to be of Hettangian age due to its stratigraphic position in the lowermost part of the Fjerritslev Formation, unconformably overlying Upper Triassic deposits.

Hett-2 sequence

The marine mudstones of the Hett-2 sequence has only been found in six wells but is considered to extend throughout the Salt Dome Province. The sequence boundary between the Hett-1 and Hett-2 sequences is located at a shift to mudstones characterized by somewhat lower clay contents (figs4,21). In the wells where the Hett-2 sequence directly overlies pre-Jurassic sediments (e.g. Edna-1), the lower sequence boundary is marked by an abrupt lithological shift. The TST varies in thickness from about 10-30 m and the HST from 30-90 m.
The abundance of bisaccate pollen of the *Pinuspollenites minimus* within this sequence in the wells O-1, John Flanke-1 and Edna-1 indicate the presence of the *Pinuspollenites - Trachysporites* Zone of Lund (1977). This zone is known from the Danish Basin, Scania and North Germany, and is referred to the Hettangian (Lund, 1977; Dybkjær, 1991). A Hettangian age is further supported by the occurrence of the dinocyst species *Dapcodinium priscum* in the wells mentioned above and the absence of the pollen species *Cerebropollenites macroverrucosus* (tab.1a show the stratigraphic significance of these species).

Sin-1 sequence

The marine mudstones of this sequence are supposed to extend throughout the Salt Dome Province. The lower sequence boundary is typically located at a marked shift to mudstones with higher clay contents (figs 4, 21). The thickness of the TST varies from about 7-55 m and the HST from 10-20 m. Generally the TST is thicker than the corresponding HST.
The last occurrence datum (LOD) of *Dapcodinium priscum* in the lower part of the sequence in the O-1 well, and the first appearance datum (FAD) of *Cerebropollenites macroverrucosus* in core samples from the middle part of the sequence in the Deep Gorm-1 well, indicate a latest Hettangian-Early Sinemurian age for the lower part of the sequence. That, in combination with the LOD of *Liasidium variabile* close to the upper boundary of this sequence in O-1, indicate a latest Hettangian to Sinemurian age for the sequence (tab. 1a).

Pliens-1 sequence

The sequence is only present in Edna-1 and Deep Gorm-1 situated in the northwestern part of the Salt Dome Province. It occur in both wells as marine mudstones.
The lower sequence boundary is located at the top of the well-defined upward coarsening HST of the Sin-1 sequence (figs 4,21). The TST is a 20-30m thick, and the HST a 35-45m thick mudstone interval.
The common occurrence (in sidewall cores) of pollen referred to the genus *Chasmasporites* indicate the presence of the *Chasmasporites* Zone (Koppelhus 1994), defined in the Korsodde section, Bornholm, Denmark. The *Chasmasporites* Zone is referred to the Pliensbachian. A Pliencbachian age is further supported by the stratigraphic position of this sequence immediately above the LOD of *Liasidium variabile*. The acme of the small, spherical pollen referred to the genus *Spheripollenites*, characteristic for the uppermost Pliensbachian - Lower Toarcian deposits in the Danish Basin and known from many other locations in northwest Europe (see further Dybkjær, 1991), has not been reported from the Danish Central Graben. That may indicate that no deposits of latest Pliensbachian - Toarcian age are present in the study area.

Pliens-2 sequence

The marine mudstones of this sequence has only been found in Edna-1 and in Deep Gorm-1 (fig. 4). The sequence boundary is positioned, where the lithology changes abruptly from a silty mudstone of the Pliens-1 HST to more clay-rich mudstones (fig. 21). In the Deep Gorm-1 well the sequence is represented by less than 10m of clay rich mudstone. In Edna-1 the TST is 18m thick. A distinctive gamma ray peak marks the position of the MFS. With a thickness of more than 70m the HST is much thicker than the TST.
A common occurrence (in sidewall cores) of *Chasmasporites*-pollen in Edna-1 and the absence of a *Speripollenites* acme and of other Toarcian bioevents (such as the FAD of the spore genera *Leptolepidites, Ischyosporites, Manumia* or *Staplinisporites)*, indicate a Pliensbachian age for this sequence too.

Aalen-1 sequence

This sequence is encountered in most wells drilled in the Søgne Basin and in the Nora-1 well in the Tail End Graben (figs5,22). It lies unconformably on either pre-Jurassic or Lower Jurassic deposits. The TST compose the major part of the sequence and consist of a number of minor, backstepping, upward fining sandstone intervals, interpreted as stacked, fluvial channels, with subordinate floodplain or lacustrine mudstones. The MFS is a distinct gamma ray high, situated close to the strongly erosive upper sequence boundary. The thickness of this sequence varies between 25m and 60m.
No stratigraphically usefull bioevents have been recorded from this sequence, but the lack of Toarcian bioevents (as discussed in the sections on the Pliens-1 and -2 sequences) and the LOD of *Kekryphalospora distincta* in the sequence above, may be seen as indirect indications of an Aalenian or earliest Bajocian age.

Baj-1 sequence

The Baj-1 sequence extends throughout the Søgne Basin and the Tail End Graben (Nora-1), and farther south to the northern and eastern parts of the Salt Dome Province (e.g. Alma-1 and O-1). It may also be present in structurally deep locations elsewhere in the Salt Dome Province.
The lower sequence boundary is a pronounced erosive surface (figs4,5,22). The lower 20 to 30m of the sequence typically consists of two laterally extensive channel sandstones separated by a fining up/coarsening up finegrained interval (e.g. Amalie-1). The channel sandstone interval may be interpreted as a lowstand systems tract (LST). Overlying this interval is an upward fining TST (Amalie-1, West Lulu-1). The HST consists of floodplain sandstones and mudstones, and varies in thickness from 25m to 80m.
The LOD of *Kekryphalospora distincta* in the upper part of this sequence in the Alma-1 well indicate an Aalenian or earliest Bajocian age for the sequence (tab.1b).

Bat-1 sequence

This sequence is present in all wells encountering Middle Jurassic deposits in the Søgne Basin, Tail End Graben, Salt Dome Province, and southernmost Heno Plateau (figs4,5,22). The lower sequence boundary is in most wells located at the base of an upward fining channel sandstone (e.g. West Lulu-1). Above the channel sandstone, log patterns indicate a gradual or abrupt change to shaly deposits. The TST, including the basal channel unit, varies in thickness between 35m and 65m. The MFS is located in a several metres thick shale interval. Due to erosion the HST is rarely present. When present (e.g. West Lulu-1) it consists of a 20-25m thick, upward coarsening interval of interbedded mudstones and sandstone

The occurrence (in a core sample) of *Adnatosphaeridium caulleryi* in the lower part of this sequence in West Lulu-1 indicate an age not older than Bathonian (tab.1b). That in combination with the occurrence of *Impletosphaeridium varispinosum* immediately above the upper boundary of this sequence in West Lulu-3 indicate a possible age-range for this sequence from the latest Bajocian to the earliest Callovian.

Cal-1 sequence

This sequence is present in the areas where also the Bat-1 sequence is found (fig.8A).

In most wells the lower sequence boundary is a very distinct erosional surface (see Amalie-1, fig.22), which occasionally may show a truncation of at least 10-20m (e.g. West Lulu-3, fig.5). The sequence boundary is overlain by an up to 30m thick section of fluvial to estuarine channel-sandstones (e.g. Amalie-1), which is interpreted as infill of an incised valley. This interval probably represents the LST and the lowermost part of the TST. In the Søgne Basin and Tail End Graben the remaining part of the TST consists of a succession of sandstone dominated, paralic to shallow marine deposits, overlain by fully marine shales (fig.5). The paralic deposits includes a number of up to 3m thick coal beds. The total thickness of the LST and TST varies from 80m to 250m. The HST consists of a rather indistinct upward coarsening interval of marine shales and attains thicknesses up to about 50m. The sequence has a depocentre in the northern part of the Tail End Graben (fig.8A).

The LOD of *Impletospaeridium varispinosum* in the lower part of this sequence in West Lulu-3 combined with the LOD of *Ctenidodinium continuum* in the sequence above in West Lulu-1 and U-1 indicate an Early Callovian to earliest Oxfordian age for this sequence. The occurrence of *Wanaea acollaris* and *W. thysanota* in the middle part of the sequence in John Flank and West Lulu-1 support this age assumption (tab.1b).

Ox-1 sequence

This sequence is restricted to the Tail End Graben, possibly the deeper parts of the Søgne Basin, the Salt Dome Province, and the flanks of the Heno Plateau (fig.8B).

The lower boundary of this sequence is located at the top of a well developed coarsening upwards (CU-) interval. At the western margin of the basin an up to 12m thick sandy LST may be present, erosively overlying pre-Jurassic deposits (e.g. Elly-2, fig.23).

The sequence consists in most wells of marine shale. Only in Elly-2 are sandstones a major component of this sequence. The thickness of the TST varies from about 8m to 80m and the HST from 9m to 110m. A depocentre for this sequence is present in the northern part of the Tail End Graben (fig.8B).

The LOD of *Ctenidodinium continuum* in the middle part of the sequence in West Lulu-1 and U-1 indicate an Early Oxfordian age for at least the lower part of the sequence. This combined with the LOD of *Rigeaudella aemula* close to the upper boundary of this sequence in the Falk-1 well indicate an Early to Middle Oxfordian age for the whole sequence (tab.1c).

Ox-2 sequence

The distribution of this sequence corresponds to that of Ox-1 (fig.8C). The lower sequence boundary is normally located at the top of a CU-interval (e.g. Nora-1, fig.23). In a few wells situated at the western margin of the basin the lower sequence boundary may be located at the sharp base of an up to 10m thick sandstone unit interpreted as a LST-interval (e.g. Elly-2).

Except for the sandstones at the basin margin, the sequence consists of marine shale.

The thickness of the TST varies from 6m to 49m and the HST from 6m to 88m. A depocentre for this sequence is located in the northern Tail End Graben and in the Rosa Basin (fig.8C).

The LOD of *Rigeaudella aemula* immediately below the lower sequence boundary in Falk-1 combined with the LOD of *Compositosphaeridium polonicum* close to the upper boundary of this sequence in U-1 indicate an earliest Late Oxfordian age for this sequence (tab.1c).

Kimm-1 sequence

The sequence is found everywhere in the study area except for the Gertrud Graben, the northern Heno Plateau, the southern Feda Graben and the Outer Rough and Ål Basins (fig.10A).

The lower boundary of this sequence is normally located at the top of a CU-interval (e.g. Nora-1, fig.23). In the Heno Plateau area the MFS is normally situated immediately below a marked gamma/sonic spike (e.g. Ravn-1 and Elly-2, figs23,24).
The sequence consists of marine shale. The thickness of the TST varies from 8m to 94m, while the HST varies from 3m to 134m. The sequence has a well-defined depocentre in the central part of the Tail End Graben (fig.10A).
The LOD of *Compositumsphaeridium polonicum* immediately below the lower boundary of this sequence in U-1 and the LOD of *Scriniodinium crystallinum* and of *Nannoceratopsis pellucida* close to the upper boundary in several wells, e.g. West Lulu-2, Amalie-1, John Flank-1, M-8, U-1, Emma-1 and Anne-3 indicate a Late Oxfordian to Early Kimmeridgian age for this sequence (tab.1c).

Kimm-2 sequence

This sequence is found in all of the study area east of the Mads and Inge Highs (fig.10B).
The lower boundary has been located at a conspicious surface, that even in the deeper parts of the basin shows an abrupt shift from high to low gamma ray values, probably indicating an erosive surface (figs23,24). In parts of the study area, the Feda Graben, the northern part of the Gertrud Graben and the northern part of the Heno Plateau, this surface coincides with the unconformity, that separates the pre-Jurassic and the Upper Jurassic deposits (Gert-4, fig.24).
LST-deposits, developed as less than 5m thick conglomerates and coarse grained sandstones are present on the Heno Plateau (e.g. Ravn-1). In more distal settings the LST is represented by a 10m-15m thick sandstone or sandy siltstone (e.g. Nora-1 and Elly-2, figs23,24).
In the proximal settings; the Heno Plateau, the Gertrud Graben and the southern Feda Graben, the TST consists of paralic and shallow marine sandstones and mudstones.
In basinal settings (e.g. Nora-1) the TST is represented by a well-defined upward fining interval that is typically thinner than the corresponding TST (fig.24). This interval may consist of silty shale, siltstone or silty sandstone becoming more coarse grained towards the Heno Plateau.
In the central part of the Heno Plateau (e.g. Ravn-1) most of the HST has been removed by erosion during the subsequent lowstand. In the northern Heno Plateau, the Gertrud Graben and the southern Feda Graben the HST consists of a CU-interval of sandy siltstones to gravelly sandstones of shoreface origin (Johannessen et al., in press).
In basinal settings the HST consists of a CU-interval of marine mudstones, siltstones and sandstones.
The thickness of the LST plus TST varies from 4m to 176m, while the HST varies from 1m to 595m. Major depocentres for this sequence are located in the southern Tail End Graben - eastern Salt Dome Province, in the northern Tail End Graben - Søgne Basin, and in the Feda Graben (fig.10B).
The LOD of *Endoscrinium galeritum* in the lower part of this sequence in Edna-1 and West Lulu-1 and the FAD of *Subtilisphaera? paeminosa* and *S.? inaffecta* in the lower part of the sequence in Gert-1 combined with the LOD in the sequence above of *Stephanelytron scarburghense* in Lulu-1, Gert-2 and Jeppe-1 indicate a latest Early Kimmeridgian to earliest Late Kimmeridgian age for this sequence (tab.1c).

Kimm-3 sequence

The distribution of this sequence corresponds to that of Kimm-2 (fig.10C).
On the central part of the Heno Plateau (e.g. Ravn-1, fig.24) the lower sequence boundary is represented by the erosive base of a shallow marine conglomerate or gravelly sandstone. Farther north on the Heno Plateau and in the Gertrud Graben - Feda Graben areas the sequence boundary is in several wells outlined by a thin conglomerate (Johannessen, this volume). In more basinal areas, south and east of the Heno Plateau, the lower sequence boundary is located at the top of a well-defined CU-interval (e.g. Nora-1, fig.24).
In the Heno Plateau - northernmost Salt Dome Province area (e.g. Ravn-1) the TST is developed as a backstepping set of parasequences that consists of marine, silty sandstones, siltstones and shales. In the Feda Graben - Gertrud Graben area the TST consists of shallow marine sandstones and siltstones, that upwards change to marine mudstones (e.g. Gert-4, fig.24). In some wells (e.g. Jeppe-1, fig.9) an abrupt change from marine sandstones to mudstones, interpreted as a flooding surface, replaces part of the upward coarsening section. In the Tail End Graben (e.g. Nora-1) the TST is represented by a thin upwards fining interval of marine shale. The HST typically consists of marine shale. In the Feda Graben - Gertrud Graben area and in the Søgne Basin the HST terminates in a distinct CU-interval, which includes silt- and sandstones (e.g. Gert-4, fig.24, Lulu-1, fig.15).
The TST varies from about 1m to 350 m and the HST from 1m to 113m. A major depocentre is located in the Feda Graben. In the remaining part of the depositional area sediment thicknesses are relatively uniform, but with the thickest deposits along the eastern margin of the Heno Plateau (fig.10C).
The LOD of *Stephanelytron scarburghense* in the lower to middle part of this sequence in Lulu-1, Gert-2 and Jeppe-1 and the LOD of *Endoscrinium luridum* in sequence Kim-4 indicate a Late Kimmeridgian age for this sequence (tab.1c).

Kimm-4 sequence

This sequence is distributed in the same areas as the Kimm-2 and Kimm-3 sequences (fig.14A).
In the Heno Plateau area the lower sequence boundary typically is situated where the lithology changes abruptly from the sandstones and siltstones of the underlying sequences to fully marine mudstones (e.g. Ravn-1, fig.24). In more basinal areas the lower sequence boundary is located at the top of a CU-interval, which in the Feda Graben - Gertrud Graben area (e.g. Gert-4) and in the Søgne Basin (e.g. Lulu-1, fig.15) may be distinct.
In the Feda and Gertrud Graben area the TST is well-developed (e.g. Gert-2, Gwen-2, fig.25), while in the main part of the Heno Plateau, the Salt Dome Province and the Tail End Graben it often occur in a condensed form (e.g. Nora-1, fig. 24). Generally the HST is much thicker than the TST (e.g. Nora-1, Gert-2, figs24,25). Both the TST and HST consist of marine shales.
The thickness of the TST varies from about 1m to 60m while the HST varies from 2m to 223m.
The sequence has an elongated depocentre in the eastern part of the Tail End Graben and a secondary depocentre in the Feda Graben (fig.14A).
The LOD of *Stephanelytron scarburghense* in the sequence below combined with the LOD of *Endoscrinium luridum* close to the upper sequence boundary in Amalie-1 and Cleo-1 indicate a Late Kimmeridgian age for this sequence (tab.1c).

Volg-1 sequence

This sequence is distributed in the same area as the previous sequences (fig.14B).
In the Feda and Gertrud Graben area and on the Heno Plateau the lower sequence boundary is located at the top of a thin but conspicious CU-interval(fig.25). In the more basinal settings of the Tail End Graben, the Søgne Basin, and the Salt Dome Province, the boundary is situated at the inflection point between rather indistinct upward coarsening and upward fining units (e.g. Nora-1 and G-1, fig.12).
In several wells in the Salt Dome Province the TST is missing and the MFS amalgamates with the underlying sequence boundary (e.g. U-1, fig.13).
The MFS is marked by a conspicuous peak on both the gamma ray, sonic and resistivity logs.
Both the TST and HST consists of marine shales. The thickness of the TST varies from about 5m to 245m and the HST from 5m to 266m.
The main depocentre of the sequence is in the eastern part of the Tail End Graben and in the eastern Søgne Basin. A secondary depocentre is present in the Feda Graben (fig.14B).
The LOD of *Endoscrinium luridum* in the sequence below combined with the LOD of *Subtilisphaera? paeminosa* in the upper part of this sequence in a number of wells, e.g. Gert-2 and -4, Gwen-2, Ravn-2, Deep Gorm-1, U-1 and Amalie-1 indicate an earliest Early Volgian age for this sequence (tab.1c).

Volg-2 sequence

This sequence is partly or fully eroded in most wells in the Salt Dome Province. Exept for that, the sequence is present all over the Danish Central Graben, including the Outer Rough and Ål Basins (fig.14C).
The lower sequence boundary of this sequence is rather indistinct in most wells, being located at the top of a weak CU-trend of the HST below (fig.25). In basinal settings, where the sequence is relatively thick, the TST is four to five times thicker than the HST.
In settings where the sequence is relatively thin the TST and HST are of allmost similar thickness. The sequence consists of marine shale.
The thickness of the TST varies from 6m to 353m and the HST from 4m to 139m.
The sequence has a significant depocentre in the Tail End Graben with thicknesses of more than 400m. A secondary depocentre is present in the Feda Graben (fig.14C).
The LOD of *Subtilisphaera? paeminosa* in the sequence below and of *Oligospaeridium patulum* in the sequence above indicate an Early Volgian age for this sequence. This is further supported by the LOD of *Cribroperidinium? longicome* in the lower part of the sequence in Emma-1 and Eg-1 (tab.1c).

Volg-3 sequence

The sequence is present in all parts of the study area; but is missing locally in the southwestern part of the Salt Dome Province and in the area around the Mandal High, probably due to erosion (fig.16A).

The lower sequence boundary is positioned at the top of an upward coarsening interval (e.g. Gert-2, Elin-1, fig.25). In a number of wells, where the section is relatively thin, the sequence boundary is in position at the base of a somewhat coarser bed (e.g. Gwen-2).
The Volg-3 sequence consists of marine shale.
The thickness of the TST varies from 7m to 174m and the HST from 3m to 220m. The primary depocentre in the Tail End Graben branches into the Arne-Elin Graben. Secondary depocentres are present in the Gertrud and Feda Grabens and in the Outer Rough Basin (fig.16A).
The LOD of *Oligosphaeridium patulum* in the lower part of this sequence in a number of wells, e.g. Gert-2 and -4, Elly-2, Falk-1, Deep Gorm-1, U-1, I-1, M-8 and V-1, combined with the LOD of *Occisucysta balia* in the middle to upper part in Gert-2, Gwen-2, Ravn-2 and Bo-1 indicate an latest Early Volgian to middle Middle Volgian age for this sequence. This is supported by the LOD of *Perisseiasphaeridium pannosum* in the upper part of the sequence in Gert-1 and -2 (tab.1c).

Volg-4 sequence

The sequence has not been found in the Søgne Basin and Mandal High area. It is missing from parts of the Outer Rough Basin and Salt Dome Province. The sequence is present in all other parts of the study area (fig.16B).
The lower boundary of the Volg-4 sequence is positioned at the top of a well defined upward coarsening HST of the sequence below (e.g. Elin-1, fig.26). In a number of wells the sequence boundary is further marked by the abrupt base of a slightly more silty or sandy unit (e.g. Jeppe-1).
In many wells (e.g. Elin-1 and Jeppe-1) the lower part of the TST typically shows a fining upward/coarsening upward pattern. In V-1 this unit is developed as a 30m thick sandstone unit (fig.18). In these wells the remaining part of the TST consists of a short, distinct upward fining mudstone section. In other wells all of the TST consists of an upward fining interval of marine mudstones (e.g. Elin-1, Bo-1).
As the upper boundary of this sequence frequently shows significant erosion, the upper part of the HST is missing in many wells (e.g. Gwen-2 and Jeppe-1, figs25,26). Where a major part of the HST is preserved it may typically show consistently high gamma ray values (e.g. Elin-1 and Bo-1). Due to incipient "hot" conditions which are attained in this sequence, the gamma ray log is not considered a fully reliable grainsize indicator. In spite of the high gamma ray readings, the description of the cuttings indicate presence of sand- and siltstone in this interval. It is therefore assumed that the high gamma ray readings are caused by the presence of "hot" shales and not by a lack of sand- and silt-sized material.
The sequence consists of marine, organic rich mudstone with silt- and sandstone interbeds.
The thickness of the TST varies from 9m to 132m and the HST from 4m to 98m.
The sequence shows a more even distribution than the previous sequences, but depocentres are still present in the Tail End Graben, in the Arne-Elin Graben, in the Feda Graben and in the Outer Rough Basin (see fig.16B).
The LOD of *Scriniodinium inritibile* in the lower part of the sequence in Bo-1 and of *Senoniasphaera jurassica* in the lower to middle part of the sequence in a number of wells, e.g. Jeppe-1, Gwen-2, W-1, Ravn-2, Elin-1, Deep Gorm-1, Bo-1 and I-1 indicate a middle Middle Volgian age for the lower part of the sequence. That, in combination with the LOD of *Egmontodinium polyplacophorum* in the middle to upper part of the sequence in Lone-1, Bo-1, E-1, I-1, V-1 and Deep Adda-1 indicate a middle Middle Volgian to Late Volgian age for this sequence. This age assumption is supported by the LOD of one or more of the following dinocyst species: *Dichadogonyaulax pannea, Glossodinium dimorphum, Muderongia simplex* (the form previously referred as *Muderongia* sp. A, see further Poulsen and Riding, this volume) and *Gochteodinia mutabilis*, within this sequence in a number of wells, e.g. Gwen-2, Deep Gorm-1, Elin-1, Iris-1, Bo-1, E-1, V-1 and I-1 (tab.1c).

Ryaz-1 sequence

The distribution of the sequence corresponds to the distribution of Volg-4.
The development of the Hot Unit within this sequence, and the transition to more calcareous sediments at the top of the Farsund Formation makes sequence stratigraphic analysis problematic. Neither a MFS nor an upper boundary of the sequence have been picked. The sequence is not neccessarily limited to the marine mudstones of the Farsund Formation but may straddle the boundary to the overlying Cromer Knoll Group.
The lower sequence boundary is normally distinct and often erosive (e.g. Elin-1,Jeppe-1 and Bo-1, fig.26). Above the boundary are in several wells turbidite sandstones (e.g. Jeppe-1 and Iris-1, fig.18). In certain wells without turbidite sandstones (e.g. Gert-2, E-1), the bioevents of the turbidite bearing section are missing, indicating a missing interval.

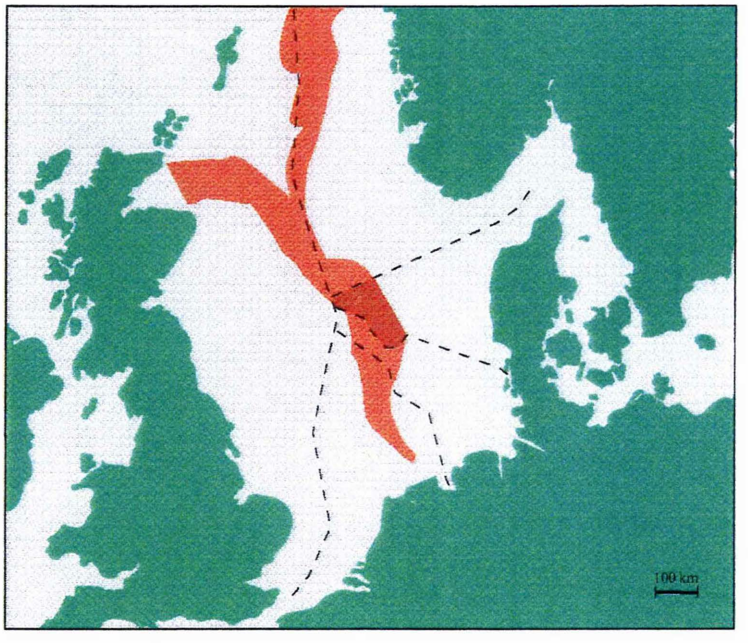



Fig.1

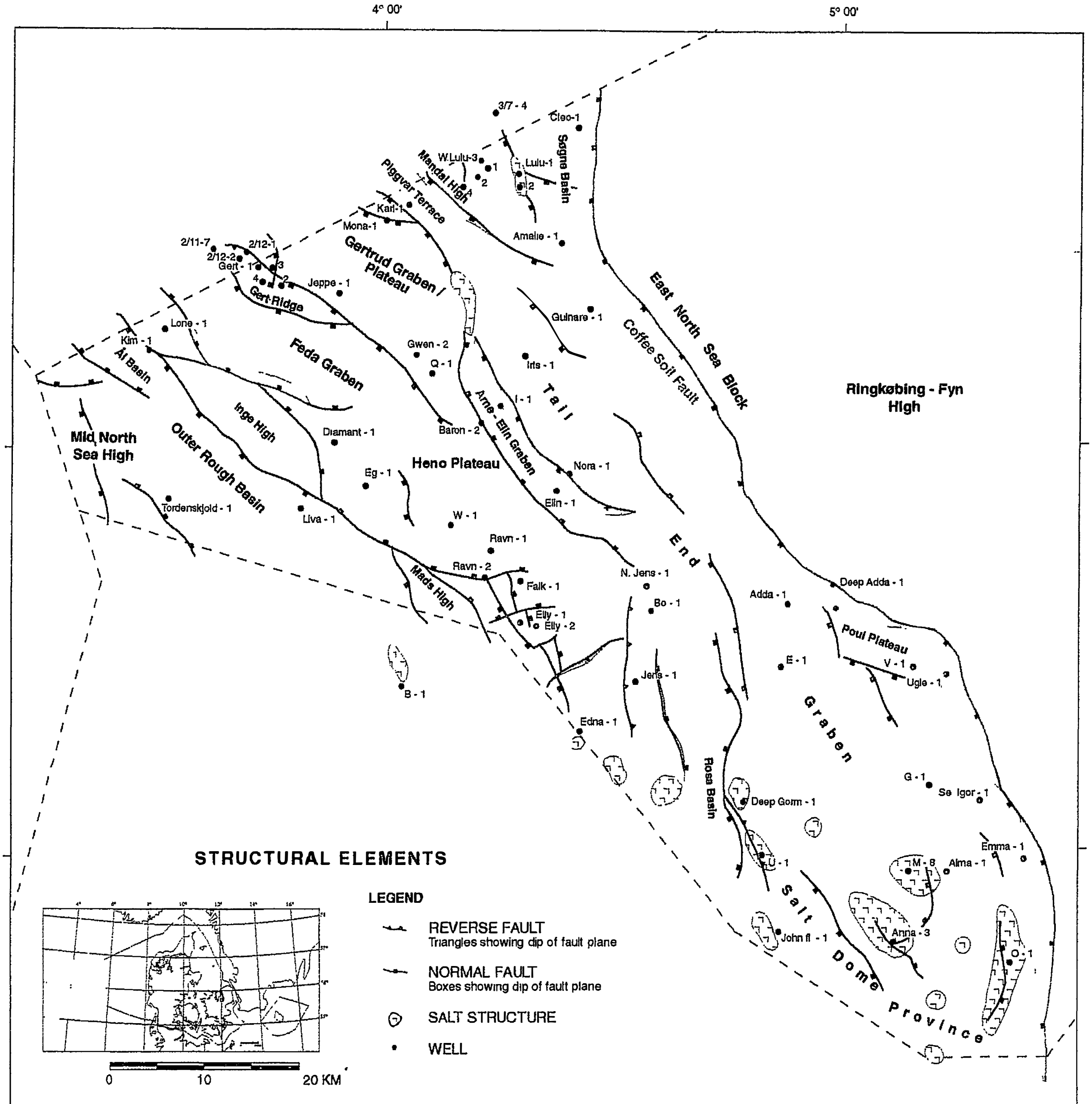

4° 00'
5° 00'
56° 30'
56° 00'
STRUCTURAL ELEMENTS
LEGEND
REVERSE FAULT
Triangles showing dip of fault plane
NORMAL FAULT
Boxes showing dip of fault plane
SALT STRUCTURE
WELL
0
10
20 KM
Ringkøbing - Fyn High
East North Sea Block
Coffee Soil Fault
Tail End Graben
Salt Dome Province
Søgne Basin
Mandal High
Piggvar Terrace
Gertrud Graben / Plateau
Gert Ridge
Feda Graben
Ål Basin
Mid North Sea High
Inge High
Outer Rough Basin
Heno Plateau
Arne - Elin Graben
Mads High
Rosa Basin
Poul Plateau
3/7 - 4
Cleo-1
W.Lulu-3
Lulu-1
Amalie - 1
Karl-1
Mona-1
2/11-7
2/12-1
2/12-2
Gert - 1
Jeppe - 1
Lone - 1
Kim - 1
Gulnare - 1
Gwen - 2
Q - 1
Iris - 1
I - 1
Baron - 2
Diamant - 1
Nora - 1
Eg - 1
Elin - 1
W - 1
Tordenskjold - 1
Liva - 1
Ravn - 1
Ravn - 2
Falk - 1
N. Jens - 1
Bo - 1
Elly - 1
Elly - 2
Adda - 1
Deep Adda - 1
V - 1
Ugle - 1
E - 1
B - 1
Jens - 1
Edna - 1
G - 1
Se Igor - 1
Deep Gorm - 1
U - 1
Emma - 1
M - 8
Alma - 1
Anna - 3
John fl - 1
O - 1

Fig.2

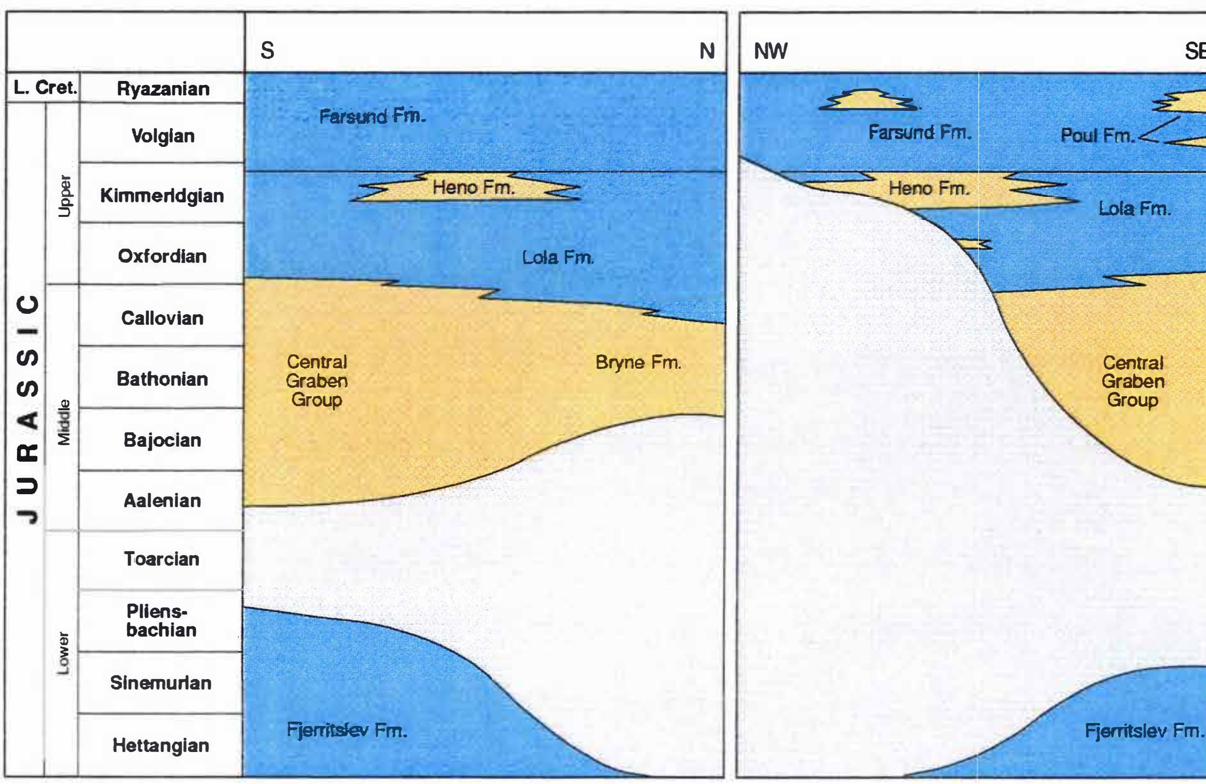
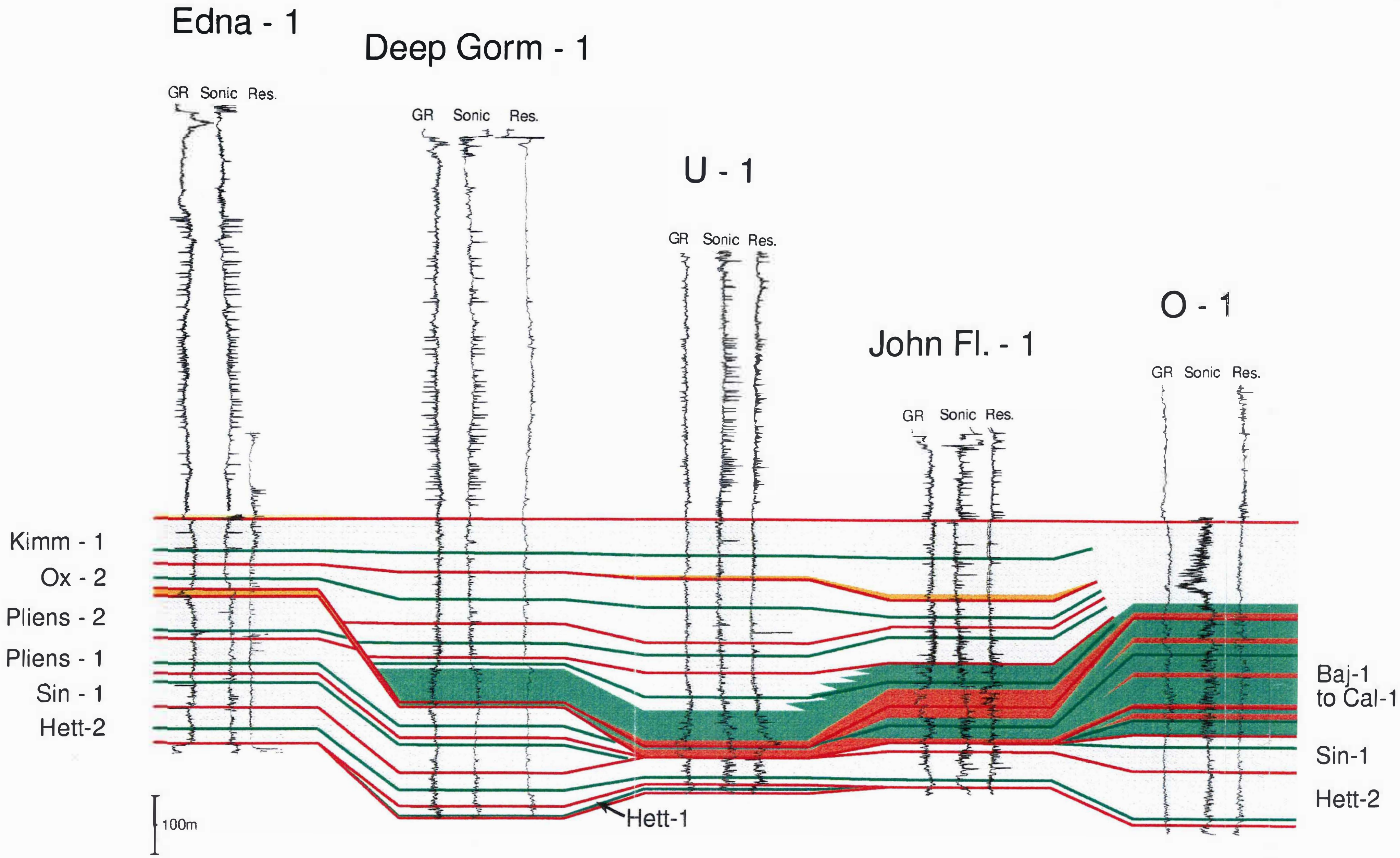

S
N
NW
SE
L. Cret.
Ryazanian
Volgian
Upper
Kimmeridgian
Oxfordian
Callovian
Middle
Bathonian
Bajocian
Aalenian
JURASSIC
Toarcian
Lower
Pliens-bachian
Sinemurian
Hettangian
Farsund Fm.
Heno Fm.
Lola Fm.
Central Graben Group
Bryne Fm.
Fjerritslev Fm.
Farsund Fm.
Poul Fm.
Heno Fm.
Lola Fm.
Central Graben Group
Fjerritslev Fm.

Fig.3




Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone

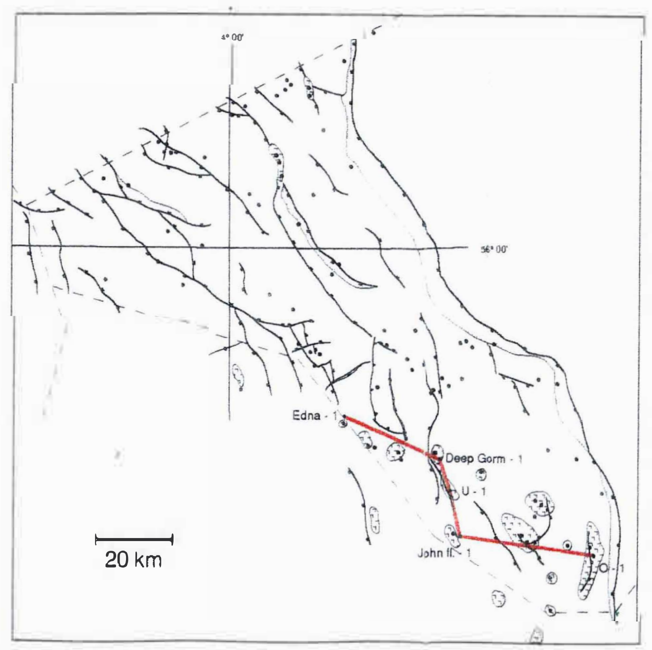



Fig. 4

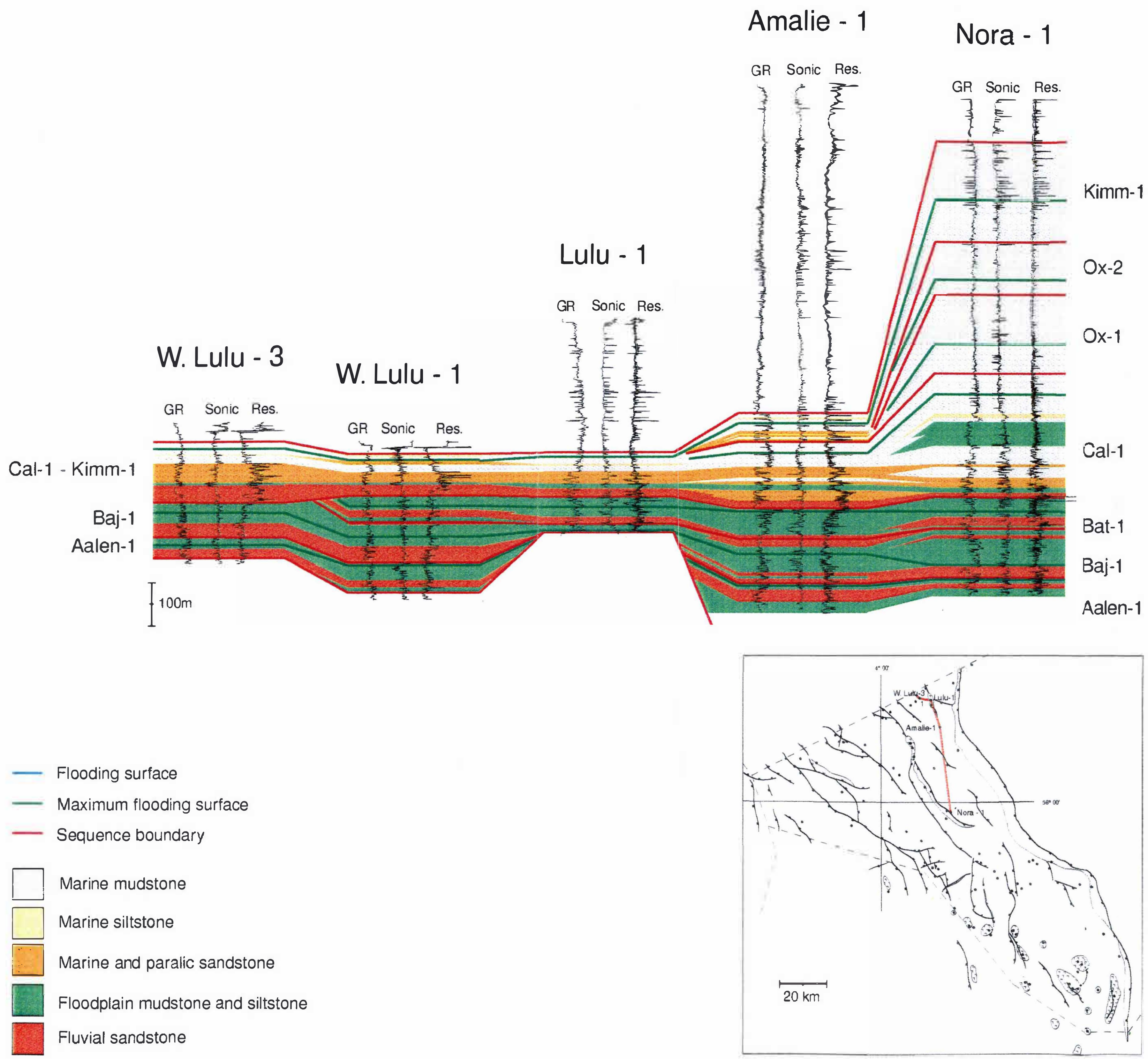

W. Lulu - 3
W. Lulu - 1
Lulu - 1
Amalie - 1
Nora - 1
GR Sonic Res.
Cal-1 - Kimm-1
Baj-1
Aalen-1
100m
Kimm-1
Ox-2
Ox-1
Cal-1
Bat-1
Baj-1
Aalen-1
Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone
Amalie-1
Nora
20 km

Fig.5

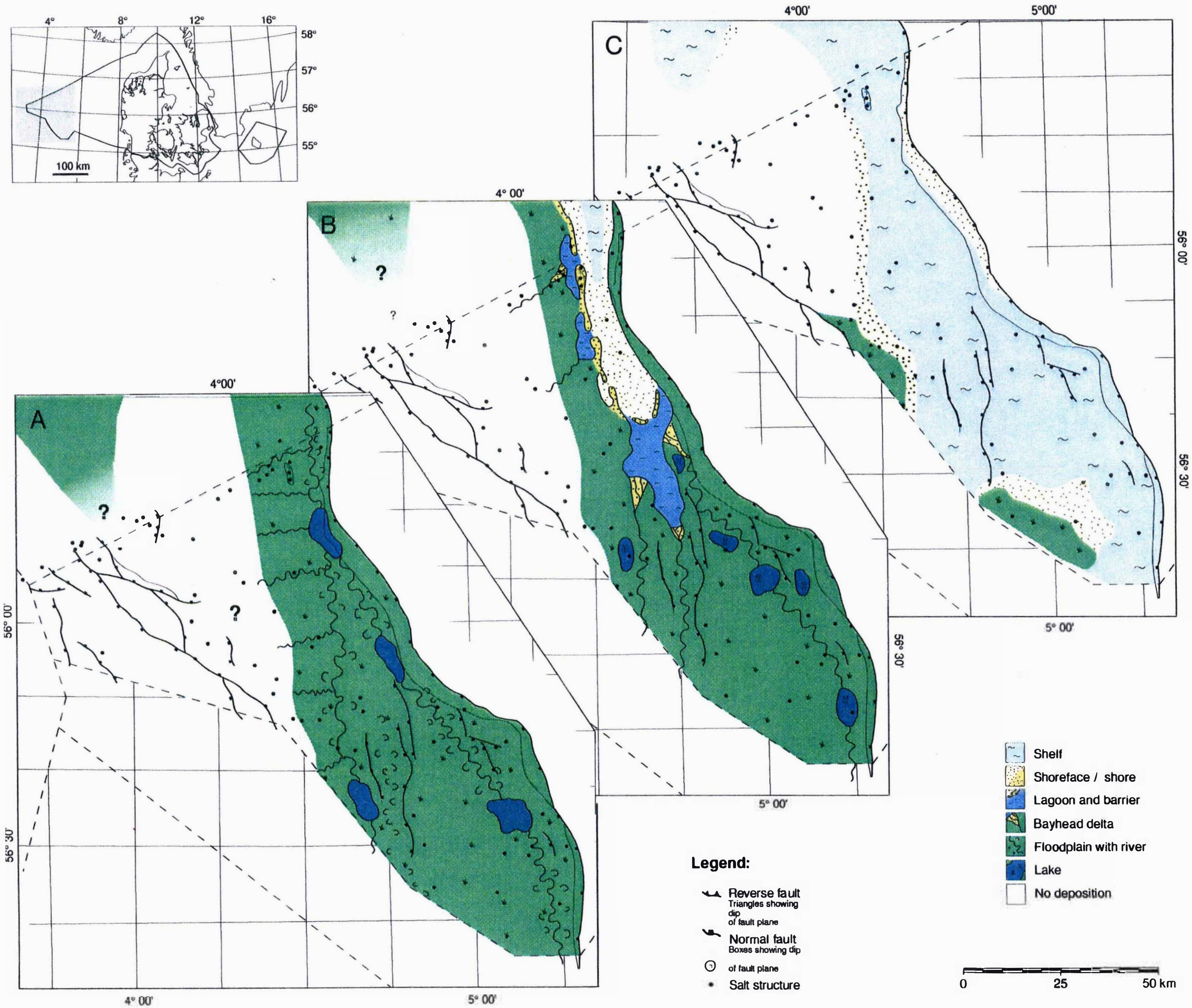

4°
8°
12°
16°
58°
57°
56°
55°
100 km
A
B
C
4°00'
4° 00'
5°00'
5° 00'
56° 00'
56° 30'
?
Legend:
Reverse fault
Triangles showing dip
of fault plane
Normal fault
Boxes showing dip
of fault plane
Salt structure
Shelf
Shoreface / shore
Lagoon and barrier
Bayhead delta
Floodplain with river
Lake
No deposition
0
25
50 km

Fig.6

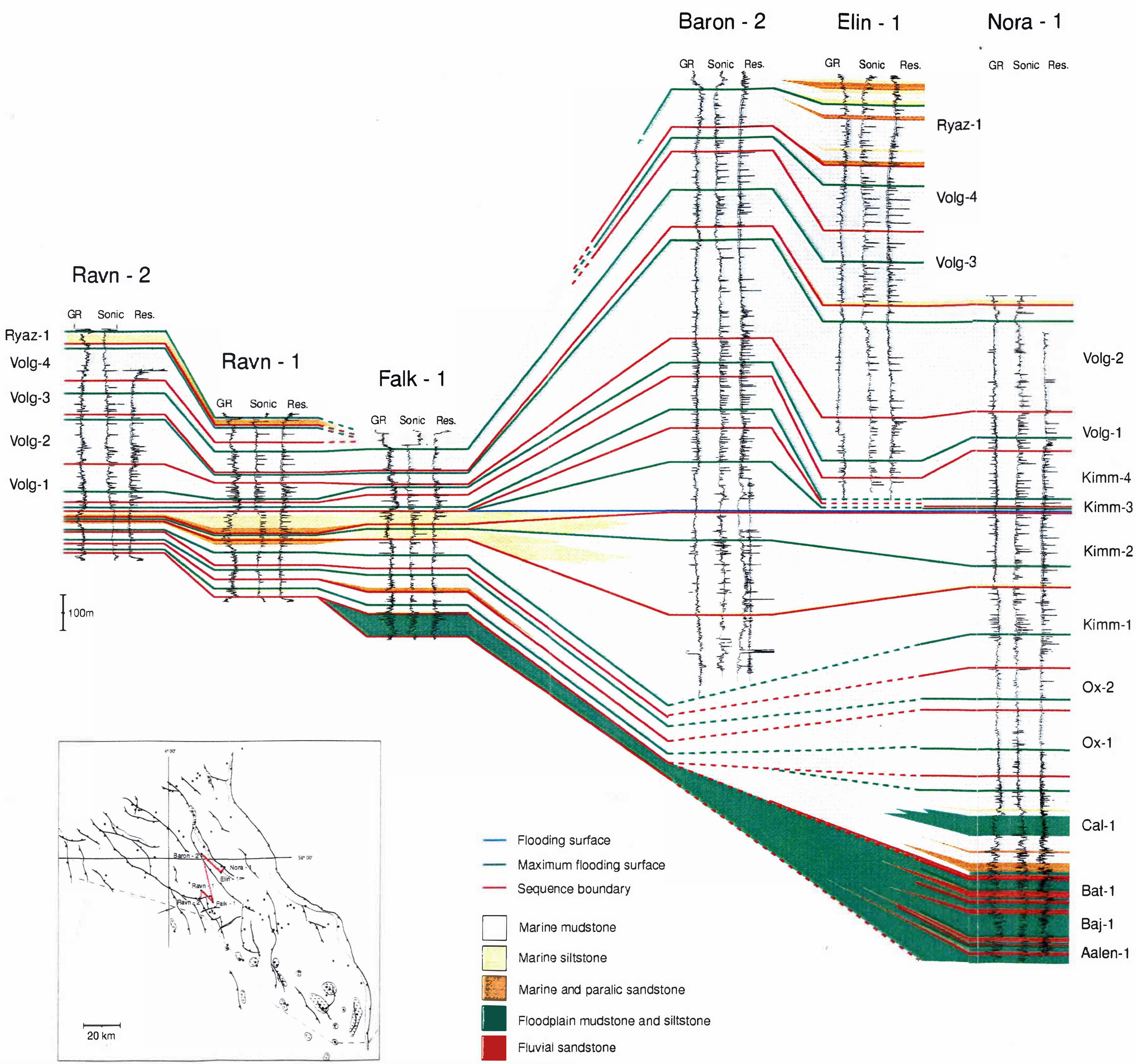

Ravn - 2
Ravn - 1
Falk - 1
Baron - 2
Elin - 1
Nora - 1
GR Sonic Res.
Ryaz-1
Volg-4
Volg-3
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Kimm-1
Ox-2
Ox-1
Cal-1
Bat-1
Baj-1
Aalen-1
100m
Baron - 2
Nora - 1
Elin - 1
Ravn - 1
Ravn - 2
Falk - 1
20 km
Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone

Fig.7

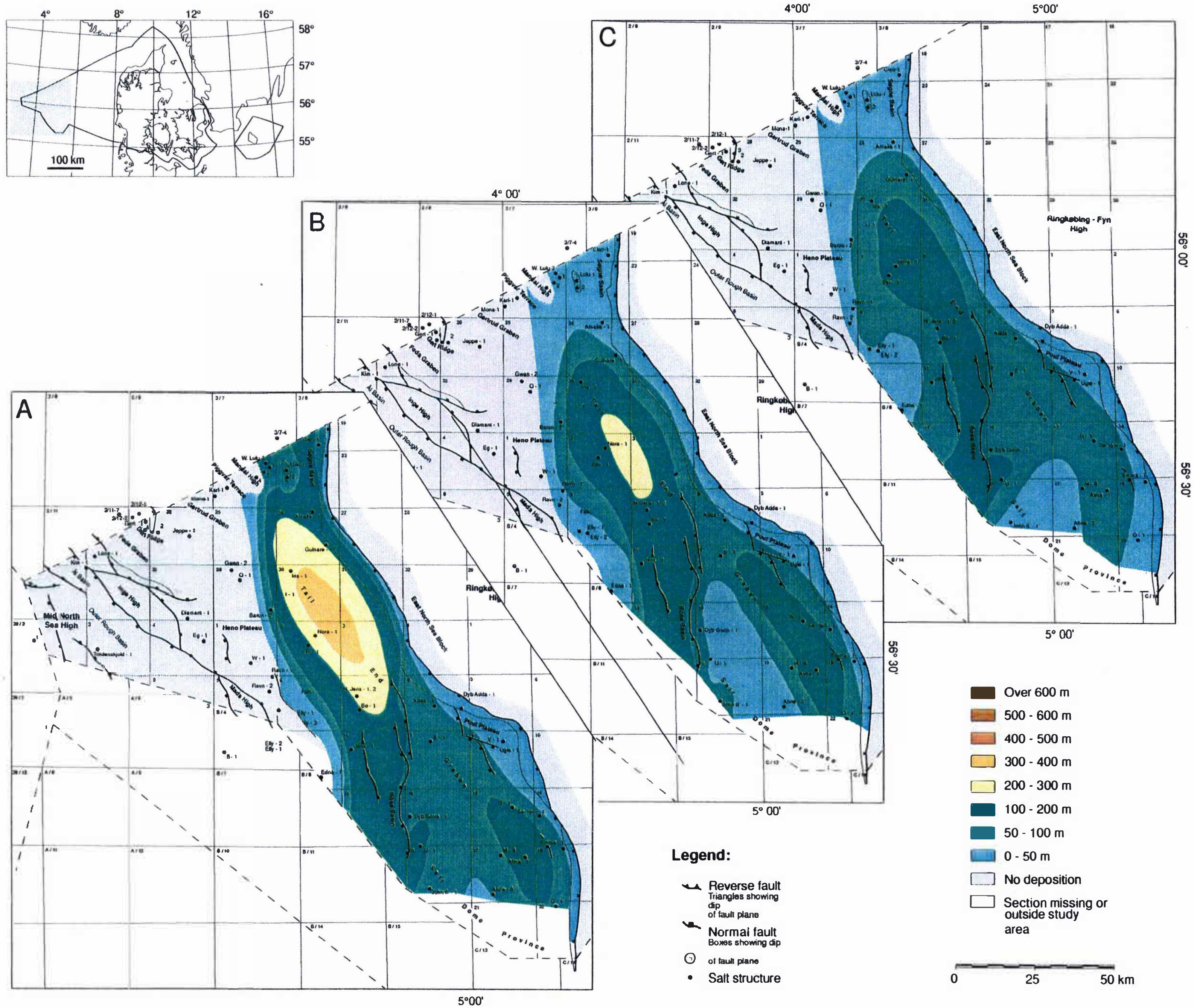
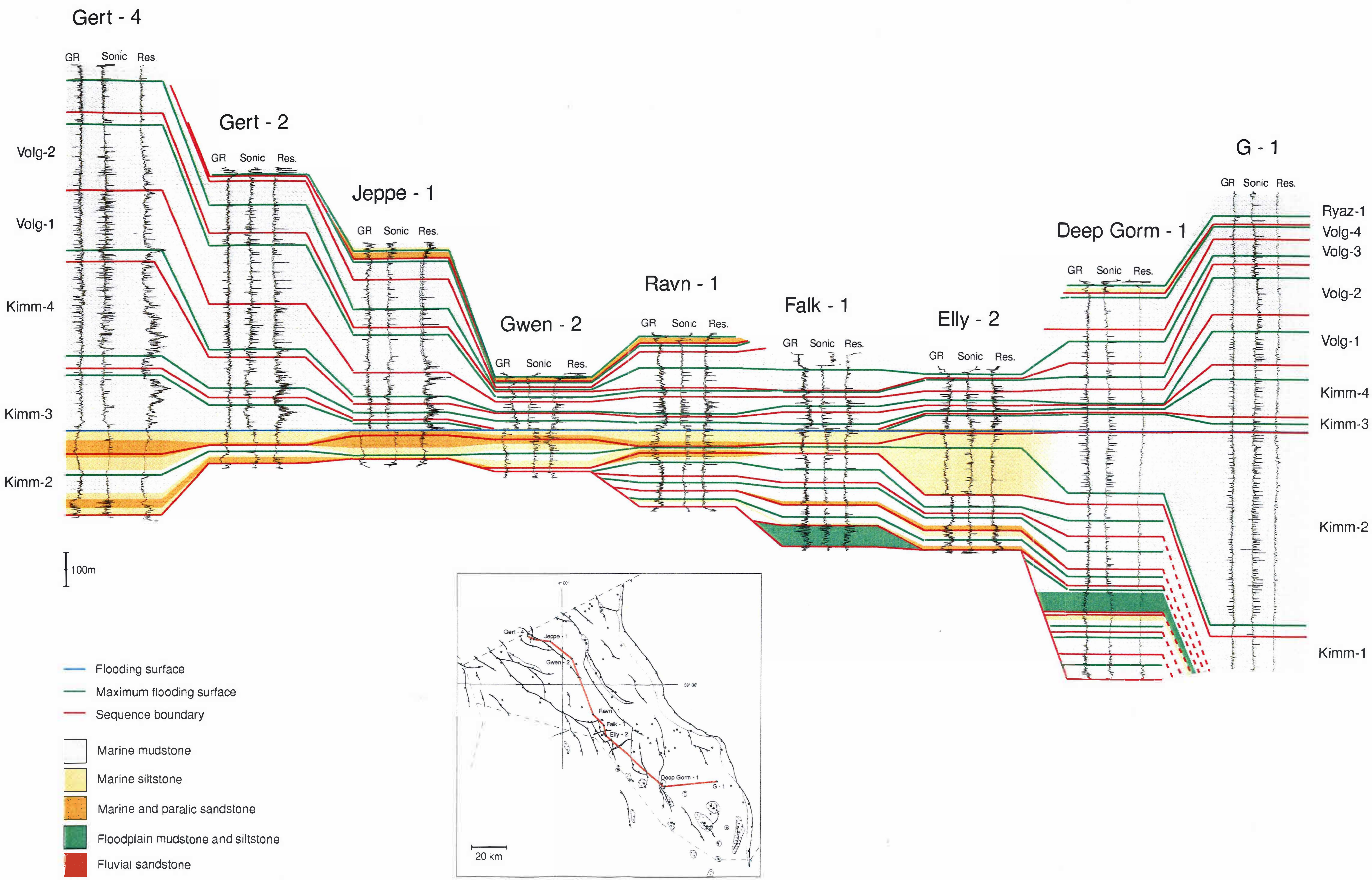

A
B
C
100 km
4°
8°
12°
16°
58°
57°
56°
55°
4° 00'
5°00'
56° 00'
56° 30'
Mid North Sea High
Heno Plateau
Ringkøbing - Fyn High
East North Sea Block
Outer Rough Basin
Gertrud Graben
Feda Graben
Piggvar Terrace
Mads High
Poul Plateau
Dome Province
Legend:
Reverse fault
Triangles showing dip of fault plane
Normal fault
Boxes showing dip of fault plane
Salt structure
Over 600 m
500 - 600 m
400 - 500 m
300 - 400 m
200 - 300 m
100 - 200 m
50 - 100 m
0 - 50 m
No deposition
Section missing or outside study area
0
25
50 km

Fig.8



Gert - 4
GR Sonic Res.
Gert - 2
GR Sonic Res.
Jeppe - 1
GR Sonic Res.
Gwen - 2
GR Sonic Res.
Ravn - 1
GR Sonic Res.
Falk - 1
GR Sonic Res.
Elly - 2
GR Sonic Res.
Deep Gorm - 1
GR Sonic Res.
G - 1
GR Sonic Res.
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Ryaz-1
Volg-4
Volg-3
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Kimm-1
100m
Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone
Gert - 4
Jeppe - 1
Gwen - 2
Ravn - 1
Falk - 1
Elly - 2
Deep Gorm - 1
G - 1
20 km


Fig.9

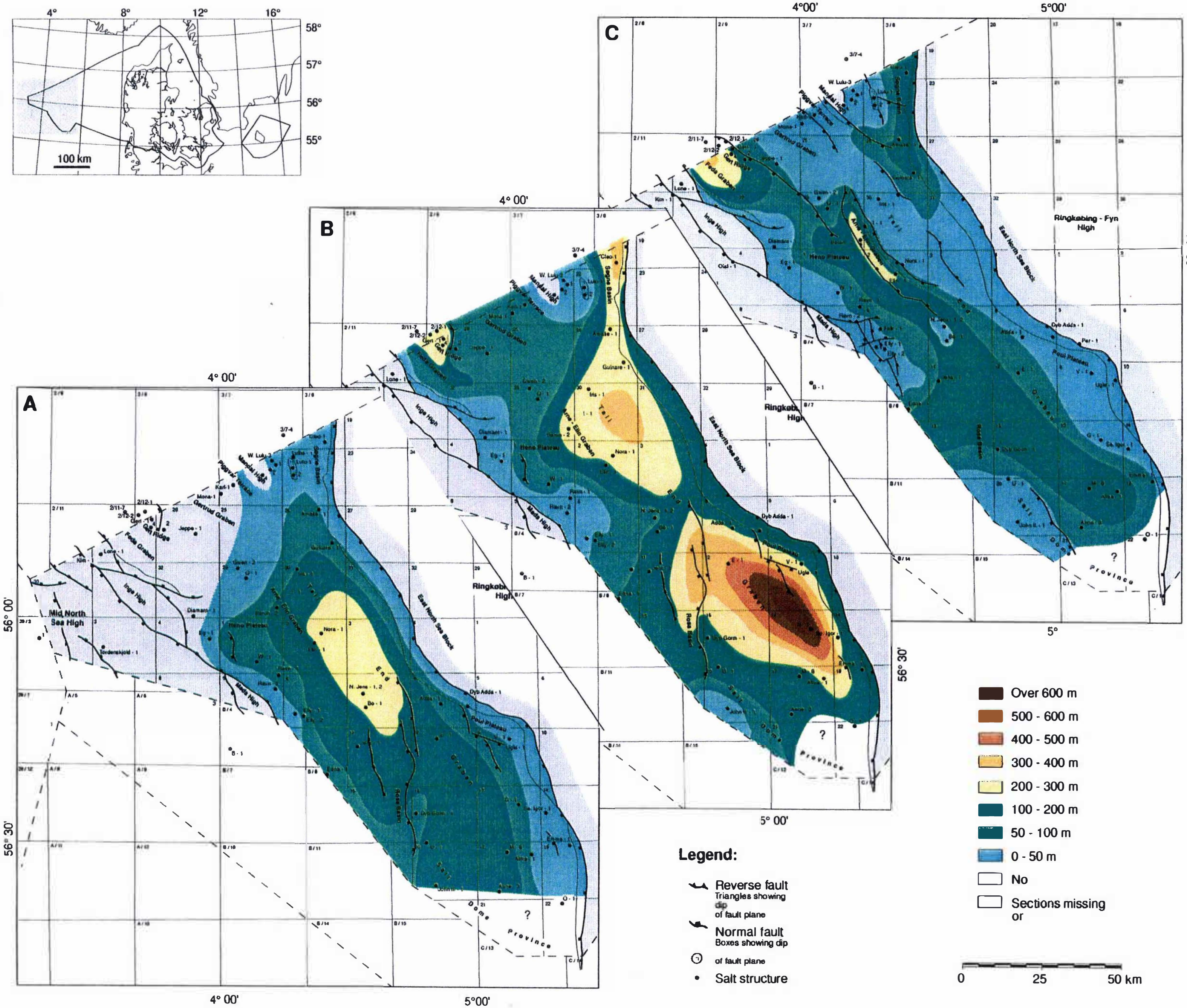
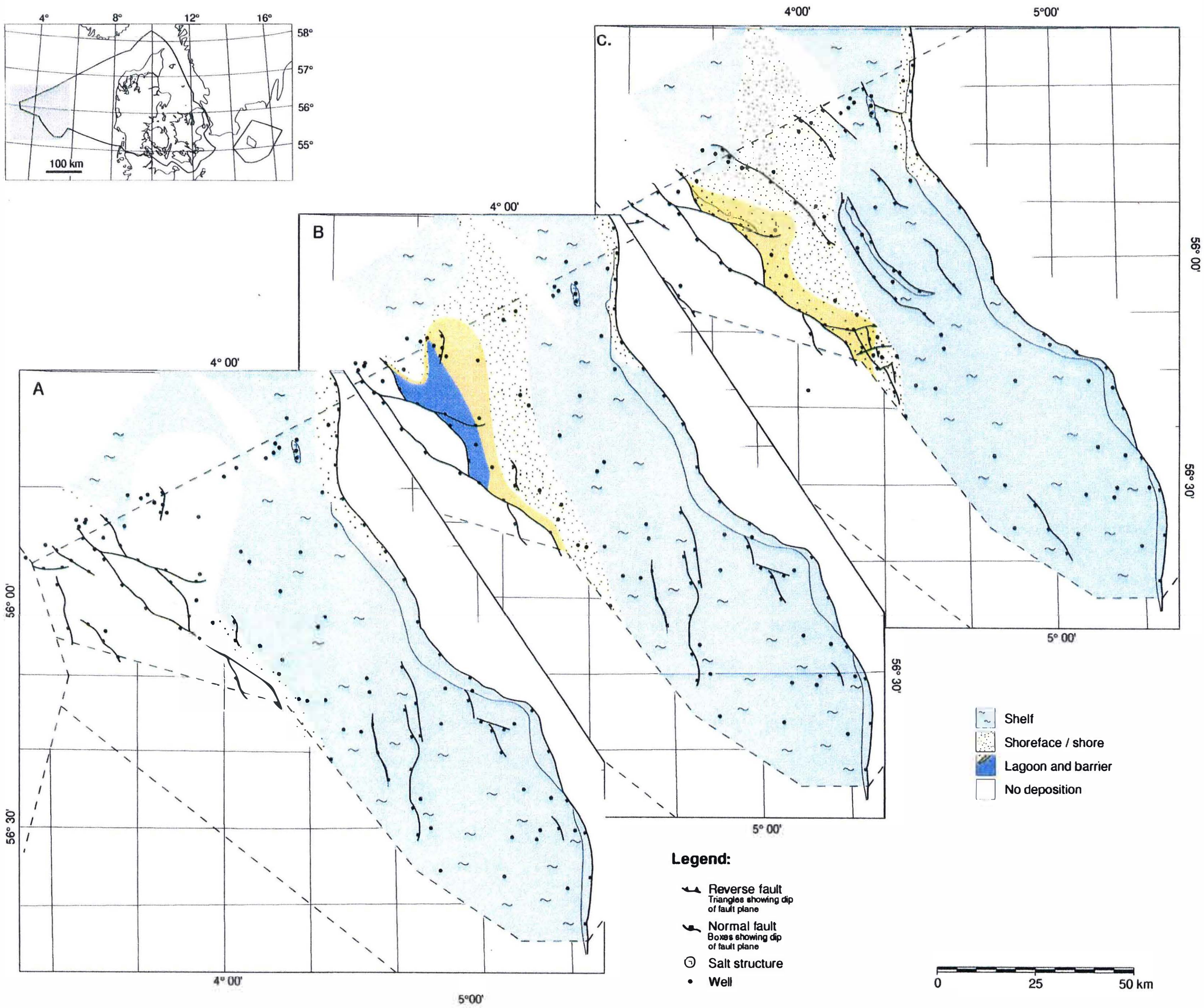
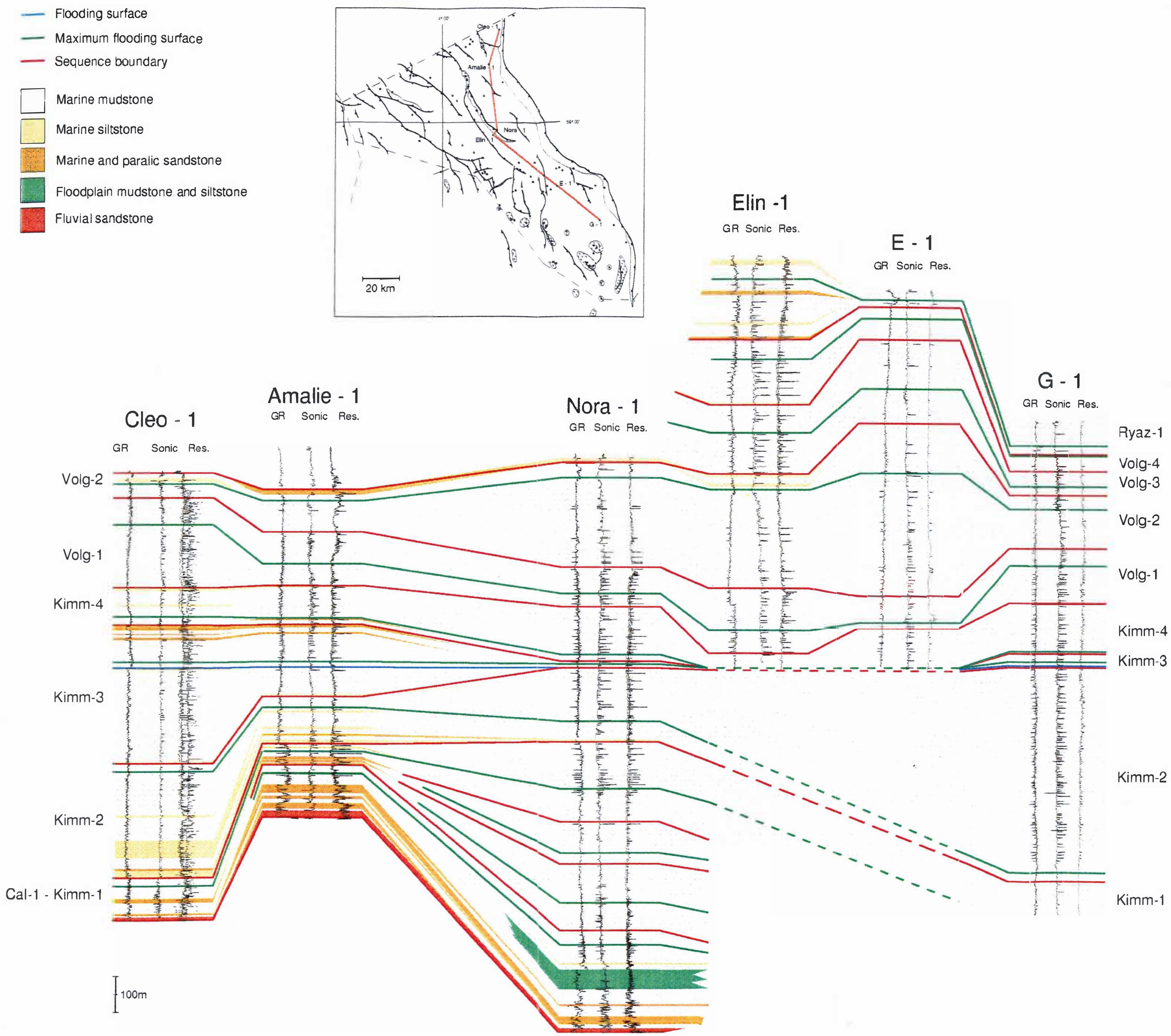

A
B
C
4° 00'
5°00'
56° 00'
56° 30'
100 km
Mid North Sea High
Ringkøbing - Fyn High
Legend:
Reverse fault
Triangles showing dip of fault plane
Normal fault
Boxes showing dip of fault plane
Salt structure
Over 600 m
500 - 600 m
400 - 500 m
300 - 400 m
200 - 300 m
100 - 200 m
50 - 100 m
0 - 50 m
No
Sections missing or
0
25
50 km

Fig.10



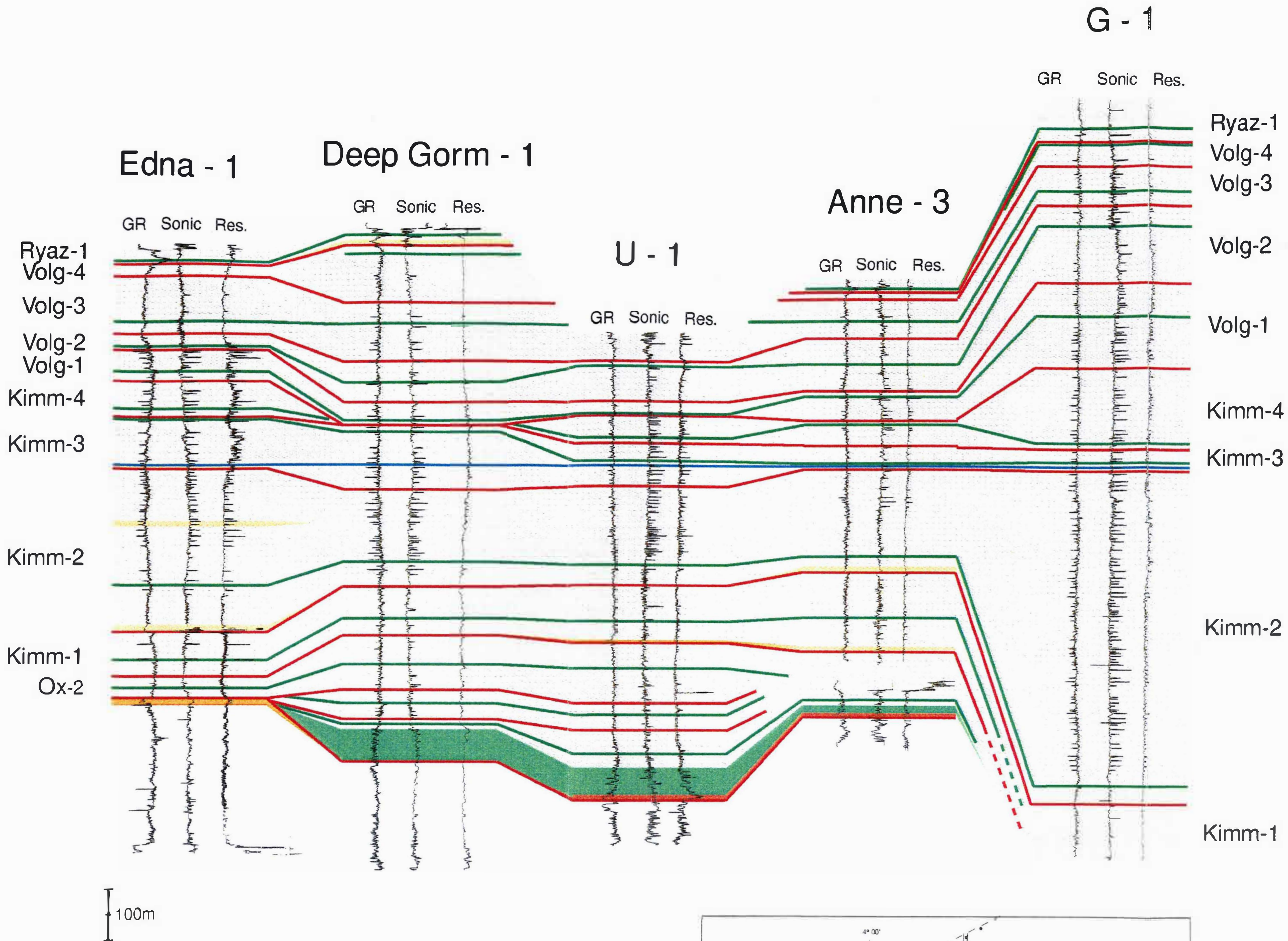
4°
8°
12°
16°
58°
57°
56°
55°
100 km
C.
4°00'
5°00'
56° 00'
56° 30'
5° 00'
B
4° 00'
56° 30'
5° 00'
A
4° 00'
56° 00'
56° 30'
4° 00'
5°00'
Shelf
Shoreface / shore
Lagoon and barrier
No deposition
Legend:
Reverse fault
Triangles showing dip of fault plane
Normal fault
Boxes showing dip of fault plane
Salt structure
Well
0
25
50 km

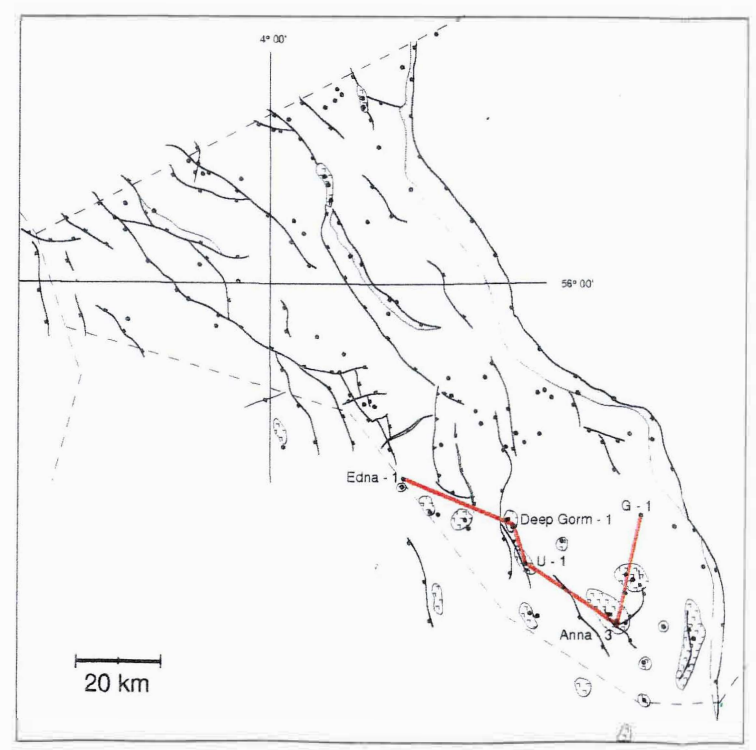

Fig.11



Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone
Cleo - 1
Amalie - 1
Nora - 1
Elin - 1
E - 1
G - 1
20 km
Cleo - 1
GR Sonic Res.
Amalie - 1
GR Sonic Res.
Nora - 1
GR Sonic Res.
Elin -1
GR Sonic Res.
E - 1
GR Sonic Res.
G - 1
GR Sonic Res.
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Cal-1 - Kimm-1
Ryaz-1
Volg-4
Volg-3
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Kimm-1
100m


Fig. 12




Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone

Fig. 13

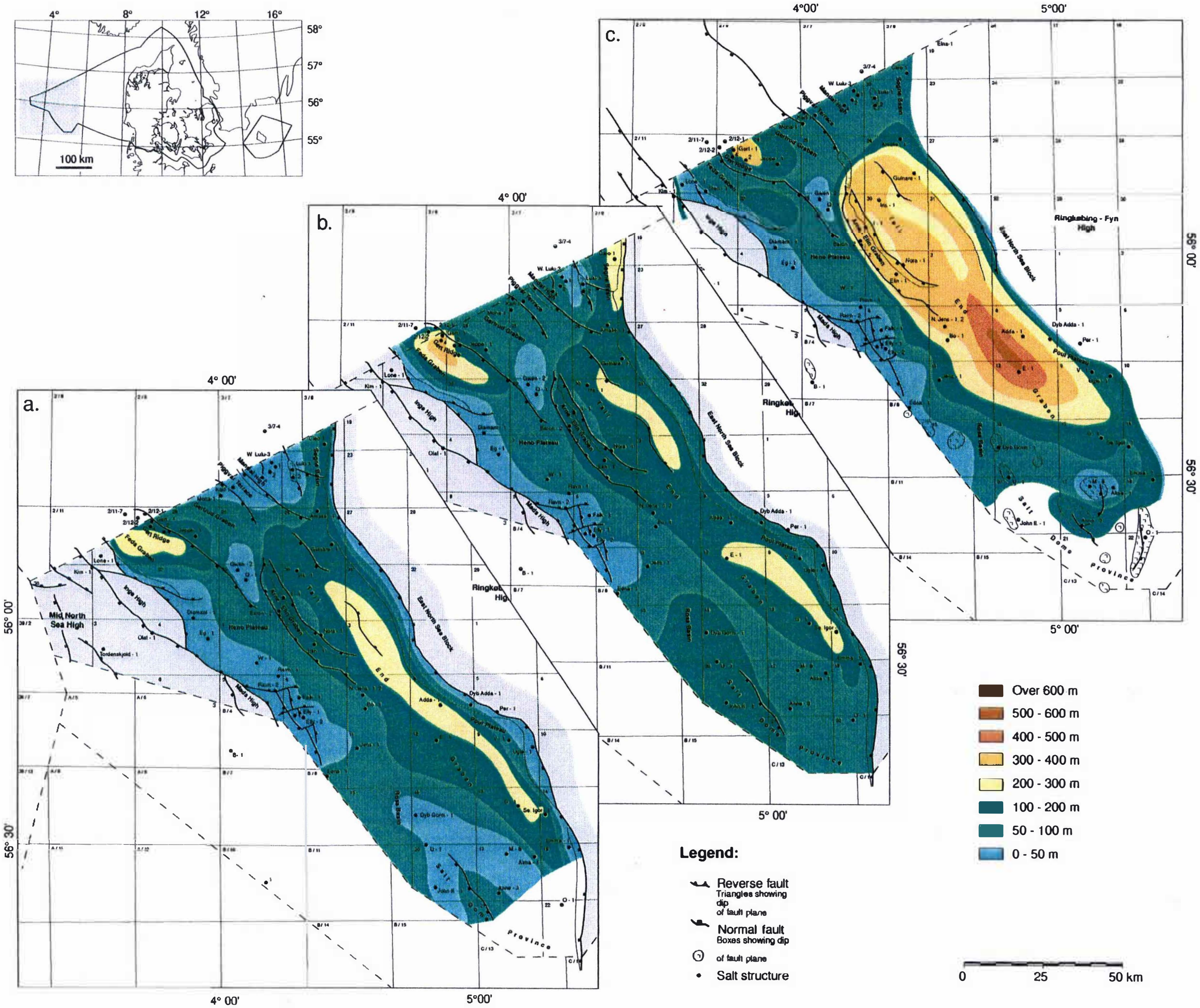

a.
b.
c.
4° 00'
5° 00'
56° 00'
56° 30'
Mid North Sea High
Ringkøbing - Fyn High
East North Sea Block
Heno Plateau
Salt Dome Province
100 km
58°
57°
56°
55°
Over 600 m
500 - 600 m
400 - 500 m
300 - 400 m
200 - 300 m
100 - 200 m
50 - 100 m
0 - 50 m
Legend:
Reverse fault
Triangles showing dip of fault plane
Normal fault
Boxes showing dip of fault plane
Salt structure
0
25
50 km

Fig. 14

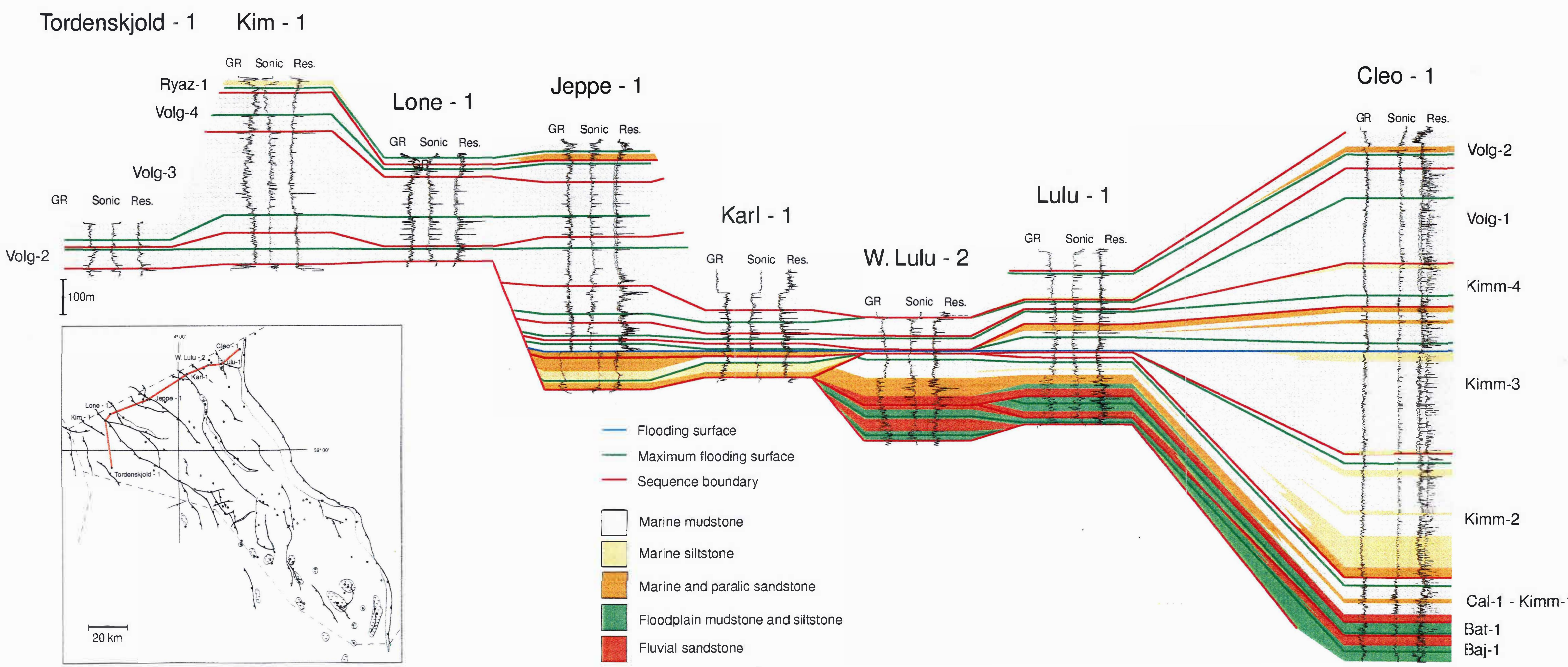

Tordenskjold - 1
Kim - 1
Lone - 1
Jeppe - 1
Karl - 1
W. Lulu - 2
Lulu - 1
Cleo - 1
GR Sonic Res.
Ryaz-1
Volg-4
Volg-3
Volg-2
Volg-1
Kimm-4
Kimm-3
Kimm-2
Cal-1 - Kimm-1
Bat-1
Baj-1
100m
20 km
Flooding surface
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Marine and paralic sandstone
Floodplain mudstone and siltstone
Fluvial sandstone

Fig 15

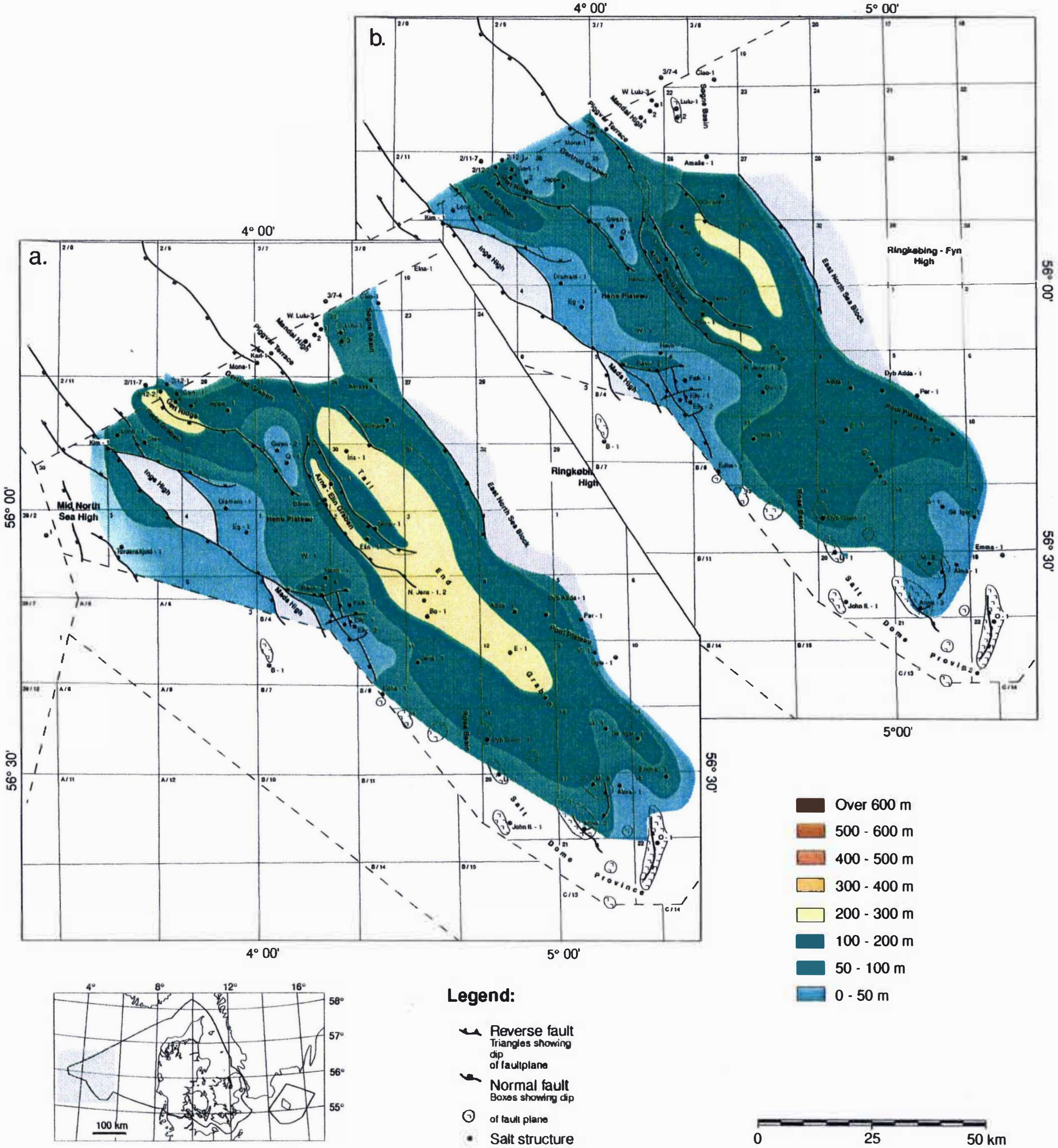

a.
b.
4° 00'
5° 00'
56° 00'
56° 30'
Mid North Sea High
Inge High
Ringkøbing - Fyn High
East North Sea Block
Salt Dome Province
Over 600 m
500 - 600 m
400 - 500 m
300 - 400 m
200 - 300 m
100 - 200 m
50 - 100 m
0 - 50 m
Legend:
Reverse fault
Triangles showing dip of faultplane
Normal fault
Boxes showing dip of fault plane
Salt structure
0
25
50 km
100 km

Fig. 16

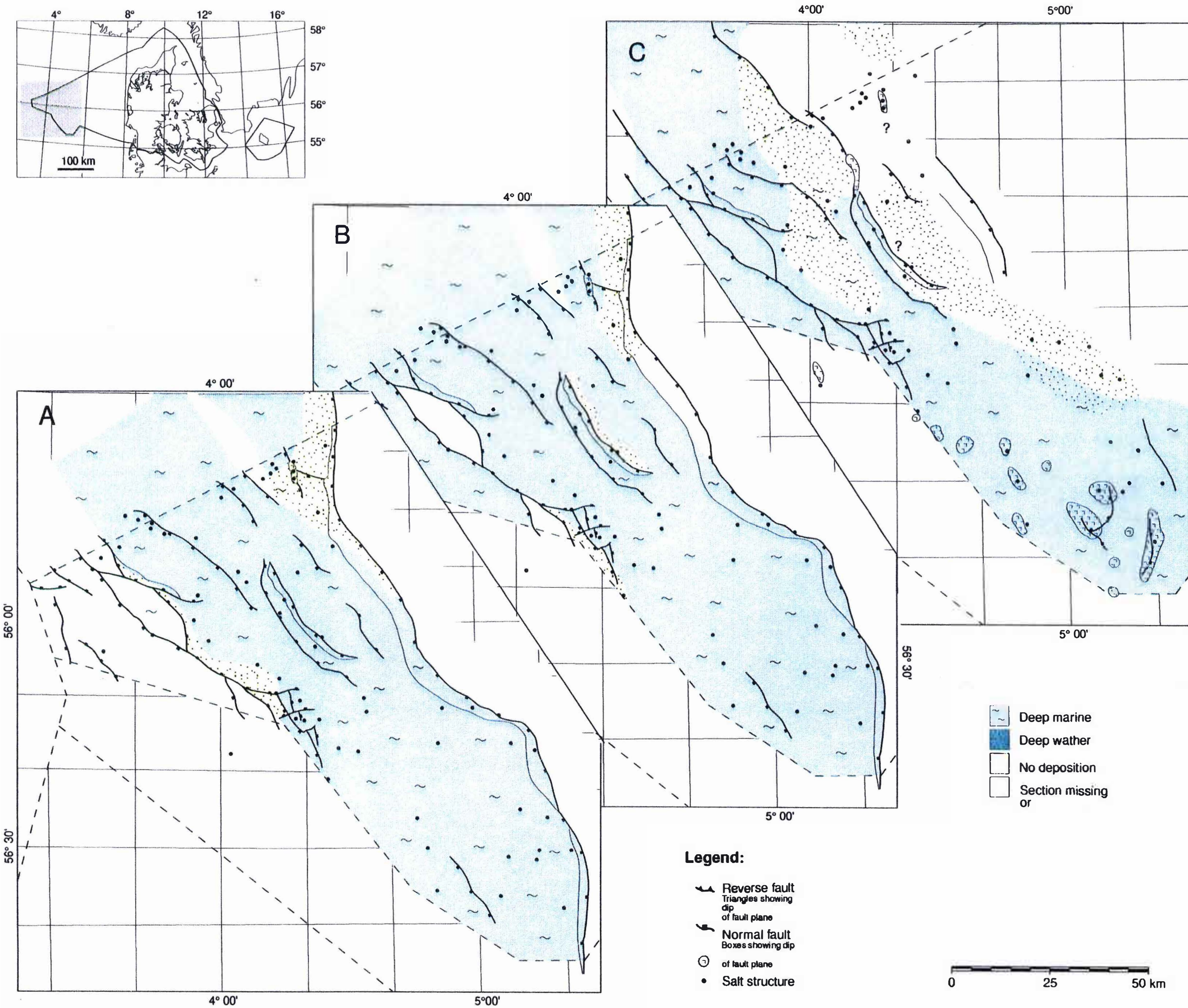

A
B
C
4° 00'
5°00'
56° 00'
56° 30'
?
Legend:
Reverse fault
Triangles showing dip of fault plane
Normal fault
Boxes showing dip of fault plane
Salt structure
Deep marine
Deep wather
No deposition
Section missing or
0
25
50 km
100 km
58°
57°
56°
55°
4°
8°
12°
16°

Fig. 17

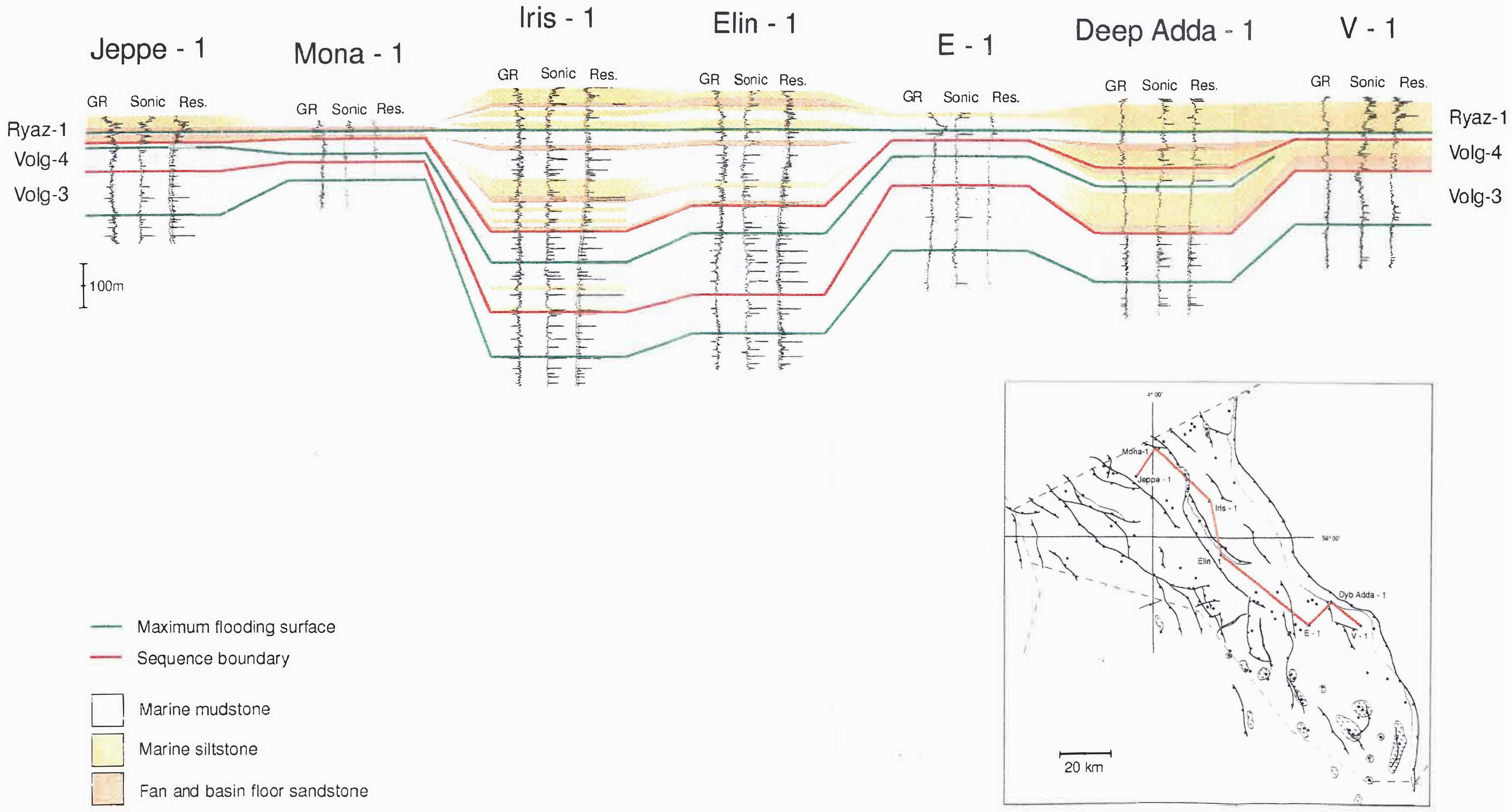

Jeppe - 1
Mona - 1
Iris - 1
Elin - 1
E - 1
Deep Adda - 1
V - 1
GR
Sonic
Res.
Ryaz-1
Volg-4
Volg-3
100m
Maximum flooding surface
Sequence boundary
Marine mudstone
Marine siltstone
Fan and basin floor sandstone
Mona-1
Jeppe - 1
Iris - 1
Elin - 1
Dyb Adda - 1
E - 1
V - 1
20 km

Fig. 18

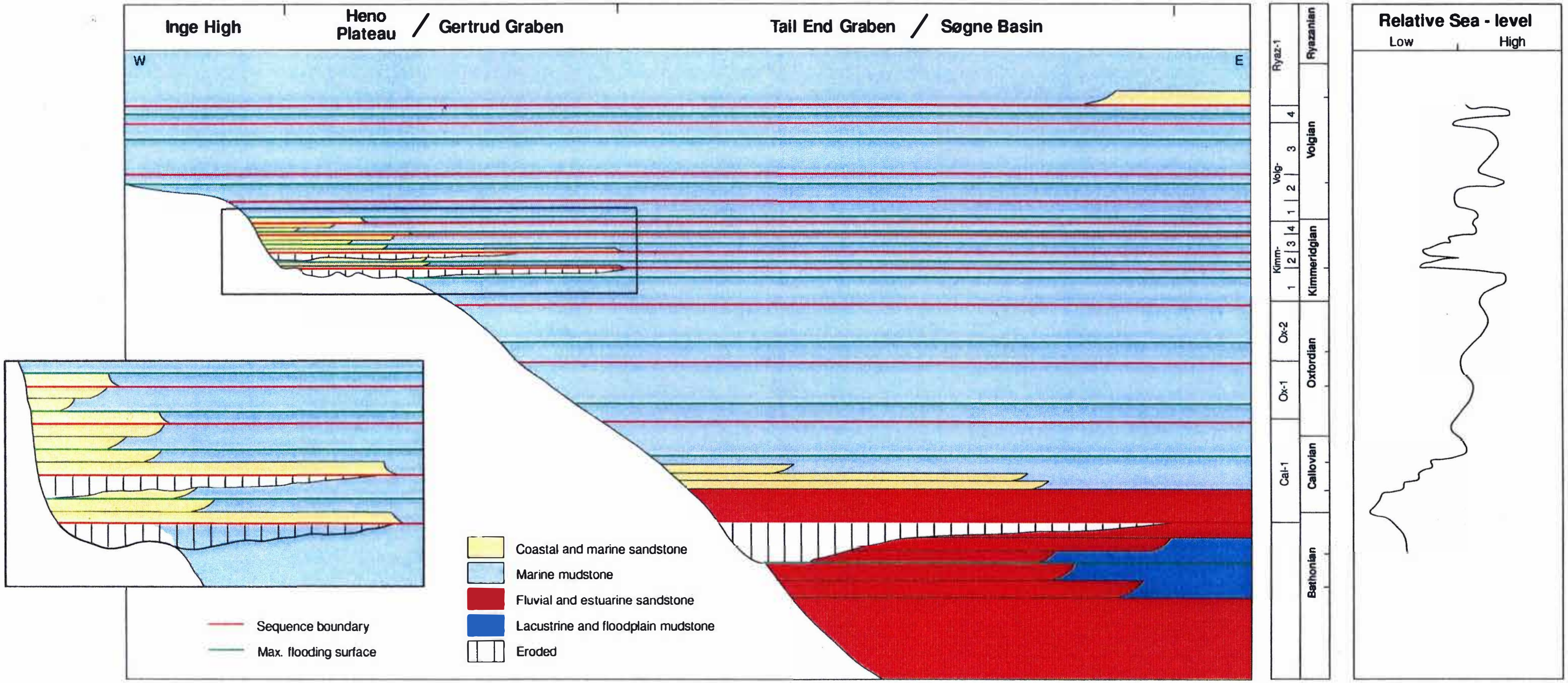
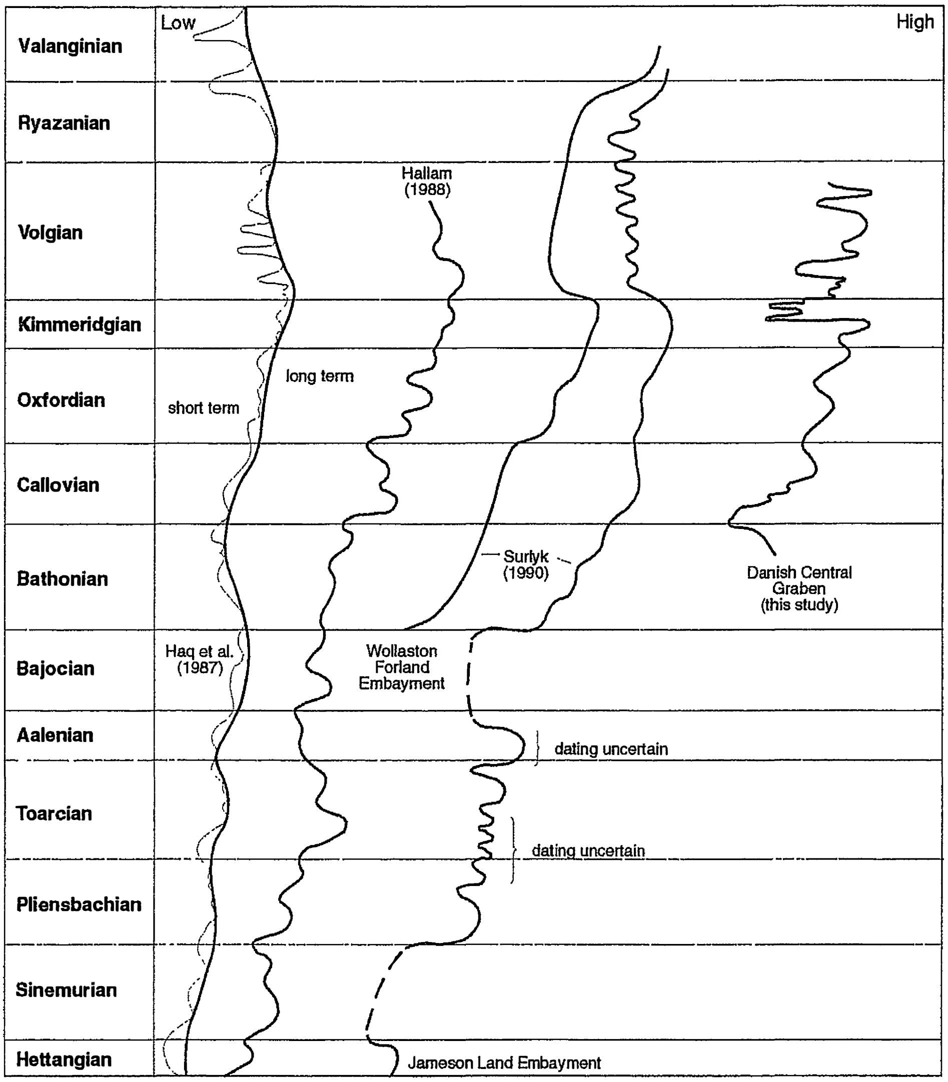
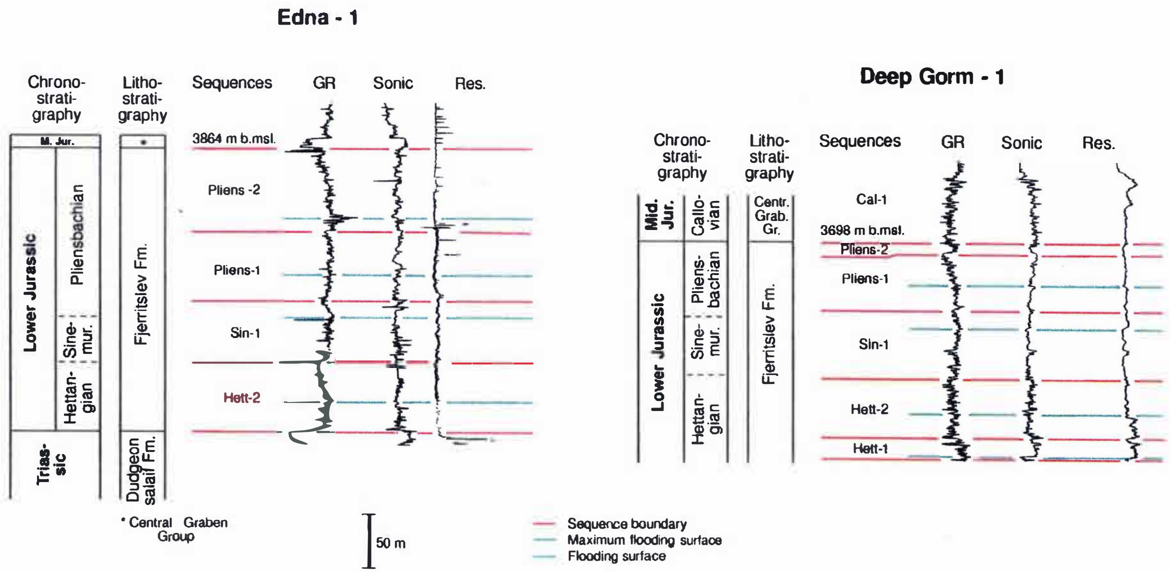

Inge High
Heno Plateau / Gertrud Graben
Tail End Graben / Søgne Basin
W
E
Coastal and marine sandstone
Marine mudstone
Fluvial and estuarine sandstone
Lacustrine and floodplain mudstone
Eroded
Sequence boundary
Max. flooding surface
Ryaz-1
Ryazanian
Volg-
4
3
2
1
Volgian
Kimm-
4
3
2
1
Kimmeridgian
Ox-2
Ox-1
Oxfordian
Cal-1
Callovian
Bathonian
Relative Sea - level
Low
High

Fig. 19



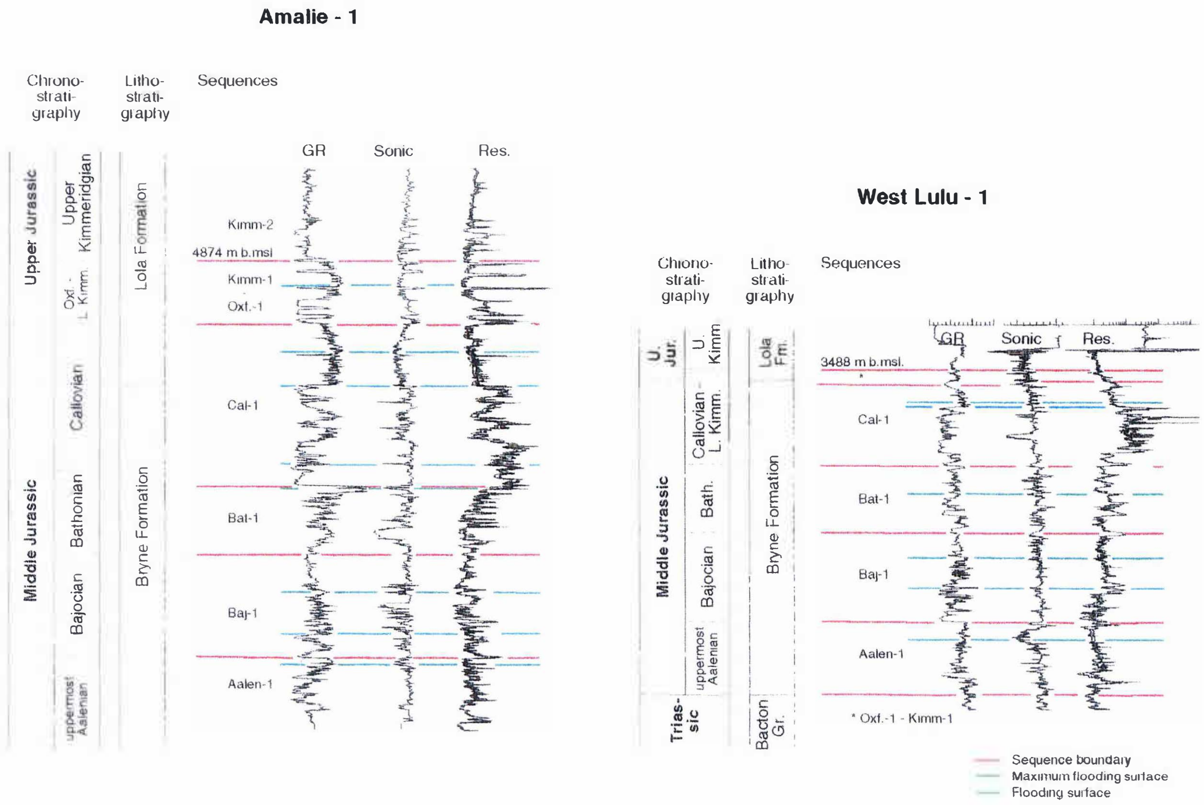
Valanginian
Ryazanian
Volgian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Low
High
Hallam (1988)
long term
short term
Surlyk (1990)
Danish Central Graben (this study)
Haq et al. (1987)
Wollaston Forland Embayment
dating uncertain
dating uncertain
Jameson Land Embayment


Fig.20



Edna - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
M. Jur.
Lower Jurassic
Pliensbachian
Sine-mur.
Hettan-gian
Trias-sic
Fjerritslev Fm.
Dudgeon salair Fm.
3864 m b.msl.
Pliens -2
Pliens-1
Sin-1
Hett-2
* Central Graben Group
50 m
Sequence boundary
Maximum flooding surface
Flooding surface
Deep Gorm - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Mid. Jur.
Callo-vian
Centr. Grab. Gr.
Lower Jurassic
Pliens-bachian
Sine-mur.
Hettan-gian
Fjerritslev Fm.
Cal-1
3698 m b.msl.
Pliens-2
Pliens-1
Sin-1
Hett-2
Hett-1


Fig.21



Amalie - 1
Chrono-stratigraphy
Litho-stratigraphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Middle Jurassic
Upper Kimmeridgian
Oxf. - L. Kimm.
Callovian
Bathonian
Bajocian
uppermost Aalenian
Lola Formation
Bryne Formation
Kimm-2
4874 m b.msl
Kimm-1
Oxf.-1
Cal-1
Bat-1
Baj-1
Aalen-1
West Lulu - 1
Chrono-stratigraphy
Litho-stratigraphy
Sequences
GR
Sonic
Res.
U. Jur.
Middle Jurassic
Triassic
U. Kimm
Callovian - L. Kimm.
Bath.
Bajocian
uppermost Aalenian
Lola Fm.
Bryne Formation
Bacton Gr.
3488 m b.msl.
Cal-1
Bat-1
Baj-1
Aalen-1
* Oxf.-1 - Kimm-1
Sequence boundary
Maximum flooding surface
Flooding surface


Fig.22

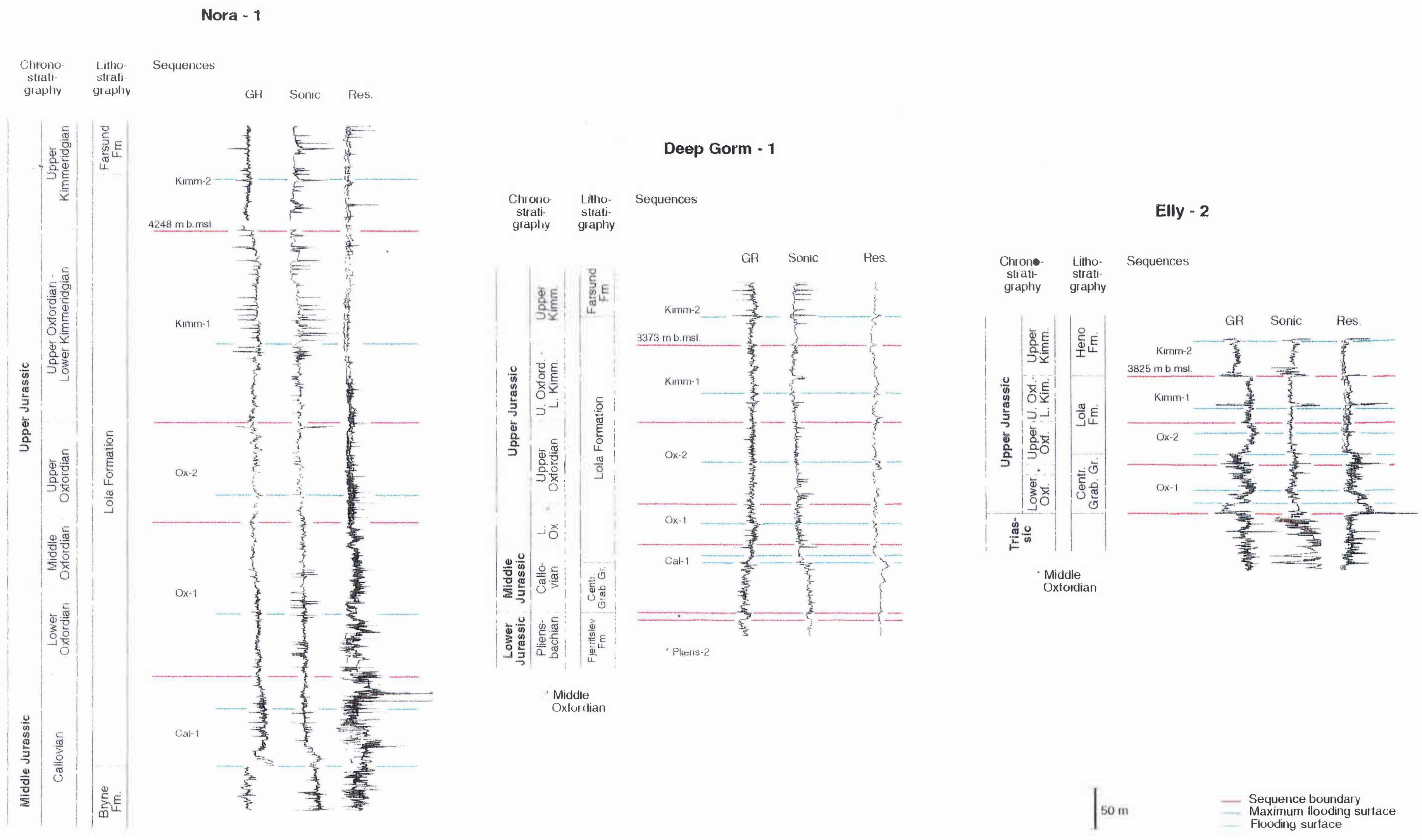

Nora - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Middle Jurassic
Upper Kimmeridgian
Upper Oxfordian - Lower Kimmeridgian
Upper Oxfordian
Middle Oxfordian
Lower Oxfordian
Callovian
Farsund Fm
Lola Formation
Bryne Fm.
Kimm-2
4248 m b.msl
Kimm-1
Ox-2
Ox-1
Cal-1
Deep Gorm - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Middle Jurassic
Lower Jurassic
Upper Kimm.
U. Oxford - L. Kimm.
Upper Oxfordian
L. Ox
Callo-vian
Pliens-bachian
Farsund Fm
Lola Formation
Centr. Grab. Gr.
Fjerritslev Fm
Kimm-2
3373 m b.msl.
Kimm-1
Ox-2
Ox-1
Cal-1
* Pliens-2
* Middle Oxfordian
Elly - 2
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Trias-sic
Upper Kimm.
U. Oxf. - L. Kim.
Upper Oxf.
Lower Oxf.
Heno Fm.
Lola Fm.
Centr. Grab. Gr.
Kimm-2
3825 m b msl.
Kimm-1
Ox-2
Ox-1
* Middle Oxfordian
50 m
Sequence boundary
Maximum flooding surface
Flooding surface

Fig.23

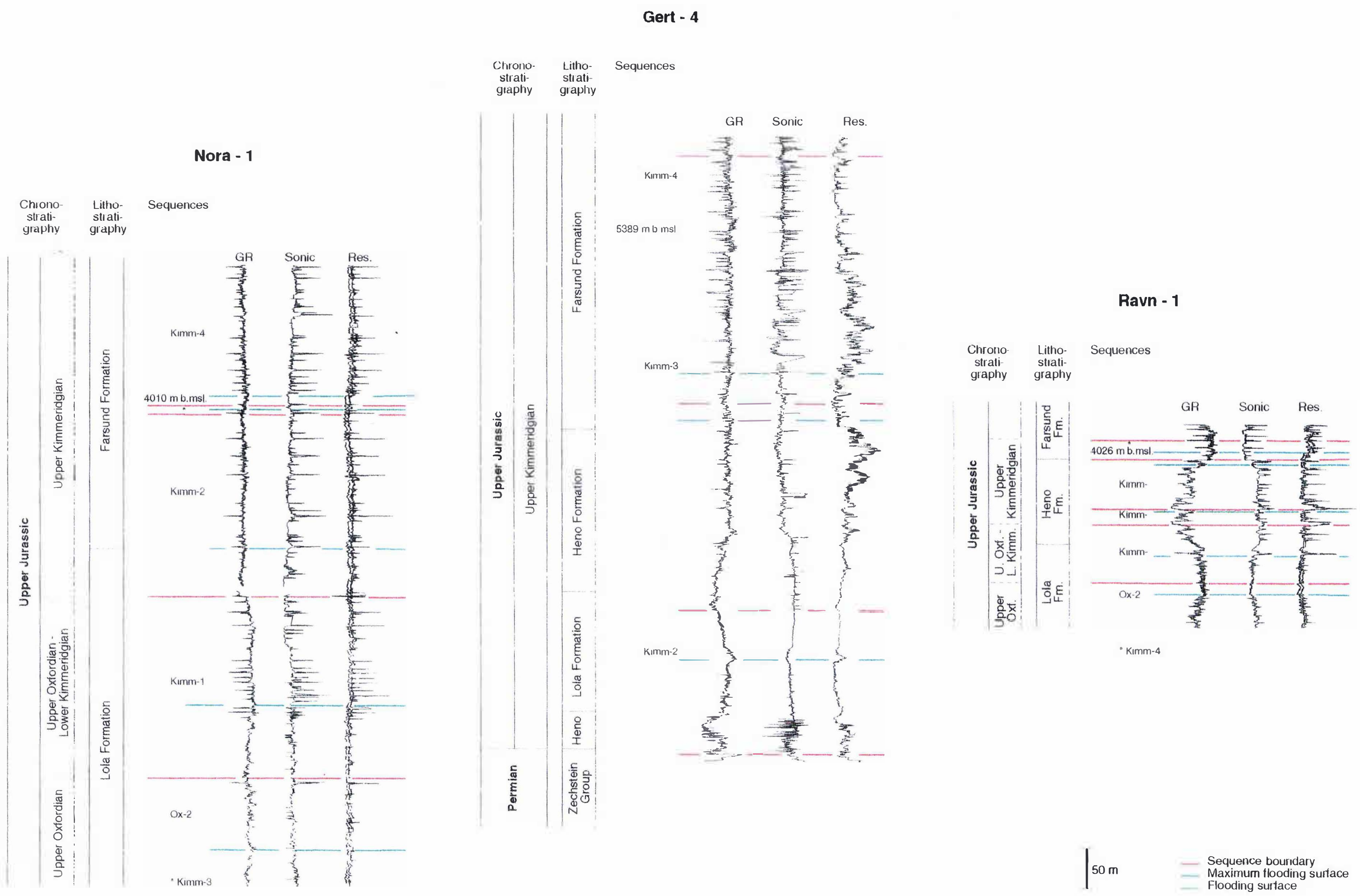
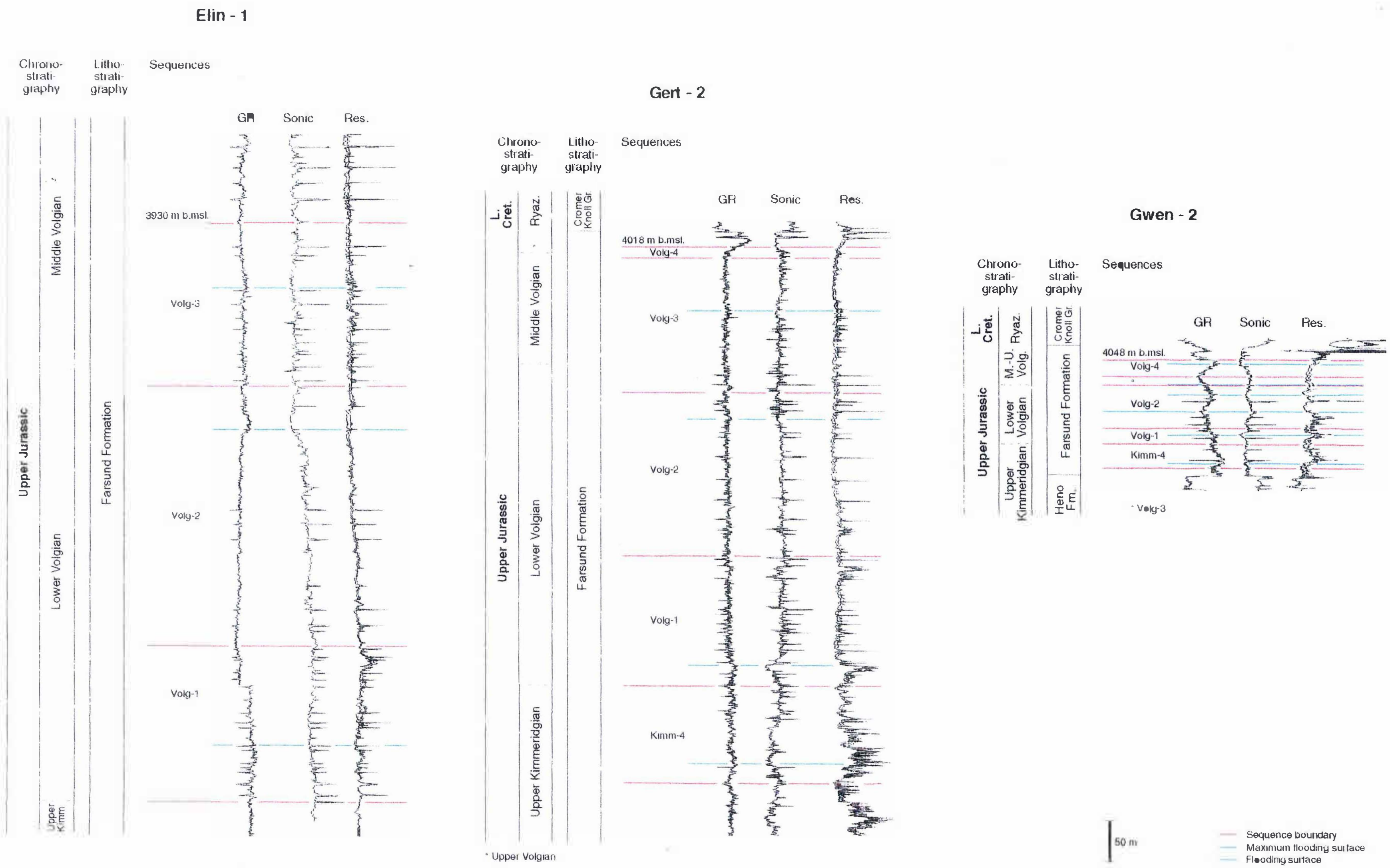
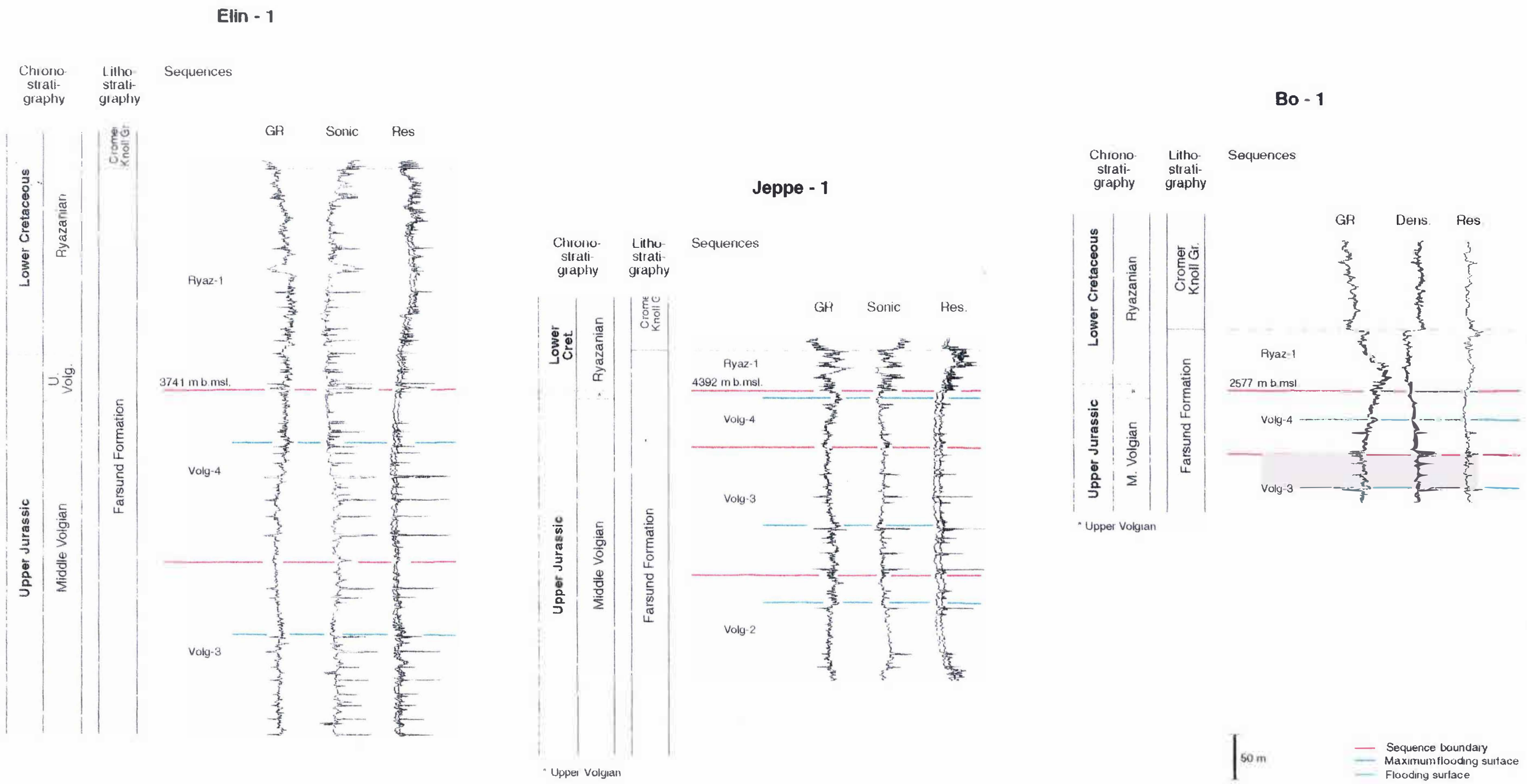

Nora - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Upper Kimmeridgian
Upper Oxfordian - Lower Kimmeridgian
Upper Oxfordian
Farsund Formation
Lola Formation
Kimm-4
4010 m b.msl.
Kimm-2
Kimm-1
Ox-2
* Kimm-3
Gert - 4
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Upper Kimmeridgian
Permian
Farsund Formation
Heno Formation
Lola Formation
Heno
Zechstein Group
Kimm-4
5389 m b msl
Kimm-3
Kimm-2
Ravn - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Upper Kimmeridgian
U. Oxf. - L. Kimm.
Upper Oxf.
Farsund Fm.
Heno Fm.
Lola Fm.
4026 m b.msl.
Kimm-
Kimm-
Kimm-
Ox-2
* Kimm-4
50 m
Sequence boundary
Maximum flooding surface
Flooding surface

Fig.24



Elin - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Upper Jurassic
Middle Volgian
Lower Volgian
Upper Kimm
Farsund Formation
3930 m b.msl.
Volg-3
Volg-2
Volg-1
Gert - 2
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
L. Cret.
Ryaz.
Cromer Knoll Gr.
Upper Jurassic
Middle Volgian
Lower Volgian
Upper Kimmeridgian
Farsund Formation
4018 m b.msl.
Volg-4
Volg-3
Volg-2
Volg-1
Kimm-4
* Upper Volgian
Gwen - 2
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
L. Cret.
Ryaz.
Cromer Knoll Gr.
Upper Jurassic
M.-U. Volg.
Lower Volgian
Upper Kimmeridgian
Farsund Formation
Heno Fm.
4048 m b.msl.
Volg-4
Volg-2
Volg-1
Kimm-4
* Volg-3
50 m
Sequence boundary
Maximum flooding surface
Flooding surface


Fig.25



Elin - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res
Lower Cretaceous
Upper Jurassic
Ryazanian
U. Volg.
Middle Volgian
Cromer Knoll Gr.
Farsund Formation
Ryaz-1
3741 m b.msl.
Volg-4
Volg-3
Jeppe - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Sonic
Res.
Lower Cret.
Upper Jurassic
Ryazanian
Middle Volgian
Farsund Formation
Ryaz-1
4392 m b.msl.
Volg-4
Volg-3
Volg-2
* Upper Volgian
Bo - 1
Chrono-strati-graphy
Litho-strati-graphy
Sequences
GR
Dens.
Res
Lower Cretaceous
Upper Jurassic
Ryazanian
M. Volgian
Cromer Knoll Gr.
Farsund Formation
Ryaz-1
2577 m b.msl
Volg-4
Volg-3
* Upper Volgian
50 m
Sequence boundary
Maximum flooding surface
Flooding surface


Fig.26

| Time in Ma (Haq et al. 1987) | Epoch | Age | | Boreal Standard Chrons | Bioevents (Palynology): First appearance datums | Bioevents (Palynology): Last occurrence datums |
|---|---|---|---|---|---|---|
| 180 | EARLY JURASSIC | Toarcian | Late | Levesquei | | |
| | | | | Thouarsense | | |
| | | | | Variabilis | | |
| | | | Early | Bifrons | | |
| | | | | Falciferum | | |
| | | | | Tenuicostatum | | |
| | | Pliensbachian | Late | Spinatum | | |
| | | | | Margaritatus | | |
| 190 | | | Early | Davoei | | |
| | | | | Ibex | | |
| | | | | Jamesoni | | |
| | | Sinemurian | Late | Raricostarum | | Liasidium variabile |
| | | | | Oxynotum | | |
| | | | | Obtusum | Liasidium variabile | |
| | | | Early | Turneri | | |
| | | | | Semicostatum | | Dapocodinium priscum 5) |
| 200 | | | | Bucklandi | Cerebropollenites macroverrocosus 2) | |
| | | Hettangian | | Angulata | | |
| | | | | Liasicus | | |
| | | | | Planorbis | | |
| 210 | L. TRIAS | Rhaetian | | | Dapcodinium priscum | |

Tab.1a

| Time in Ma (Haq et al. 1987) | Epoch | Age | | Boreal Standard Chrons | Bioevents (Palynology): First appearance datums | Bioevents (Palynology): Last occurrence datums |
|---|---|---|---|---|---|---|
| | MIDDLE JURASSIC | Callovian | Late | Lamberti | | |
| | | | | Athleta | | |
| | | | Middle | Coronatum | | |
| | | | | Jason | | |
| | | | Early | Calloviense | | Impletosphaeridium varispinosum |
| | | | | Koenigi | | |
| | | | | Herveyi | | |
| | | Bathonian | Late | Discus | | |
| | | | | Orbis | Impletosphaeridium varispinosum | |
| | | | | Hodsoni | | |
| 160 | | | Middle | Morrisi | | |
| | | | | Subcontractus | | |
| | | | | Progracilis | | |
| | | | Early | Tenuiplicatus | | |
| | | | | Zigzag | | |
| | | Bajocian | Late | Parkinsoni | Adnatosphaeridium caulleryi | |
| | | | | Garantiana | | |
| | | | | Subfurcatum | | |
| | | | Early | Humphriesianum | | |
| | | | | Sauzei | | |
| 170 | | | | Laeviuscula | | Kekryphalospora distincta 1) |
| | | | | Discites | | |
| | | Aalenian | | Concavum | | |
| | | | | Murchisonae | | |
| | | | | Opalinum | | |

Tab. 1b

| Time in Ma (Haq et al. 1987) | Epoch | Age | | Boreal Standard Chrons | Bioevents (Palynology) First appearancee datums | Bioevents (Palynology) Last occurrence datums |
|---|---|---|---|---|---|---|
| | EARLY CRET. | Valanginian | | Paratollia | | |
| | | Ryazanian | Late | Albidum | | Dingodinium spinosum 4) |
| | | | | Stenomphalus | | Dichadogonyaulax culmula 4) |
| | | | | Icenii | | |
| 130 | | | Early | Kochi | | Rotosphaeropsis thula 4) |
| | | | | Runctoni | | Egmontodinium expiratum 4) |
| | LATE JURASSIC | Volgian | Late | Lamplughi | | |
| | | | | Preplicomphalus | | |
| | | | | Primitivus | | Egmontodinium polyplacophorum |
| | | | Middle | Oppressus | | Dichadogonyaulax pannea |
| | | | | Anguiformis | | Glossodinium dimorphum |
| | | | | Kerberus | | Muderongia simplex * |
| | | | | Okusensis | | Gochteodinia mutabilis<br>Senoniasphaera jurassica 6)** |
| | | | | Glaucolithus | | |
| | | | | Albani | | Scriniodinium inritibile<br>Occisucysta balia |
| | | | | Fittoni | | |
| | | | | Rotunda | | |
| | | | | Pallasioides | | Perisseiasphaeridium pannosum |
| | | | Early | Pectinatus | | Oligosphaeridium patulum |
| | | | | Hudlestoni | | Cribroperidinium longicorne |
| | | | | Wheatleyensis | | |
| | | | | Scitulus | | |
| | | | | Elegans | | Subtilisphaera? paeminosa |
| 140 | | Kimmeridgian | Late | Autissiodorensis | | Endoscrinium luridum |
| | | | | Eudoxus | | |
| | | | | Mutabilis | Subtilisphaera? paeminosa 3)<br>S.? inaffecta 3) | Stephanelytron scarburghense |
| | | | Early | Cymodoce | | Endoscrinium galeritum |
| | | | | Baylei | | Scriniodinium crystallinum<br>Nannoceratopsis pellusida |
| | | Oxfordian | Late | Rosenkrantzi | | |
| | | | | Regulare | | |
| | | | | Serratum | | |
| | | | | Glosense | | Compositosphaeridium polonicum |
| | | | Middle | Tenuiserratum | | Rigaudella aemula |
| 150 | | | | Densiplicatum | | |
| | | | Early | Cordatum | | Wanaea spp. |
| | | | | Mariae | | Ctenidodinium continuum |

Tab.1c

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Sedimentology and sequence stratigraphy of Middle Jurassic deposits

## Danish and Norwegian Central Graben
## Part 2

Jan Andsbjerg

Ph.D. Thesis, University of Copenhagen, Geological Institute

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Sedimentology and sequence stratigraphy of the Bryne Formation

## Middle Jurassic, Danish Central Graben

Jan Andsbjerg

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

# Sedimentology and sequence stratigraphy of the Bryne Formation; Middle Jurassic, Danish Central Graben

Jan Andsbjerg

# Contents

# Abstract

The Middle Jurassic Bryne Formation of the Søgne Basin (northern part of the Danish Central Graben) consists of fluvial channel and floodplain dominated coastal plain deposits, overlain by interfingering shoreface and tidally-influenced backbarrier deposits. The Bryne formation and the marine mudstones of the overlying Lola Formation shows an overall transgressive development.

The alluvial plain/coastal plain deposits of the lower Bryne Formation are dominated by laterally continuous, mainly upward-fining fluvial channel sandstones. The sandstones are separated by units of fine-grained floodplain sediments showing a characteristic fining/coarsening upward pattern. In the upper part of the lower Bryne Formation the fine grained units may grade into lacustrine mudstones in central and eastern parts of the basin. A large number of mud laminae in some channel sandstones may suggest deposition in the lower tidally influenced part of a river system.

The backbarrier/shoreface dominated upper Bryne Formation is separated from the lower Bryne Formation by the strongly erosional base of stacked estuarine and fluvial channel sandstones. Log correlations suggest that several tens of metres of the lower Bryne Formation have been removed by erosion at this level. Above the erosion surface are channel sandstones up to 10 m thick stacked in sections of up to 45 m thickness. Most channel sandstones in this unit show abundant mud laminae and flasers, and rare herringbone structures, suggestive of a tidal influence. The large thickness of the tidally influenced channel sandstones may indicate deposition in large estuary channels. The stacked estuarine channel sandstones are capped by a succession of coal beds, that attain thicknesses of several metres in the western part of the study area; but change to thin, poorly developed coals in the central part of the basin. Above the coal beds the upper Bryne Formation is dominated by estuarine channel sandstones and other back-barrier deposits in the western part of the study area and by coarsening upward shoreface deposits in central parts of the basin. Evidence for an interfingering relationship between deposits of the two environments is provided by the thin units of upward coarsening shoreface deposits, that can be traced into areas dominated by back-barrier deposits. The back-barrier deposits were deposited during successive transgressions; but partly removed, especially in more distal settings, by erosion at the ravinement surface. The shoreface deposits prograded into deeper parts of the basin during periods with a decreasing rate of sea-level rise, sea level stillstand, or fall. The distal parts of a final progradational shoreface sandstone/siltstone is present in the lowermost Lola Formation.

The succession, comprising the Bryne Formation and the lowermost part of the Lola Formation, is subdivided into 10 sequences. Sequence boundaries are situated at the base of laterally continuous fluvial channel sandstones in the lower Bryne Formation. In that part of the succession are maximum flooding surfaces located in laterally extensive floodplain or lacustrine mudstones, usually at the inflection point between a fining upward and a coarsening upward unit. The strongly erosional channel base, separating the alluvial plain deposits of the lower Bryne Formation from the estuary and shoreface deposits of the upper Bryne Formation is interpreted as a major sequence boundary, forming an incised valley. Other sequence boundaries in the upper Bryne Formation are situated at the top of progradational shoreface units or at the base of estuarine channels. The sequences are

dominated by thick units of transgressive estuarine and other back-barrier deposits in the proximal western part of the basin, and by progradational highstand or forced regressive shoreface deposits in more distal parts of the study area.

The change from uniformly distributed facies showing little thickness variations in the lower Bryne Formation to asymmetrically distributed facies and thicknesses in the upper Bryne Formation may be attributed to the onset of rift related subsidence in a half graben.

# Introduction

## The Bryne Formation

Middle Jurassic sandstones with interbedded mudstones and coals were encountered by the first exploration well in the Danish part of the Søgne Basin, Lulu-1 (figs. 1,2). Similar deposits encountered in the Norwegian part of the Central Graben were included in the Bryne Formation, that was established by Vollset and Doré (1984). The Bryne Formation was extended to the Middle Jurassic deposits of the northern part of the Danish Central Graben by Jensen et al. (1986). Similar and coeval deposits of the southern part of the Danish Central Graben were referred to the Central Graben Group of NAM and RGD (1980) by Jensen et al. (1986).

In the Søgne Basin the Bryne Formation unconformably overlies Triassic and Permian deposits and is conformably overlain by marine mudstones of the Upper Jurassic Lola Formation (Jensen et al., 1986) and unconformably by Cretaceous deposits on structural highs. The Bryne Formation shows thicknesses from 130 to 300 m in the wells of the Søgne Basin. It may be absent from the top of structural highs, but it may attain slightly larger thicknesses in deeper parts of the basin.

Based on detailed sedimentological analysis of cores the Middle Jurassic of the Lulu-1 well was interpreted deltaic interdistributary bay deposits overlain by coastal sediments (Frandsen, 1986). Middle Jurassic deposits farther south in the Danish Central Graben were previously interpreted as alluvial plain and delta plain deposits by Koch (1983). Damtoft et al. (1992) suggested a fluvial channel and floodplain environment for the Bryne Formation, whereas Johannesen and Andsbjerg (1993) interpreted the Bryne Formation as an alluvial plain succession overlain by tidal and shallow marine deposits.

## Regional setting and structural development

The Danish Central Graben is part of the Central Graben (fig. 1), a complex N - S trending Mesozoic intra-cratonic rift basin. Subsidence of the Danish Central Graben was initiated in the Triassic and was most active during the Middle and Late Jurassic (Møller, 1986). The Central Graben separates the Mid North Sea High to the west from the East North Sea of the Ringkøbing -Fyn High to the east Block (Japsen et al., this volume).

The development of the Danish Central Graben was determined by differential subsidence of grabens along N - S and NW - SE trending faults. The Søgne Basin and Tail End Graben began to subside as separate half-grabens during the Middle Jurassic (Gowers and Sæbøe, 1985; Møller, 1986). Initiation of rift-associated subsidence was probably related to domal uplift and subsequent dome collapse in the North Sea area (Ziegler, 1982,1990; Underhill and Partington, 1993). Most authors agree that asymmetric subsidence was initiated in the Søgne Basin in connection with boundary fault activity during the Middle Jurassic (e.g. Gowers and Sæbøe, 1985, Møller, 1986; Cartwright, 1991; Michelsen et al., 1992, Farther et al., 1993). It has been suggested, however, that no syndepositional rotation took place in the Søgne Basin until Volgian time (Sundsbø and Megson, 1993).

According to Mogensen et al. (1992) salt structures were generated in the Søgne Basin in the Triassic. Middle Jurassic subsidence and faulting initiated the development of boundary fault salt pillows and updip salt structures in the southern Søgne Basin.

## Wells and well logs

Data from 9 of the 12 wells penetrating the Bryne Formation in the Søgne Basin are used in the present study(fig. 2). Approximately 700 m of core has been examined and described. Graphic core logs are matched to gamma ray (GR) and sonic logs supplemented by density, neutron and resistivity logs, in order to gain an improved interpretation of the cored successions. The observed core to log relationships are used in the interpretation of well logs from uncored intervals, where sedimentological interpretations of cores are extrapolated to the uncored sections. The well logs are used to construct cross-sections. Well to well correlations of key surfaces and characteristic units form a framework that guide correlations of other units and form the basis for the construction of palaeogeographic maps.

## Biostratigraphy

Stratigraphically useful microfossils are rare in the studied succession. The sparse biostratigraphic information available for this study comes from unpublished reports from the Geological Survey of Denmark and Greenland (GEUS), reports from service companies, and the results of new investigations prepared for the study presented by Andsbjerg and Dybkjær (this volume). Only palynomorphs were used for the datings of that study, and the events are presented mainly as last occurrence datums (LOD) of dinoflagellate cyst species. The events used and their relation to boreal standard chrons are presented in Andsbjerg and Dybkjær (this volume, their table 2).

Age specific microfossils have not been found in the lower part of the Bryne Formation. However, the occurrence of the LOD of *Kekryphalospora distincta* in a supposedly correlatable section in Alma-1 farther south in the Danish Central Graben indicate an Aalenian or earliest Bajocian age. The occurrence of *Adnatosphaeridium caulleryi* in the upper part of the Bryne Formation in West Lulu-1 indicates an age not older than the Bathonian, and a LOD of *Impletosphaeridium varispinosum* in the same interval indicates a latest Bathonian to early Callovian age. The LOD of *Ctenidodinium continuum* higher in the succession indicates an Early Callovian - earliest Oxfordian age for the uppermost part of the Bryne Formation. The LOD of *Liesbergia scarburghensis* in the basal part of the Lola Formation in several wells (Andsbjerg and Dybkjær, this volume), indicates a mid Oxfordian age for the final transgression of the major part of Søgne Basin. The uppermost unit of coal-bearing sandstones and mudstones in West Lulu-4 cannot be correlated to the Bryne Formation in other wells of that area. This may indicate that a sand-prone paralic environment lasted somewhat longer at the western fringe of the basin.

# Sedimentary facies and depositional environments

## Facies descriptions

Approximately 500 m of slabbed cores were available for the description of sedimentary facies. Facies descriptions include the registration of lithology, grain size, primary sedimentary structures and degree and type of bioturbation. Facies are grouped into facies associations, each of which are characteristic for 9 specific sedimentary environments. Facies of the Bryne Formation are listed in Tables 1 - 3.

## Non-marine deposits

### Facies associations

Sediments interpreted as mainly non-marine dominates the lower part of the Bryne Formation. They are grouped into four facies associations representing fluvial channel fill, proximal floodplain, lake and distal floodplain, and vegetated floodplain.

### Fluvial channel fill association

The fluvial channel fill association occur as erosionally based, upward fining, sandstone dominated, channel units up to 8 m thick. A conglomerate of mudstone clasts commonly occur right above the erosional base. The most common facies of the channel fill association are trough and planar cross-bedded sandstone and ripple cross-laminated sandstone. Another common facies is chaotic bedded sandstone, characterised by contorted bedding, soft sediment deformation and a chaotic texture with abundant plant debris and sometimes intraformational mudstone clasts. Chaotic bedding may be a result of bank collapse, and post-depositional collapse of stems and other plant material deposited behind obstacles in the channel. Similar deposits have been described by Alexander and Gawthorpe (1993) as their facies S4 and Guion et al. (1995) as part of their minor channel facies. Heterolithic deposits and mudstones may dominate the upper part of the fining upward units. Occasional 10 to 30 cm thick heterolithic beds interbedded with sandstone may represent inclined heterolithic strata (Thomas et al., 1984) a variant of epsilon cross-stratification characteristic of tidally influenced fluvial channels (Smith, 1987). Mudstone laminae, double mud drapes and flaser bedding are abundant in the sandstone facies of some units, and suggest occasional tidal influence in the river system.

Several upward fining, channel units can be correlated between most wells in the study area, thus representing laterally extensive channel sandstones, deposited by laterally migrating, sinuous rivers. The occasional tidal influence indicates deposition in a coastal plain environment.

### Proximal floodplain association

The proximal floodplain association consists of interbedded sandstone, siltstone and mudstone. The sandstones are generally less than 2 m thick, but may occur amalgamated into units 4 to 5 m thick. The sandstone units may be upward fining, upward coarsening or massive. Primary structures include cross-bedding, current ripple lamination, climbing ripple lamination, wave ripple cross-lamination, parallel lamination and chaotic bedding with abundant mudstone and coal clasts. Soft sediment deformation structures are common.

The sandstones were deposited in small channels, crevasse splays, and small lacustrine deltas and on levees. Some sandstone units that show bi-directional current ripples, mud flasers and abundant mud laminae were probably influenced by tidal processes during deposition in fluvial channels and bay-head deltas. Siltstones and mudstones of this association commonly are massive or show abundant deformation structures, parallel lamination and lenticular bedding. They are interpreted as waning flow deposits on levees and in small fluvial and crevasse channels.

### Lake and distal floodplain association

Mudstones and siltstones dominate the lake and distal floodplain association. Interbedded sandstones are not thicker than a few decimetres. Mudstones and siltstones occur as up to 5 m thick units, that most commonly are massive or show parallel lamination. The parallel lamination commonly is faint or appear irregular and slightly deformed. More heterolithic units may show lenticular and wavy bedding and current and wave ripples in thin sand beds.

The sediments are interpreted as deposited in ponds, shallow lakes and on the distal levee. Sediments of this association may also represent passive infill of abandoned channels.

### Vegetated floodplain association

Sediments of all lithologies with abundant root traces, mottled siltstone and mudstone and thin coal beds are combined in this facies association. The depositional environment was a floodplain where primary deposits were modified by vegetation and soil forming processes.

## Marginal marine deposits

### Facies associations

Backbarrier and estuarine deposits are common in the western part of the study area, where they dominate the upper part of the Bryne Formation. The marginal marine deposits are separated into five facies associations, representing estuary channels and bars, flood tidal deltas and washover fans, bay-head deltas, low-energy estuary and lagoon, and marsh and swamp.

## Estuary channel and bar association

The estuary channel and bar association occur as 4 - 10 m thick upward fining, massive, or occasionally upward coarsening sandstone dominated units, and as 0.5 - 4 m thick, upward fining, fine- to very fine-grained sandstones and heteroliths. The sandstone units are planar and trough cross-bedded with abundant mudstone laminae and ripple cross-laminated with abundant mudstone flasers. Coal fragments and mudstone clasts occur in some beds, most commonly above erosional bases of upward fining or massive sandstone units. Heterolithic strata, 5 - 20 cm thick, interbedded with the sandstones may represent beds of inclined heterolithic stratification (Thomas et al., 1987). Interbedded sandstones, mudstones and heteroliths in the fine-grained units show flaser, wavy and lenticular bedding and parallel lamination. Bioturbation in channel deposits varies from moderate to intense with common *Teichichnus*. Up to 5 m thick coarsening upward units occur as progressively thicker and coarser grained sandstone beds separated by thin mudstone and siltstone beds. These sandstone beds may show cross-bedding, ripple cross-lamination, and mudstone flasers and laminae, but may also occur massive except for a few inclined mudstone laminae and mudstone flasers.

Several metres thick sandstones dominated by cross-bedding and ripple cross-lamination are interpreted as channel deposits. The largest fining upward sandstone units can be traced between several wells, although with highly variable thickness. This indicates that they were deposited by laterally migrating channels. The abundance of mudstone laminae, double drapes and flaser bedding suggests deposition in estuary channels. The finer-grained fining upward units are passive infills of major channels, or active fill of minor channels. The coarsening upward sandstone units may represent bars in major tidal channels or mouth bars of bay-head deltas.

## Flood tidal delta and washover fan association

The flood tidal delta and washover fan association consists of up to 3 m thick, generally coarsening upward units of sandstones and heteroliths, that may be overlain by fining upward units of well-sorted sandstone. In the coarsening upward units fine-grained heterolithic beds show lenticular and wavy bedding. The most fine-grained sandstones are commonly strongly bioturbated, but may some show flaser bedding and parallel lamination. Coarser grained sandstone facies include trough cross-bedded, parallel laminated and ripple cross-laminated sandstone. The coarser grained sandstones may have erosional surfaces overlain by thin conglomerates. The upward fining units are dominated by well-sorted, fine- or very fine-grained sandstone, showing parallel lamination, low-angle planar cross-bedding, ripple cross-lamination, and soft-sediment deformation structures.

The fine-grained heterolithic beds characterised by wavy and lenticular bedding and the coarsening upward sandstones with abundant mudstone laminae and flaser bedding, frequently interbedded with lagoonal mudstones, are interpreted as the deposits of flood tidal deltas and tidal sand flats. The upward coarsening trend and the association of physical structures correspond well with the description of recent flood-tidal deltas (e.g. Nichol and Boyd, 1993). this interpretation is further supported by the interbedding with lagoonal sediments. The well-sorted, erosionally based, upward fining units, that occasionally overlie flood tidal delta and tidal flat deposits show a good likeness to washover deposits described by (Schwartz,1982).

### Bay-head delta and bay-fill association

Sandstones and heteroliths arranged in overall upward coarsening successions up to 8 metres thick. The sediments are dominated by current-generated structures, but wave-generated structures may be common. Sandstones with current-generated structures may occur as channel deposits in the upper part of upward coarsening successions. Short intervals of well sorted sandstone and heterolith may show low-angle planar cross-bedding, swaley and hummocky cross-bedding, and wave ripple cross-lamination. The sandstones of this association frequently overlie fine-grained lagoon deposits.

This association is interpreted as bay-head deltas, that prograded into estuaries, lagoons, or bays. Depending on the amount of wave influence the deposits were either slightly modified by small-scale wave activity, or reworked into bay shorefaces by storm wave activity.

### Low-energy estuary and lagoon association

The low-energy estuary and lagoon association is represented by organic-rich mudstones, siltstones and heteroliths, showing parallel lamination, wavy and lenticular bedding, and ripple cross-lamination with mud-flasers, partly obliterated by biogenic activity. Sedimentary units of this association varies in thickness from a few decimetres to several metres.

### Marsh and swamp association

Coals, mudstones and associated rooted heteroliths are grouped in the marsh and swamp association. Mudstones and rooted heteroliths have a dark grey to black appearance, reflecting the high organic content. Both vitrinite-rich and inertinite-rich coals are present. The vitrinite-rich coals represent deposition in a waterlogged, anoxic, mire environment. The inertinite-rich coals represent a somewhat drier environment, with periodically oxic conditions in a swamp or raised bog. Pyrite in some coal beds suggest occasional influx of marine water. The indications for marine water influxes, and the association of coals and rooted sediments with lagoonal deposits suggest that deposition took place in backbarrier swamps and marshes.

## Marine deposits

### Facies associations

Marine deposits dominate the upper part of the Bryne Formation in the central parts of the Søgne Basin, but thin units can be traced into the mainly paralic deposits in the western part of the study area. The marine deposits are separated into three facies associations: offshore, prograding shoreface and beach, and transgressive shelf and shoreface.

## Offshore association

The offshore association consists of up to 50 cm thick units of massive and laminated siltstone and claystone, and cm-scale interbedded, heterolithic siltstone and sandstone. The association frequently occur as coarsening upward units with massive mudstone in the basal part overlain by siltstone and sandstone laminae and beds showing an increasing thickness upward. The sandstone beds are commonly sharp-based. Laminae may be normally graded, and show parallel lamination and wave and combined flow ripple lamination. The sandstone dominated upper part of coarsening upward units may grade into HCS-dominated deposits of the prograding shoreface and beach association. Bioturbation in the offshore association varies from weak to intense, but mudstones are commonly completely bioturbated with few remaining physical structures. *Anconichnus*, *Planolites*, *Palaeophycus* and *Teichichnus* occur in the sandstone beds.

Mudstones with rare laminae of silt- or sandstone indicates that deposition took place below storm wave-base. The thorough bioturbation of the mudstones suggests, they were deposited on a shelf with oxic bottom conditions. A higher content of siltstone and sandstone laminae suggests occasional influence of oscillatory currents about storm wave-base. Sharp-based sandstone laminae are interpreted as storm-sand deposits, and their finer-grained interbeds are fair-weather sediments and suspension fall-out after storms. Deposition took place between storm wave-base and fair-weather wave-base.

## Prograding shoreface and beach association

The prograding shoreface and beach association is represented by up to 12 metres thick coarsening upward successions of very fine-grained, hummocky cross-stratified and swaley cross-stratified sandstone with siltstone interbeds overlain by low angle cross-bedded fine- to medium-grained sandstone and trough and planar cross-bedded fine- to coarse-grained sandstone. Horizontally laminated, low-angle cross-bedded and massive fine to medium grained sandstones and pebble conglomerates may occur at the top of the successions. The hummocky and swaley cross-stratification dominated sandstone occur as sharp-based, laminated sandstone beds ranging between a few decimetres and a few metres in thickness, separated by centimetres to decimetres thick siltstone beds. Lamination may be gently undulating and typically intersect and truncate at low angles. Individual hummocky cross-stratified units may grade into wave-rippled heterolithic silt- and sandstone. Swaley cross-stratified sandstones typically occur as larger amalgamated units, that lack the heterolithic subunits and the silty interbeds. The cross-bedded sandstones occur in poorly defined sets usually a few decimetres thick.

The coarsening upward successions are interpreted as the deposits of prograding shelf, shoreface and shoreline systems. Minor, 2 to 4 metres thick, coarsening upward units of typical shoreface deposits may represent wave influenced mouth bars or ebb tidal deltas. The hummocky cross-stratification dominated units, commonly lowermost in the successions, were deposited by storm wave activity below fair-weather wave-base in the offshore transition zone. The swaley cross-stratified deposits represent more continuous wave activity on the lower shoreface, whereas the cross-bedded of the upper part of the succession represent migrating dunes on the upper shoreface. The horizontally laminated and low-angle cross-bedded sandstones uppermost the successions represents fore-shore, beach and beach plain deposits.

## Transgressive shelf and shoreface association

Deposits of the transgressive shelf and shoreface association consists of poorly sorted, bioturbated muddy sandstones, sandy silt- and mudstones and heteroliths; poorly sorted, pebbly sandstones, and conglomerates. The deposits are characterised by intense burrowing and a diverse ichnofauna.

These sediments were deposited in a shoreface or shallow shelf environment during a transgression. Physical structures, reflecting the high energy level on the upper shoreface, were partly or completely obliterated by burrowing organisms under more quiet conditions.

# Systems tracts and key surfaces

## Sequence stratigraphic nomenclature

Sequence stratigraphic principles and nomenclature in this study follow Van Wagoner et al. (1988), Posamentier et al. (1988), Posamentier and Vail (1988), Van Wagoner et al. (1990) and Hunt and Tucker (1992, 1995).

The subdivision and naming of sequences in the study area is presented by Andsbjerg and Dybkjær (this volume). The present study attempts a more detailed sequence stratigraphic subdivision, and most often Middle Jurassic sequences of Andsbjerg and Dybkjær are subdivided further, and are given the suffix A, B, or C (e.g. Cal-1 to Cal-1A, Cal-1B and Cal-1C). The subdivision of sequences into a number of smaller sequences reflects that sequences may represent varying time-spans due to different combinations of causal factors. Influenced by a variety of factors such as glacio-eustacy, tectono-eustacy, tectonics of various scales, and climate, sequences occur over time scales ranging from tens of thousands of years to hundreds of millions of years (e.g. Vail et al., 1977, Van Wagoner et al., 1990, Miall, 1996). Whereas the Middle Jurassic sequences outlined by Andsbjerg and Dybkjær (this volume) are considered to represent timespans of 5-10 ma. which is consistent with influence of intraplate stress (Cloetingh, 1988; Hallam, 1988; Miall, 1996), the present study attempts to delineate 1-5 ma. sequences probably reflecting a stronger influence of local tectonics.

## Systems tracts

A systems tract is defined as a linkage of contemporaneous depositional systems defined by stratal geometries at bounding surfaces, position within the sequence, and internal stacking patterns (Posamentier et al., 1988). Sequences are subdivided into lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and forced regressive systems tract (FRST) following Hunt and Tucker´s modifications of the EXXON system (Hunt and Tucker, 1992, 1995). Identification of systems tracts is based on the identification of their bounding surfaces, stacking patterns and their position within sequences. The link between sequence development and sea-level changes is direct in the marine and marginal marine deposits, but more circumstantial in the non-marine realm. However, the sporadic occurrence of tidal indicators in the non-marine deposits of the lower Bryne Formation suggests, that deposition took place on a coastal plain, where sea-level changes may have had a pronounced influence on sedimentation patterns.

### Lowstand systems tracts

With the sediments deposited during falling relative sea-level combined in the FRST in accordance with Hunt and Tucker (1992, 1995) the lowstand systems tract (LST) consists of deposits formed at the lowest relative sea-level stand, which are bounded below by the mainly subaerial sequence bounding unconformity (SB) and above by the first transgressive surface (TS). The LST may be represented in the alluvial plain deposits of the lower Bryne Formation by laterally extensive, amalgamated, channel sandstone bodies, but it is difficult to distinguish these LST-deposits from channel deposits of the TST formed during an early phase of the transgression, unless a marked increase in sedimentary structures or trace fossils typical for tidal influence or in the presence of brackish or marine microfossils can be discerned. In the paralic and marginal marine deposits of upper part of the Bryne Formation the LST may be represented by massive channel sandstones in the incised valley fills, that show little or no evidence for tidal processes. However, the majority of the channel sandstones in the incised valley fill deposits, that show clear evidence for tidal processes, are interpreted as TST deposits. During the lowest sea-level stand incised valleys acted as conduits for sediment by-pass, and most deposition is supposed to have taken place farther basinward. It must be emphasised that the transition from fluvial LST-deposits to tidally influenced TST-deposits is diachronous, and that this change inland may be marked by a change in fluvial style or by the development of a coal bed (Miall, 1996).

## Transgressive systems tracts

The TST consists of a succession of backstepping units or parasequences, where individual parasequences may exhibit a progradational pattern. The lower boundary of the TST is the first TS and the upper boundary the maximum flooding surface (MFS).

In the alluvial plain succession the TST can be subdivided into a lower part dominated by fluvial channel deposits, which may show tidal influence, and an upper part consisting of upward fining units of floodplain, lacustrine and possibly lagoonal deposits. Transgression down-dip is commonly indicated by the occurrence of abundant flaser bedding and double mud drapes in the channel sandstones, by a transition to more loosely stacked channel sand bodies, and by a greater proportion of overbank fines. In this setting is the MFS represented by a lacustrine, distal floodplain or lagoonal mudstone, which can be discerned in well logs as the highest GR-peak and the inflection point between the increasing values of the GR-log in upper part of the TST and the generally decreasing GR values of the lower part of the HST above.

The typical TST of paralic to marine settings consists of a lower succession, dominated by tidally influenced fluvial channel and estuary channel sandstones, which may have been deposited in an incised valley commonly capped by a coal bed or coal zone, and an upper succession of upward fining bay, shoreface and shelf deposits. A wave ravinement surface (WRS) may separate the lower estuarine part of the TST from transgressive shoreface deposits. The upper succession of the TST normally wedges out in a basinward direction. The TST is bounded upwards by the maximum flooding surface (MFS), represented by a bed of shelf or lagoonal mudstone which is recognised as a GR spike on the well logs.

## Highstand systems tract

The HST is characterised by a progradational stacking pattern which may be interrupted by transgressive events. The systems tract is bounded at the base by the MFS and at the top by the SB or by a regressive surface of marine erosion (RSE) if it is overlain by a forced regressive systems tract (FRST).

In the alluvial plain succession HST deposits commonly occur as coarsening upward units of floodplain and crevasse splay deposits, minor channel sandstones, lacustrine, and lacustrine delta deposits. Channel sandstones typically show an upward increase in thickness and grainsize.

In the marine and paralic successions the HST occur basinwards as a coarsening upward succession dominated by shoreface or tidally influenced delta deposits. The HST typically wedges out in a landward direction, where it overlies gradually thicker estuarine deposits of the TST, and is cut from above by an incised SB. Landward the HST is represented by ebb- or flood tidal delta, bay-head delta or other deposits, that reflect a rapid, progradational infilling of estuaries or bays.

### Forced regressive systems tract

A significant erosional break within the coarsening upward succession suggests that the upper shoreface and foreshore deposits above the break may belong to the forced regressive systems tract (FRST) (Hunt and Tucker, 1992, 1995). The FRST consists of coarsening upward shoreface, estuary mouth, foreshore and beach deposits that prograded during falling relative sea-level (Plint, 1988). The basal, erosional boundary of the FRST is a regressive surface of marine erosion (RSE), which formed as a result of wave erosion of shelf deposits as a response to the falling relative sea-level. The formation and preservation of the FRST depends on the balance between sea-level change and subsidence.

## Key surfaces

Sequence boundaries (SB) that occur in the alluvial or coastal plain deposits of the lower Bryne Formation as distinct erosion surfaces or unconformities that can be traced across the Søgne Basin. Whereas some sequence boundaries may show a striking contrast between facies above and below the SB, others display little evidence their importance.
Sequence boundaries in the lower Bryne Formation commonly are represented by the erosive bases of major, laterally extensive channel sandstones. Maximum flooding surfaces (MFS) in the lower Bryne Formation are located in lacustrine mudstones overlying fining upward channel sandstones or located at the inflection point between fining upward and upward coarsening floodplain deposits. Flooding surfaces (FS) are not identified in the alluvial plain dominated successions, as the alluvial plain deposits were not subjected to marine floodings; however, surfaces that separates units of amalgamated, laterally extensive channel sandstone's from floodplain dominated successions with only minor, isolated channel sandstones may represent a landward expression of marine flooding events. Also the beginning of coal formation, that were due to rises in ground-water table and the generation of new accommodation space may represent a landward expression of a marine flooding (Petersen and Andsbjerg, 1996).

In the marine and marginal marine deposits of the upper Bryne Formation sequence boundaries can be seen as erosional bases of estuary channel sandstones or as more subtle shifts from shoreface to beach plain deposits. In this setting surf zone erosion may have caused amalgamation of SB and ravinement surface or transgressive surface of marine erosion (TSE). In some units a regressive surface of marine erosion (RSE) separates HST-sandstones of the offshore transition zone and lower shoreface below from upper shoreface and foreshore sandstones of the FRST above. In this setting the MFS is commonly picked at a laterally extensive offshore or lagoonal mudstone. Flooding surfaces (FS) separate terrestrial or more proximal marine deposits from marine or more distal marine deposits. The first FS above a SB usually is taken as the boundary between LST and TST.

# Sequence stratigraphic subdivision

The lower part of the Bryne Formation consists of seven sequences of alluvial plain or fluvially dominated coastal plain deposits. there is evidence for occasional tidal activity. Thick mudstone units uppermost in this succession were deposited in lakes or in brackish lagoons in axial parts of the basin. The lower Bryne Formation is separated from the marine and marginal marine deposits of the upper part of formation by a major erosion surface, interpreted as a significant sequence boundary. Estuarine and lagoonal deposits interfingers with progradational shoreface deposits of the three sequences in the upper Bryne Formation. The Bryne Formation is overlain by offshore mudstones of the Lola Formation, which interfingers with the uppermost progradational shoreface unit.

## Aalen-1A sequence

### LST and TST

This sequence is bounded below by the base Middle Jurassic unconformity. The lowermost part of the Bryne Formation onlaps this unconformity, but the Aalen-1A sequence is recognised only in a few wells, supposedly at topographic lows in the sub-crop as there is no evidence for deeper erosion at the base of the overlying sequence at these locations (e.g. West Lulu-1 and West Lulu-2). In West Lulu-1 and West Lulu-4 the sequence occurs as a 15 - 18 m thick, slightly upward fining unit of mudstones with interbedded minor sandstones. A 5 m thick mudstone interval near the base of Amalie-1 is also referred to this sequence. No cores have been cut from the sequence but based on log patterns it is interpreted as distal floodplain and lacustrine deposits. The slightly fining upward trend in West Lulu-1 and West Lulu-4 may suggest that the sequence is represented by LST and TST deposits in these wells. The HST may have been removed erosively at the base Aalen-1B SB, which occurs as an erosional channel base in most wells. A slightly upward coarsening unit below the base Aalen-1B SB in the Norwegian well 3/5-2 may represent HST deposits of the Aalen-1A sequence.

## Aalen-1B sequence

### LST and TST

A 16 - 35 m thick succession of stacked , mainly fining upward sandstone units interbedded with thin mudstones (e.g. West Lulu-3) occurs above an erosional sequence boundary. The sandstone units generally become thinner and increasingly finer grained upwards. The sandstone units represent stacked channels separated by overbank mudstones. In West Lulu-1 a succession of fining upward siltstone and mudstone devoid of sandstone units except for the basal unit may represent a gradual lacustrine flooding of the floodplain, possibly related to channel belt migration. This succession may represent both the LST and TST of the sequence.

### HST

Above a mudstone bed, which represents the MFS, a 10 to 20 m thick succession of weakly upward coarsening floodplain deposits is interpreted as the HST of the sequence. Thickness variations are mainly due to variable erosion at the top of the sequence.

## Baj-1A sequence

### LST and TST

The basal sequence boundary is a distinct erosion surface interpreted as a channel base diastem. The sequence is 20 - 30 m thick, and has a uniform appearance in large parts of the Søgne Basin (e.g. West Lulu-2, -3, -4, Amalie-1) (fig. 5). In these wells the sequence consists of a fining upward, single or amalgamated channel sandstone unit, 10 - 15 m thick, referred to the LST and TST. The fining upward pattern and the uniform appearance across a large area suggest that deposition took place in laterally migrating river channels.

### HST

A thin lacustrine or overbank mudstone, which incorporates the MFS, separates the TST from a 10 - 15 m thick coarsening upward succession interpreted as the HST. The HST consists of stacked minor sandstones deposited in crevasse splays and small deltas. In two wells, West Lulu-1 and 3/7-4, most of the sequence is dominated by stacked, amalgamated, massive channel sandstones.

## Baj-1B sequence

### LST and TST

This sequence shows a larger thickness variability than the underlying sequences. It varies in thickness between 30 m in West Lulu-2 and 75 m in Amalie-1, and may be represented by the lowermost 20 m of the Middle Jurassic section in Lulu-1. The lower SB occurs as a channel base, that shows a variable but generally low amount of erosion into the HST of the Baj-1A sequence.

The basal part of the sequence is a laterally extensive fluvial channel sandstone representing the LST and possibly the lower part of the TST. An fining upward succession of minor fluvial channel and crevasse splay sandstones interbedded with floodplain mudstones represents the remainder of the TST (e.g. West Lulu-3; fig. 6). The thickness of the LST/TST succession shows a strong variation between 8 m in West Lulu-2 and 48 m in West Lulu-1.

### HST

A distinct mudstone bed, that represents the MFS, separates the TST from the distinctly upward coarsening HST succession. In the western part of the study area the HST consists of several stacked, 2 to 8 m thick, upward coarsening units of siltstone and sandstone, that are interpreted as deposited in minor deltas or large crevasse splays (e.g. West Lulu-2). In this area the thickness of the HST varies between 12 and 25 m. In the eastern part of the basin the HST the more than 50 m thick in Amalie-1 and Cleo-1 is represented by an almost continuous, coarsening upward succession of interbedded siltstones and sandstones interpreted as prograding delta and floodplain deposits (fig. 4). Due to the lack of core data from this interval in Amalie-1 it is not possible to discern whether the deltaic deposits are marine or a lacustrine. Channel sandstones seem to be absent from this unit.

## Bat-1A sequence

### LST and TST

In the western part of the study area the SB is a slightly erosive channel base and the lower part of this sequence is a 6 to 8 m thick, upward fining, laterally extensive channel sandstone, which is referred to the LST and TST (figs. 4, 5, 7). The channel sandstone is dominated by cross-bedding and cross-lamination, but the presence of double mud-drapes (Visser, 1980), abundant flaser bedding (Reineck and Wunderlich, 1968) in West Lulu-1 and decimetre thick sand/mud couplets in the upper part of the channel unit (Smith, 1987) in West Lulu-2 (fig. 7) indicates that the channel system was influenced by tidal processes. In the wells farther east in the basin the basal sequence boundary is positioned at the shift from the progradational succession of the Baj-1B HST below, to an upward fining succession of backstepping minor sandstones interpreted as the TST in the lower part of the Bat-1A sequence. These wells do not exhibit an erosionally based channel sandstone at this level, suggesting that the laterally migrating channel belt was located in the western part of the basin only.

### HST

In the western part of the area the HST is only present in West Lulu-1 and 3/7-4, where it consists of interbedded thin floodplain sandstones and mudstones with isolated minor channel sandstones. The HST has been removed from other wells in the western part of the study area by erosion at the base Cal-1A sequence boundary. In the wells in the central part of the basin the TST is separated from a HST unit of mudstones and siltstones by a several metres thick mudstone unit, containing the MFS. Where complete the sequence varies in thickness from 25 m in West Lulu-1 to 48 m in Amalie-1.

## Bat-1B and Bat-C sequences

### Bat-1B LST and TST

The Bat-1B sequence is completely or partially missing from several wells in the study area mainly due to strong erosion during formation of the Cal-1A SB. It is missing completely from West Lulu-3 and West Lulu-2, and seems to be completely preserved in West Lulu-1, Lulu-1 and 3/7-4.

The lower sequence boundary is an erosional channel base. A 25 to 30 m thick fining upward succession of stacked , fining upward channel sandstones represents the LST and TST. Double mud-drapes and abundant flaser bedding in the channel sandstones indicate tidal influence during deposition. Thin coals, roots and soil horizons are common within this succession. In Amalie-1 in the eastern part of the study area the sequence consists of 37 m thick TST of backstepping upward fining and coarsening upward sand- and siltstone units interbedded with mudstone. The MFS is situated within a mudstone unit, 6 m thick, which is cut erosively by the base Cal-1A sequence boundary. No marine microfossils have been retrieved from this unit, but the occurrence of tidally influenced channel sandstones in association with metre thick mudstones may suggest a lagoonal or estuarine depositional environment for the MFS-mudstones in Amalie-1 and Lulu-1.

### Bat-1B HST

In West Lulu-1, Lulu-1 and 3/7-4, where the HST is preserved, is it separated from the TST by a 1 m thick mudstone. The HST occurs as a 4 to 6 m thick upward coarsening unit of interbedded mudstone, siltstone and sandstone deposited on a floodplain with occasional tidal influence.

### Bat-1C

The Bat-1C sequence is only present in West Lulu-1, Lulu-1 and 3/7-4, where it achieves a maximum thickness of 25 m. In all three wells is it cut by the Cal-1A sequence boundary. It is represented by fining upward channel sandstones overlain by floodplain sediments or coals.

# Cal-1A sequence, incised valley fill

## SB

The regional unconformity that separates the fluvially dominated coastal plain succession of the lower Bryne Formation from the marginal and shallow marine deposits of the upper Bryne Formation, can be traced across the Søgne Basin and northern Tail End Graben (figs. 3, 4) and possibly throughout the southern part of the Danish Central Graben (Andsbjerg and Dybkjær, this volume). In most wells the unconformity is seen at the base of a series of stacked massive channel sandstones. In the lower part of the Bryne Formation correlations indicate that missing section at the unconformity may in some wells amount to as much as 40 m. In West Lulu-4, where no erosion is observed, the unconformity may be represented by an interfluve bypass surface. However, In most of the study area the unconformity bounds an incised valley with a relief amounting to at least the 40 metres of missing section below the unconformity.

Two different types of valley fill deposits are present in the incised valley: stacked, amalgamated estuarine and fluvial channel sandstones, and interbedded tidal channel and low-energy estuary deposits.

## Channel dominated valley fill

In West Lulu-1,-2, -3 and Amalie-1 the valley fills are dominated by amalgamated channel deposits. Stacked channel sandstones intercalated by fine-grained overbank deposits, may attain thicknesses of up to 18 m (e.g. West Lulu-3). Two to three storeys of amalgamated channel sandstones can be discerned in the valley fill deposits. A conglomerate of intraformational mudstone clasts up to 60 cm thick is present at the base of the lowermost channel sandstone (the basal unconformity). Each sandstone storey is a simple, fining upward channel sandstone, or an amalgamated sandstone unit with an almost constant grain size. Evidence for tidal influence is present in some channel sandstones. Channel units without evidence for tidal influence are characterised by trough cross-bedded sandstone interbedded with chaotically bedded sandstone with abundant scattered coal and mudstone clasts. Channel units interpreted as tidally influenced are characterised by an association of trough and possibly planar cross-bedding with abundant double mud laminae, commonly with abundant coal- and mudstone clasts on foresets and bed boundaries, flaser bedding and also rare bimodal cross-lamination. When these indicators occur in fining upward sandstone units, they are typically associated with an upward increase in numbers and thickness of heterolithic beds (compare Smith, 1987, his fig. 6; Shanley et al., 1992). Most channel sandstones show some degree of tidal influence, e.g. uppermost and lowermost channel storey of West Lulu-1, and may represent the upper estuary channels of Allen (1991). The middle channel storey of West Lulu-3 is a typical example of a sandstone without evidence for tidal conditions.

### Low energy estuarine valley fill

The upper part of the valley fill is dominated by interbedded minor sandstone's, heteroliths and mudstones, typically arranged in an upward fining succession in the wells closest to the basin centre (3/7-4, Lulu-1 and Amalie-1). Sandstones show trough cross-bedding, wavy, flaser and lenticular bedding, bi-directional ripple cross-lamination, and double mud-drapes indicating a tidal environment. Some beds are strongly altered by soft sediment deformation and occasionally by pedogenesis. A few thin coal beds with associated root horizons, that occur within the succession, suggest the occurrence of periods with vegetation cover. The combination of a tidal environment, periodic vegetation growth and only few channel sandstones suggests deposition in the low energy outer or marginal part of an estuary or estuary central basin (Dalrymple et al., 1992).

### LST and lower TST

The combination of fluvial and tidal features shows, that most of the stacked channel sandstones of the incised valley fill were deposited in large, fluvially influenced estuary channels or in river channels upstream from an estuary, where a varying degree of tidal influence is present (cf. Smith, 1987; Allen, 1991; Alexander, 1992; and Shanley et al., 1992). Some channel sandstones with no evidence for tidal influence were deposited during intervals with little tidal activity. When located at the base of the valley fill the non-tidal channel deposits may represent preserved fluvial terrace remnants of the LST (Allen and Posamentier, 1993; and Zaitlin et al., 1994). The upper, more fine-grained unit, most common in wells of the central parts of the basin, was deposited in the estuary central basin, and on tidal flats and in minor tidal channels of the outer and marginal parts of the estuary.

The high degree of tidal influence seen in the valley fill deposits indicates an overall base level rise between the time of valley incision and deposition of the bulk of the valley fill sediments. Hence, the main part of the valley fill deposits belong to the TST.

## Cal-1A sequence, TST and HST

### Upper TST

A regionally extensive coal seam caps the incised valley fill. The coal seam, sometimes split into several thinner seams, is up to 5 m thick. It is described from West Lulu-2 as seams R1 and T2, which represents relatively dry peat-forming environment below (R1) succeeded by a waterlogged peat-forming environment above (T2) (Petersen and Andsbjerg, 1996). The coal seam occur as one almost massive coal bed in West Lulu-1 and 3/7-4, form 2 or 3 distinct coal beds in West Lulu-2, -3 and -4, and occur as a zone of interbedded thin coals and lagoon and marsh sediments in Lulu-1 and Amalie-1. The succession above the coal seam/coal zone shows a strong regional variability. In the western part of the study area the coal seam is conformably overlain by estuarine and lagoonal sediments of the upper part of the Cal-1A TST, whereas shelf and shoreface deposits of the Cal-1A TST and HST are separated from the coal seam by a transgressive surface of erosion in the central part of the basin.

In the central part of the basin in both Lulu-1 and Amalie-1 are the sediments of the coal zone overlain by an erosionally based, upward fining, , 40 - 60 cm thick bed of silty sandstone. The sandstone becomes increasingly heterolithic upwards, but primary structures have been obliterated by pervasive bioturbation. The sandstone is interpreted as a transgressive shelf deposit. It is overlain by shelf mudstones, that varies in thickness from about 0.5 m in Lulu-1 to about 11 m in Amalie-1. The MFS of the sequence is picked in this mudstone, and the transgressive shelf sandstone thus represents the upper part of the TST.

In the West Lulu area the succession above the coal bed is interpreted as mainly estuarine, showing a large lateral variability. In West Lulu-1 and 3/7-4 up to 10 m of fining and coarsening upward sandstones are present above the coal. They exhibit an association of climbing ripple cross-lamination, flaser bedding and paired mudstone laminae. Heterolithic intervals show wavy and lenticular bedding. Some beds have abundant *Teichichnus* burrows. The succession, which is interpreted as bay-head delta and minor tidal channel deposits, constitutes the upper part of the TST in that area. In West Lulu-1 a pebble veneer interpreted as a wave ravinement lag separates the tidal deposits below from a 0.5 m thick upward fining, transgressive shoreface sandstone. This shoreface sandstone is overlain by a thin offshore mudstone in which the MFS has been picked. In West Lulu-2 and -3 the 13 m thick succession above the coal seam, is dominated by a coarsening upward succession of mainly stacked fining upward channel sandstones. In West Lulu-3 the stacked channel sandstones erosionally overlie a coarsening upward heterolithic siltstone unit. The channel sandstones are cross-bedded with current and climbing ripple cross-lamination, flaser bedding, double mud-drapes and soft sediment deformation structures. Beds with abundant *Teichichnus* burrows (fig. 9a), and the less common occurrence of *Planolites* and *Skolithos* occur in the upper part of the coarsening upward succession. The depositional environment of the channel sandstone dominated succession is interpreted as a bay-head delta prograding into an estuary. the succession is referred to the TST. The strongly bioturbated upper unit may represent flooding during abandonment of the bay-head delta. The MFS has been picked above the bay-head delta succession right below the base Cal-1B sequence boundary.The HST has been removed by erosion below that sequence boundary.

## HST/FRST

Above the shelf mudstones, that contain the MFS in Lulu-1 and Amalie-1, is a coarsening upward succession, 8 m to 12 m thick, of lower shoreface/offshore transition deposits with abundant hummocky cross-stratification overlain by lower and upper shoreface sandstones with swaley cross-stratification and trough cross-bedding and uppermost by parallel bedded and low angle cross-bedded beach sandstone (fig. 9d, fig. 13). An erosion boundary, interpreted as a regressive surface of erosion (RSE; Hunt and Tucker, 1995), within the shoreface sandstones separates the succession into a lower part belonging to the HST of the sequence and an upper part belonging to the forced regressive systems tract (FRST; Hunt and Tucker, 1992, 1995). The RSE developed as a result of increased wave scour on the inner shelf in advance of the prograding shoreface during a relative sea-level fall (Plint, 1988). The succession is bounded upward by the base Cal-1B sequence boundary at the base of the beach deposits. The HST/FRST in West Lulu-1 and 3/7-4 is represented by a 3 m thick unit of coarsening upward, well sorted sandstone with swaley cross-stratification and *Teichichnus* burrows, which is interpreted as a thin prograding shoreface unit or deposits of an ebb tidal delta.

## Cal-1B sequence

### SB

In the wells of the central part of the study area the basal sequence boundary is picked, where beach deposits overlie the prograding shoreface deposits of the Cal-1A HST. The succession of beach deposits with a regionally extensive coal bed at the top indicates a basinward shift of facies. In West Lulu-1 and 3/7-4 the SB is identified at the base of the first channel above the HST shoreface of Cal-1A. In West Lulu-2 and -3 where several erosionally based channel sandstone's are present, and the HST and MFS of Cal-1A are missing, the SB is picked at the base of the most coarse-grained channel sandstone in West Lulu-3 and a correlative sandstone bed in West Lulu-2. In these wells the channel base chosen for SB may actually represent a channel base diastem, formed by laterally migrating channels that caused the erosional removal of the original SB (Nummedal and Swift, 1987).

### LST and lower TST

The presence of up to 6 m thick channel deposits above the sequence boundary in those wells may indicate the presence of a minor incised valley. Whereas about 6 m of channel deposits separates the SB from the first coal seam in West Lulu-3, the SB occur less than 1 metre below the coal in more basinward areas, and there is no evidence for incision at this level at well locations east of West Lulu-2 and -3. The upward fining channel sandstones are dominated by trough cross-bedding and The erosional removal of the HST deposits of the Cal-1A sequence in West Lulu-2 and -3 and structures commonly associated with tidal activity, such as flaser bedding, paired mud drapes and sigmoidal foresets. The association of physical and biogenic structures in combination with the dimension of the channel sandbodies, suggests that they originated as large estuary channels. The occurrence of minor coal beds and root horizons interbedded with the estuarine deposits indicates periods with vegetation cover and peat growth.

The up to 1 m thick unit between the sequence boundary and the coal seam in West Lulu-1 and 3/7-4 consists of massive sandstone with root traces and sandstone with irregular ripple cross-lamination. In Lulu-1 this unit consists of parallel laminated and low-angle planar cross-bedded sandstone overlain by massive sandstone with root traces. The interval is interpreted as foreshore and beach plain deposits in Lulu-1 and as undifferentiated fore- and backshore environments in West Lulu-1 and 3/7-4.

The beach deposits and the interpreted incised valley fills of West Lulu-2 and -3 represent the LST and the lower part of the TST. The dominance of tidally influenced sediments in the channel sandstones suggests that they mainly belong to the TST, but the partition cannot be picked with certainty.

## Upper TST

A fining upward unit, 2 to 3 m thick, overlies the coal zone in most wells. In Lulu-1 the unit consists of two backstepping parasequences. The lower parasequence was deposited in a tidally influenced environment, possibly an estuary mouth, whereas the upper one, which is strongly wave-influenced, was deposited in a lower shoreface or offshore transition zone. In West Lulu-1 the unit is represented by sandstone with parallel lamination, wave ripple-lamination, lenticular bedding, and possibly hummocky cross-stratification. In 3/7-4 a flaser bedded, poorly sorted sandstone at the base of the unit is overlain by wavy and lenticular bedded sandstone. Both West Lulu-1 and 3/7-4 show *Teichichnus* and *Diplocraterion* burrows. The unit is interpreted as low-energy shoreface sediments deposited during transgression. It is overlain by dark, organic rich, shelf mudstones, 0.5 - 1 m thick, that incorporates the MFS. Farther to the east in West Lulu-2 is the MFS traced into estuarine or lagoonal mudstones.

## HST and FRST

In West Lulu-3, 3/7-4, Lulu-1 and Amalie-1 the deposits between the Cal-1B MFS and the base Cal-1C SB, occur as an 8 - 12 m thick overall coarsening upward succession, that exhibits a pronounced likeness with the HST/FRST succession of the Cal-1A sequence. No such succession is present in West Lulu-2, but the presence of an erosional channel base, interpreted a the base Cal-1C SB, that cut into the lagoonal mudstones supposed to contain the Cal-1B MFS, suggests that it may have been removed by erosion below the Cal-1C SB. The upper partof this succession has probably been removed by faulting in West Lulu-1.

In Lulu-1 the coarsening upward succession consists of three, stacked, upward coarsening sandstones or parasequences, 1.2 - 4 m thick, that are separated from the underlying shelf mudstones by an erosion surface. The sandstones consist of a heterolithic lower part with thoroughly bioturbated beds and beds dominated by hummocky cross-stratification and parallel lamination, and an upper part dominated by swaley cross-stratified sandstone but with a few heterolithic subunits showing hummocky cross-stratification, wave cross-lamination or parallel lamination. Above the coarsening upward succession is a sandstone unit, that show cross-bedding, wave cross-lamination and subordinate flaser bedding and paired mud drapes. The top of the succession is cut by a minor erosion surface. The section is interpreted as prograding shoreface deposits overlain by back-barrier sediments.

Farther to the west in 3/7-4 and West Lulu-1 this succession has a similar architecture. Only the lower part of the succession is preserved in West Lulu-1, probably due to faulting. The erosion surface, that cuts into the basal mudstone, has a thin pebble conglomerate veneer. The 2 m to 6 m thick parasequences in 3/7-4 are separated by distinct flooding surfaces. Each parasequence consists of a basal unit of heterolithic sandstone and siltstone that coarsen upward to sandstones with showing both wave- and tide-generated structures. Root horizons occur in the upper part of each unit. The coarsening upward sandstone succession also overlie heterolithic mudstone erosionally in West Lulu-3, where the succession has a heterolithic lower part, characterised by many thin, frequently double mudstone laminae, and an upper part of rather poorly sorted, fine-grained sandstone, with some double mud drapes and many coal clasts.

Although the succession is characterised by an overall coarsening upward trend throughout the study area, sedimentary structures show that the succession was not deposited in the same depositional environment everywhere. The dominance of hummocky and swaley cross-stratification in Lulu-1 is evidence for deposition in a wave-dominated shoreface environment in the eastern part of the study area close to the basin axis. The mixing of wave- and tide-generated structures in 3/7-4 and West Lulu-1 and the lack of wave-generated structures in West Lulu-3 suggest that the environment changed from open shoreface in the central parts of the basin to a protected, tide-influenced embayment or estuary mouth towards the west.

The offshore mudstones in the lowermost part of the succession represents a HST developed during a decreasing rate in base-level rise. The erosion surface that separates the offshore mudstones from the overlying coarsening upward sandstone unit is interpreted as a regressive surface of erosion. The RSE developed as a result of increased wave scour on the inner shelf in advance of the prograding shoreface during a relative sea-level fall (Plint, 1988). The RSE can be correlated from Amalie-1 and Lulu-1 to West Lulu-1 and 3/7-4, but cannot be found with certainty in West Lulu-3. The succession above the RSE in the wells where it is developed, belongs to a forced regressive systems tract . The FRST consists of shoreface and beach deposits or by estuary mouth deposits in proximal settings, that lie erosionally on more distal shoreface or shelf deposits. The RSE was formed by storm-wave erosion of shelf deposits, as a response to falling relative sea-level. Nummedal et al. (1993) suggested that the RSE is only expressed near the updip pinch-out of shoreface sandbodies, where the relative change in water depth is the greatest. If that is the case, such a pinch-out was present in most of the study area during deposition of the upper part of the Cal-1B sequence.

## Cal-1C sequence

### Key surfaces

The SB is a rather subtle erosion surface in Lulu-1. In West Lulu-2, West Lulu-3 and 3/7-4 it is picked at a distinct channel base, where it may represent either a channel base diastem or the floor of a minor incised valley. A marine flooding surface separates the sequence into a lower unit dominated by paralic sandstones and a mud- and siltstone dominated upper unit. In some wells a transgressive surface of marine erosion (ravinement surface) can be seen right below the flooding surface.

## LST and TST

In both 3/7-4 and Lulu-1 the sandstone dominated lower unit consists of a succession of parallel laminated and low-angle cross-bedded sandstone, approximately 1 metre thick, representing a beach environment, overlain by a heterolithic succession, up to 2.5 metres thick, with flaser, wavy, and lenticular bedding deposited in a low-energy estuary or lagoon environment. In 3/7-4 the heterolithic succession is abruptly overlain by 3 metres of stacked sandstones with coal and mud clasts, which fine upwards to an organic rich, heterolithic mudstone with abundant roots, and finally a coal bed. These sandstones are interpreted as the fill of a minor distributary channel. The sandstone dominated unit is abruptly overlain by shelf and offshore mudstones and heteroliths.

In West Lulu-2 and West Lulu-3 the sandstone dominated unit below the marine flooding surface consists of approximately 15 m of mainly estuarine sandstones. This succession is dominated by fining upward and massive, amalgamated channel sandstones with cross-bedding, double mud-drapes, chaotic bedding and abundant coal fragments. Heterolithic beds are common. Coarsening upward sandstone units with cross-bedding, current and climbing ripple cross-lamination and flaser bedding, that probably represent estuarine sand bars and bay-head delta deposits also occur. This part of the sequence has been influenced by tidal processes in all the studied wells. Only a thin unit shows evidence for tidal processes in Lulu-1, where tidal influence probably was smallest. In the other wells the main body of sediment is interpreted as the deposits of estuarine channels, tidal sand bars, and tidal and bay head deltas. A unit of coal and rooted organic-rich, fine-grained sediments near the top of the unit indicates a period with stable, low-energy conditions in a partly filled estuary.

The channel and estuarine bar sandstones are erosionally overlain by sandstone and pebble conglomerate, 4 m thick, with a pebble veneer on the basal erosion surface. In this unit in West Lulu-3 there are above a coarsening upward sandstone with a few root traces, several up to 10 cm thick, erosively based, upward fining, clast supported pebble conglomerates (fig. 9B), interbedded with well sorted sandstones and pebbly and granule-rich sandstone's.

The erosional surface at the base of the conglomerates in West Lulu-2 and -3 and the separating the tidally influenced sandstones from the overlying fine-grained marine sediments in Lulu-1 and 3/7-4 is interpreted as a transgressive surface of marine erosion (ravinement surface). The coarse grained deposits above the ravinement surface in West Lulu-2 and -3 were deposited after wave erosion in the shore and shoreface zones during transgression(Bourgeois and Leithold, 1984). Sediments of that grain size are rare in the underlying succession, and they are therefore interpreted as the result of storm-wave reworking of coarse fluvial sediments supplied to the near-shore zone. The fining upward, pebbly sandstone present between the conglomerates and the overlying marine mudstones in West Lulu-2 represents rapid deposition of sediment eroded by waves breaking on the shoreface (Bourgeois and Leithold, 1984).

The shelf mudstones and heteroliths above the sandstone unit belong to the Lola Formation. The MFS of the sequence is present close to the base of the section.
The succession from the SB the to MFS represents an overall transgressive development. The bulk of the sediments belong to the TST, but LST deposits may be present. Some incision may have taken place below the basal SB in the western part of the area.

## HST

The HST of the sequence is a coarsening upward succession of mainly mudstone and siltstone, 9 to 18m thick, but with silty sandstone present in the upper part of the succession in some wells. In most wells the succession consists of a series of stacked, coarsening thickening upward units (parasequences). Core evidence, which is available from West Lulu-1, West Lulu-3 and 3/7-4, show that the sediments at the MFS are dark to almost black silt- and mudstone, that change upwards to sandy siltstone and silty sandstone. The sediments are almost completely bioturbated. *Teichichnus* and *Diplocraterion* burrows can be identified. A few beds may show parallel lamination. The coarsest sediment at the top of the coarsening upward succession is picked as the top Cal-1C sequence boundary.

The succession represents shelf and offshore transition progradation resulting from a decreasing rate of sea-level rise. Stacked parasequences organised into a progradational parasequence set (Van Wagoner et al., 1990), reflect minor fluctuations in relative sea-level during HST progradation.

# Base-level changes and deposition in the lower Bryne Formation

## Sequence stratigraphy applied to non-marine strata

Sequence stratigraphic principles have so far only been used on alluvial successions to a limited extent. This is mainly due to the complex nature of the mechanisms influencing depositional patterns in non-marine settings. Any fluvial system must respond through adjustments in profile, sinuosity and sediment load to strongly variable influence from sea-level changes, tectonic movements, climate changes and autocyclic processes (Schumm, 1993), thus impeding the identification of sedimentary responses to base-level changes. Nevertheless a number of studies (e.g. Shanley and McCabe, 1991, 1993, 1994; Dam and Surlyk, 1992,1993; Aitken and Flint, 1995; Dreyer et al., 1995; Olsen, 1995; Olsen et al., 1995) have proved, that it is possible to apply sequence stratigraphic concepts to continental strata. In coastal plains and in the lower reaches of alluvial plains deposition is strongly influenced by relative sea-level changes (Törnquist et al., 1993; Surlyk et al., 1995. In such areas the use of sequence stratigraphic concepts is somewhat simpler than in intramontane basins, and the sequence stratigraphic concepts and terminology, originally defined for marine and coast-near deposits, can be applied (Vail et al., 1977; Posamentier et al., 1988; Posamentier and Vail, 1988; and Van Wagoner et al., 1988).

The alluvial plain succession of the present study was deposited in a coast-near setting. In several wells sedimentary structures normally associated with tidal processes, double mud drapes and abundant flasers, have been found in a few beds, a few dinoflagellate cysts have been found in the alluvial plain deposits, and data from the Dutch part of the North Sea indicate that fully marine conditions existed less than 100 km away (Van Adrichem Boogaert and Kouwe, 1993). Thus, the systematic variations in depositional facies and the sediment stacking patterns may thus in part be ascribed to sea-level changes.

Sequence boundaries in the alluvial plain succession of the lower Bryne Formation are identified as erosion surfaces at the base of extensive, laterally amalgamated fluvial sandstones following Shanley and McCabe (1991; 1993), Dreyer et al. (1995) and Olsen et al. (1995). These surfaces allow the lower part of the Bryne Formation to be subdivided into unconformity bounded units. Whereas Shanley et al. (1992) could document an increased tidal influence at their maximum flooding surfaces, this is not the case for the lower Bryne Formation. Here maximum flooding surfaces are located where fluvial channel influence is at a minimum and lacustrine and wet overbank deposits are most extensive, comparable to the examples shown by Olsen (1995), Olsen et al. (1995) and Surlyk et al. (1995).

## Sequence boundaries of the alluvial plain/coastal plain succession

Sequence boundaries in the alluvial plain/coastal plain succession of the lower Bryne Formation are recognised as the basal erosion surfaces of the laterally amalgamated fluvial sheet-sand deposits. The sequence boundaries can be traced in all wells that penetrate the respective stratigraphic levels. The fluvial channel deposits overlying the basal erosion surfaces normally show a coarser grain size than the underlying floodplain deposits. The basal erosion surfaces also separate successions with contrasting alluvial architecture. The channel sandstones above the surfaces are laterally continuous and amalgamated, whereas the successions below the surfaces normally are dominated by overbank deposits with only a few isolated channel bodies. This suggests that significant changes in aggradation and accommodation generation rate took place synchronously with the formation of the basal erosion surfaces.

Both incision during the base level fall and frequent avulsions during the early base level rise may have contributed to the formation of the sequence bounding unconformity. Detailed correlations of the successions cut by the sequence boundaries indicate that the amount of incision at the most of the sequence boundaries generally was small.

## Amalgamated fluvial channel deposits

The amalgamated, laterally continuous, fluvial sand sheets typically found above the sequence boundary in the alluvial plain (fig. 20) compares with the low accommodation systems tract of Dreyer et al. (1995), and the amalgamated fluvial sand sheet of Olsen et al. (1995) and Shanley and McCabe (1991, 1993, 1994). In the Bryne Formation the amalgamated fluvial sheet sands most commonly are fining upward but also occur as massive amalgamated sandstones without a fining upward trend at a few locations (e.g. Baj-1A in 3/7-4). The occurrence of multi-storey sandstones at some locations may have been caused by subsidence due to local tectonics. The dominance of fining upward sandstones suggest that the floodplain was extensively reworked by lateral channel migration, reflecting the slow creation of accommodation space at an early stage of base level rise, that effectively prevented floodplain aggradation (Wright and Marriott, 1993). Development of the channels probably was initiated during base level fall or stillstand. However, the combination of laterally migrating channels and a slowly increasing accommodation space during the early base level rise, may have caused erosional removal of most lowstand channel deposits.

## Floodplain transgressive deposits

The overbank dominated deposits between the amalgamated sandstone sheets and the MFS consist of interfingering proximal and distal floodplain deposits organised into a fining upward succession with a gradual decreasing sand/shale ratio. Mudstones, probably of lacustrine origin, becomes increasingly common upwards. Soil profiles and root horizons are common. An example of such a succession from the Baj-1B sequence is illustrated in fig. 6. Fining upward channel sandstones, 2 to 4 m thick, may occur within this type of succession. These channel sandstones cannot be correlated from well to well, and they probably were deposited in non-migrating channels, or in channels that only migrated laterally for short distances (e.g. Bat-1B in 3/7-4, fig. 5). Tidal influence is noted both in the amalgamated sandstone sheets formed under low accommodation conditions and in the channel fills of non-migrating channels deposited during rising base level. However, it has not been possible to discern any difference in the degree of tidal influence between the two settings, and the degree of tidal influence cannot be used to identify the maximum flooding surface unlike the study of Shanley of McCabe (1991, 1993).

The overall fining upward trend and decreasing sandstone/mudstone ratio is interpreted as a result of a rising base level, that caused rising water table and wetter conditions on the coastal plain. The rising base level resulted in increased accommodation space, and this caused an increased storage of sediment on the floodplain and more isolated fluvial channels in combination with reduced sediment supply due to decreased stream gradients. Both Shanley and McCabe (1993) and Wright and Marriott (1993) similarly described how the increasing accommodation rates during rising base level, favour high levels of storage of floodplain sediments resulting in isolated channels. The transgressive floodplain deposits are equivalent to the heterolithic unit with isolated fluvial sandbodies of Olsen et al. (1995) and the lower part of the high accommodation systems tract of Dreyer et al. (1995).

## Floodplain highstand deposits

The highstand floodplain deposits are separated from the floodplain transgressive deposits by a MFS. The MFS occur as an organic mudstone bed or a zone of beds, that can be correlated through most or all wells in the study area. The highstand floodplain deposits occur in a coarsening upward succession, that show an upward increasing sandstone/mudstone ratio and an increasing sandbed thickness. The highstand succession consist of lacustrine and distal floodplain mudstones interbedded with silt- and sandstones, that were deposited as levee deposits, crevasse splays and crevasse deltas. Channel sandstones seem to be less common than in the transgressive floodplain deposits. The highstand floodplain deposits developed as a result of decreasing rates of base level rise and accommodation space generation. The decrease in accommodation space generation eventually caused deposition of laterally extensive, amalgamated channel sandstones in laterally migrating rivers above the SB.

In wells Amalie-1 and Cleo-1, situated in the deeper part of the basin, the HST of the Baj-1B sequence developed a delta-like coarsening upward profile, that represents lake or bay deltas prograded into relatively deep lakes or possibly brackish bays in the axial parts of the basin during deposition of the HST. In Cleo-1 a channel sandstone unit is present above the base Bat-1A SB similar to those that caps the Baj-1B HST farther west; but such a channel unit is not developed in Amalie-1, where the base Bat-1A SB is directly overlain by a fining upward succession of floodplain to lacustrine deposits of the Bat-1A TST. This development probably was caused by a lower decrease in the rate of accommodation space generation in the wells situated near the basin axis than in the wells farther west. Similar successions are described by Shanley and McCabe (1990, 1993) as their highstand systems tract, by Wright and Marriott (1993) as highstand depositional systems and by Olsen et al. (1995) as their uppermost heterolithic interval.

## Base-level and cyclicity

A rhythmic alternation in an alluvial plain succession between levels dominated by laterally coalescent channel sandstones and fine-grained overbank deposits may be ascribed to both autocyclic and allocyclic causes. Autocyclic causes would imply, that a migrating channel belt was present continuously somewhere in the basin. In that case the large channel bodies seen in the wells represent a passage by the migrating channel belt. The thick fining upward successions of overbank deposits represent a channel belt moving away from the well location; the coarsening upward overbank sections result from a channel belt approaching a well location. However, the detailed log correlations indicate that the development of each type of succession: large channel bodies, fining upward and coarsening upward overbank successions, and the mudstone units separating the fining and coarsening upward successions, developed synchronously at well locations in different parts of the basin. It is then highly unlikely that the migrating channel belts, responsible for the tabular channel sand bodies, were present within the study area while the thick overbank successions were deposited. The deposits are rather seen as alternating facies associations controlled by cyclic base-level changes.

Laterally coalescent, erosionally based, thick channel sandstones are overlain by a fining upward floodplain succession increasingly dominated by distal overbank or subaquatic deposits. A distinct mudstone layer separates the fining upward part of the cycle from a coarsening upward succession dominated by crevasse splay and crevasse delta deposits. A full cycle is completed by the next erosionally based channel sandstone. Successions like these compare well with those described by Shanley and McCabe (1991, 1993), Shanley et al. (1992), Dreyer et al. (1995), Hettinger et al. (1995), and by Olsen et al. (1995) and Olsen (1995).

In the present study base-level is defined as sea level (Davis, 1902 and Schumm, 1993). It may for practical purposes occasionally be useful to operate with temporary local base-levels in some alluvial plain settings. The many indications of tidal activity found in the deposits of the lower Bryne Formation suggest a coastal plain setting, where no need exists to operate with any other base-level but sea level.

# Base level changes and deposition of the upper Bryne Formation

## Sequence geometry in the upper Bryne Formation

Proximal parts of the LST and lower TST consist of mainly estuarine deposits in the western part of the study area and are situated in incised valleys and in deeply entrenched estuarine channels. The valley axes were orientated roughly east-west, perpendicular to the basin axis and main faults. The deepest incision is recorded from West Lulu-3 in the westernmost part of the valleys, but the smaller depth of incision recorded from wells farther downstream, e.g. West Lulu-1 and Lulu-1 may reflect a marginal position in the valley. The valley-fill deposits are completely dominated by channel and bay-head delta sandstones in the proximal western part of the incised valleys, whereas the valley-fill in the eastern, more distal part of the valleys consists of tidal channel and tidal delta sandstones interbedded with mudstones and heteroliths of low-energy lagoon, tidal flat and estuary central basin environments. Only a sediment unit, less than 0.5 m thick, in West Lulu-4 can be correlated to the incised valley fill deposits of the Cal-1A sequence in wells of the study area.

Thus, the West Lulu-4 well may represent an interfluve area at this stratigraphic level. The upper TST, HST and FRST deposits in the upper part of the Bryne Formation are not constrained by valley sides. However, these systems tracts are not uniformly distributed in the study area. In the upper part of the Cal-1A sequence laterally extensive coal beds constrain correlations. However, when correlations are attempted for the upper TST and HST succession between the coal markers, the systems tracts show a strongly asymmetric distribution. In the wells near the central parts of the basin a very thin upper TST, that mainly consists of transgressive shoreface deposits, is separated from a thick HST of progradational shoreface deposits by a MFS situated close to the base of the succession. While the upper TST thickens to the west changing from shoreface to mainly estuarine deposits, the HST unit wedges out towards the west (fig. 20). In West Lulu-1 and 3/7-4 the MFS is near the top of the succession with only a thin HST/FRST above it. In West Lulu-2 and -3 in the westernmost part of the study area the HST is missing due to erosion at the overlying SB. A similar distribution of systems tracts can be seen in the Cal-1B sequence (fig. 20). Also in sequence Cal-1B is the proximal western part of the sequence dominated by TST deposits, mainly estuarine, whereas the proportion of HST and FRST deposits, mainly shoreface sediments, shows an increase to the east until they are completely dominant in the wells closest to the basin axis, e.g. Lulu-1 and Amalie-1. In both the Cal-1A and Cal-1B sequences is the deepening upward TST succession separated from the shallowing upward HST/FRST deposits by an inclined MFS, which is situated low in the sequence in the distal wells and relatively high in the sequence in the proximal western wells (fig. 20). The depositional pattern leading to similar deepening-upward paralic successions asymmetrically overlain by shallowing upward regressive successions has been termed reciprocal sedimentation by Kidwell (1988) and Nummedal and Molenaar (1995).

In the present case, where deposition took place in an active rift basin, the development of reciprocal sedimentation may be related to slope gradients and subsidence patterns during transgression. A relatively high gradient on the hanging wall slope during an event of rift induced subsidence will favour the development of thick TST deposits. If sediment supply and rate of sea-level rise are kept constant during transgression of a low gradient and a high gradient slope, a larger area will be transgressed on the low gradient slope than on the high gradient slope during each time increment. The amount of sediment supplied during each time increment thus will have to cover a larger area on the low gradient slope than on the high gradient slope, resulting in the development of thick package of TST deposits with a relatively small area extent on the high gradient slope and a thin package with a large area extent on the low gradient slope. After completion of TST deposition on a high gradient hanging wall slope much accommodation space is still available in central parts of the basin for deposition of HST and FRST sediments to complete the reciprocal pattern of sediment distribution with thick TST deposits updip on the hanging wall slope separated from the basinwards thickening HST by a MFS.

In the Cal-1A sequence the upper TST, situated above regionally extensive coal marker, shows such a reciprocal relationship with the HST of the sequence. In the Cal-1B sequence the main part of the TST shows a reciprocal relationship with the HST and FRST of that sequence. Due to the progressive backstepping of the three Cal-1 sequences the possibility of a reciprocal distribution pattern cannot be evaluated for the Cal-1C sequence, as only relatively distal parts of the sequence are penetrated by wells in the study area.

## Depositional history of the upper Bryne Formation

Major incised valleys were cut both at the western fringe of the Søgne Basin and in the south-eastern part of the basin close to the basin axis (Amalie-1) during formation of the base Cal-1A SB. The incised valley fill has been dated to the latest Bathonian - Early Callovian with the observation of the Nannoceratopsis gracilis LOD (Discus Standard Zone) and the LOD of the Cleistosphaeridium varispinosum (Calloviense Standard Zone). Deposition of the incised valley fills at the western fringe of the basin took place mainly in major estuarine and fluvial channels in the proximal western parts of the valleys, and in estuary central basin, tidal flat, tidal creek and flood tidal delta environments in the more distal eastern part. The incised valley fill deposits in Amalie-1 near the basin axis show deposition in major fluvial and estuarine channels followed by a period with deposition of dominantly fine grained sediments in tidal flat and lagoonal environments. The strong, sometimes upward increasing tidal influence in the valley fill deposits suggest that deposition took place during rising sea level.

The development of an extensive coal-forming mire or swamp environment on top of the incised valley fill succession in the western part of the basin, and probably also in an area close to the boundary fault along the eastern edge of the basin, suggests that the supply of siliciclastic sediments diminished abruptly, when sea level stepped over the valley rim. The resulting coal seam shows a stepwise increase in marine influence. A relatively dry peat-forming environment was succeeded by a continuously waterlogged environment with occasional salt water incursions. The extensive peat-forming environment was terminated by the incursion of transgressive coastal sandstones in the east and the spreading of a lagoonal environment with clastic influx from bay head and tidal deltas in association with continued sea level rise and transgression. The coastal sandstones were transgressed in basin central areas, where deposition of shelf mud took over, whereas a lagoonal/estuarine environment continued to exist in the western part of the basin.

At the point of maximum flooding open shelf conditions were established in the central and eastern parts of the Søgne Basin east of the West Lulu-1 and 3/7-4 wells except at a fringe near the eastern boundary fault. Mudstones, heteroliths and sandstones were deposited in a protected embayment, that included the West Lulu-1 and 3/7-4 sites. HST deposits developed during decreasing rates of rising relative sea level. In the West Lulu-1 - 3/7-4 area the HST was deposited as a thin prograding wedge of protected shoreface and mouth bar deposits. A thick wedge of wave dominated shoreface deposits prograded into the central and eastern parts of the basin. The deposits of both the MFS and the HST were removed from the western part of the study area by erosion at the base Cal-1B SB.

The progradational wedge of shoreface deposits was terminated by deposition of a sheet of beach sandstones, and large parts of the basin were turned into a beach ridge plain. The base of the beach deposits is picked as the base Cal-1B SB. This SB can traced into the western parts of the basin as the erosional base of estuary channels. The estuarine channels of Cal-1B were probably deposited in an incised valley of somewhat smaller dimensions than the Cal-1A valley. Also bay head delta deposits and fine-grained estuary sediments were deposited in the incised valley. Thin fluvial or estuarine channel deposits were deposited on the beach ridge plain farther east in the central parts of the basin. Whereas the sheet-like channel deposits on the beach ridge plain may have been deposited during relative sea level lowstand, clear evidence for tidal influence in the interpreted incised valley fill in the western part of the basin suggests, that it was deposited during early rise of sea level.

A peat forming environment developed over most of the basin after infill of the incised valley was completed as in the Cal-1A sequence. At locations where the resulting coal seam has split an upwards rising groundwater level and associated increase in marine influence can be seen. Continued sea level rise caused deposition of transgressive shoreface sandstones on top of the coal in all but the westernmost parts of the basin. Shelf conditions were shortly after established in most of that area. A low-energy estuary or lagoon, or a protected embayment was established in the western area.

The estuary and lagoon, that had developed and subsequently been inundated during the transgressive phase, changed into open shelf in the basin axial areas and probably into a tidally influenced embayment or lagoon in the West Lulu area at the time of maximum flooding. The West Lulu embayment was filled by bay muds and prograding bay-head deltas during decreasing rates of sea-level rise (HST). During a subsequent relative sea-level fall a decrease in accommodation space resulted in increased wave scour on the inner shelf. Deposition of the shoreface sediments was forced basinwards, where the shoreface sandstones were deposited abruptly on the RSE, without the gradational profile created by a "normal" regression.

A sequence boundary developed by subaerial erosion at the lowest sea-level. A minor incision may have taken place in the western part of study area at sea-level lowstand. An estuary developed at the beginning of relative sea-level rise. Wave-influenced estuary mouth deposits developed in basin axial areas. The coastal plain was eroded by wave action during continued transgression resulting in the formation of a ravinement surface. The rapid transition from paralic and shallow marine sandstones to offshore mudstones and siltstones indicates a rapid transgression across a low-gradient coastal plain. Sediment sources were effectively removed from the vicinity of the study area at this stage of transgression.

## Sea-level influence on deposition

The three sequences, that constitute the paralic and shallow marine succession of the upper Bryne Formation, show a clear overall transgressive development from channel deposits with limited evidence of tidal influence in the incised valley of the Cal-1A sequence to offshore deposits of the HST in the Cal-1C sequence. The three sequences represent three relative sea-level cycles during the overall transgression. Parasequences, recognised within some systems tracts, may reflect minor, short-duration sea-level fluctuations.

Sequence boundaries were formed by fluvial incision during falls in relative sea-level, which may have taken place as two distinct but continuous phases (cf. Wood, 1994). The early phase of sea-level fall caused laterally widespread, but relatively minor fluvial erosion in subaerially exposed areas. An increased rate of sea-level fall caused large-scale fluvial erosion confined to incised valleys. During falling sea-level wave erosion in front of the prograding shoreline might cause the development of a regressive surface of erosion (RSE) overlain by upper shoreface and shoreline deposits (forced regressive systems tract, FRST). Lowstand deposits with a low preservation potential may have been deposited in the incised valleys, but the bulk of the lowstand deposits were deposited in more basinward settings outside the study area.

Estuaries developed in the incised valleys with the initiation of relative sea-level rise. Each incised valley was filled by fluvial, tidally influenced fluvial and estuarine deposits during an early phase of sea-level rise. After the valleys were filled, sedimentation was no longer laterally confined, and deposition spread across former interfluve areas. In at least two of the three sequences a major, laterally continuous coal bed or coal zone developed at this stage as a cover over both incised valley fills and interfluve areas. Peat growth may have filled in a time gap between the disappearance of fluvial sediment sources with the landward movement of the bayline and the commencement of shoreface erosion. Shelf mudstones were deposited in large parts of the study area at the time of most rapid relative sea-level rise (MFS). Estuary or bay muds were deposited in more proximal areas at this stage. With the decrease in the rate of relative sea-level rise that took place after formation of the MFS, did progradation commence again.

Sequence boundaries, maximum flooding surfaces and several coal beds can be correlated in a basin-wide area. A large proportion of the sediment package cannot, however, be correlated from basin axial areas to more marginal parts of the basin. Each of the three sequences consists of a transgressive succession, of mainly tidally influenced deposits belonging to the TST, and a regressive succession dominated by shoreface deposits of the HST and FRST. The TST reaches maximum thicknesses in the basin-marginal West Lulu area, where it dominates the succession completely. The HST/FRST shows a similar dominance in wells near the basin axis. Also the amount of incision at the sequence boundary follows this trend. A similar mutually exclusive distribution of transgressive and regressive successions has been described from the Miocene of Maryland as reciprocal sedimentation by Kidwell (1988), and by Nummedal and Molenaar (1995) from the Gallup Sandstone in New Mexico.

# Base level changes and tectonic influence

The general transgressive development which is reflected by the latest Bathonian-Late Callovian depositional patterns of the upper Bryne Formation (Andsbjerg and Dybkjær, this volume), is in accordance with the eustatic sea-level curve of by Haq et al. (1988). However, the relative sea-level changes in the Søgne Basin during the Callovian may be influenced by tectonics. Several authors suggest initiation of rifting and asymmetric subsidence during the Middle Jurassic(e.g. Møller, 1986; Korstgård, 1993). The small thickness variations and the homogeneous facies distribution seen in the lowermost sequences in the lower part of the Bryne Formation, may suggest that asymmetric subsidence was not initiated, when they were deposited. The first unit with thickness variations, that may reflect asymmetric subsidence and half-graben geometry, is the HST of the Baj-1B sequence, which was deposited near the Bajocian - Bathonian transition. The Bat-1A, -B and -C sequences in the upper part of the lower Bryne show strongly heterogeneous facies distribution patterns with lacustrine and distal floodplain deposits in the eastern part of the basin and units dominated by fluvial channel and more proximal floodplain deposits in the western parts of the basin. Thickness variations, however, are not pronounced, and they vary strongly between units. In sequences Baj-1B and Bat-1B the HST shows a thickness ratio varying from one to two or three with the largest thicknesses in the east, but no systematic thickness variations have been observed in Bat-1A. This may be due to punctuated fault activity at the main boundary fault, that caused rapid creation of accommodation space near the boundary fault and on the lower hanging-wall slope. The amount of new accommodation space created during faulting events decreased gradually updip on the hanging-wall slope. The asymmetrically distributed accommodation space was filled by fluvial and lacustrine deposits in the periods shortly after major faulting events. During tectonically more quiet periods the creation of accommodation space was strongly influenced by other factors such as eustacy, regional subsidence and compaction. This resulted in thickness variations and facies distribution patterns, that cannot be related to the half-graben geometry of a subsiding rift basin.

In the upper Bryne Formation at least two of the three sequences show shoreface deposits of the HST or FRST dominate succession on the lower hanging-wall slope and estuarine deposits of the TST dominate the succession on the upper hanging-wall slope. As shown earlier this reciprocal systems tract distribution pattern depends on the presence of a relatively high gradient on the hanging-wall slope during deposition of the TST. However, both at the base of the first unit showing reciprocal distribution, the upper TST and the HST of Bat-1A, and between that unit and the TST, HST and FRST of Bat-1B, which also shows a reciprocal distribution pattern, are regionally extensive coal beds. The coal beds are interpreted as deposited in a low-energy environment in an area with a low-gradient surface. This clearly shows that periods with infilling of asymmetrically distributed accommodation space created during faulting events alternated with periods of slow deposition on a low-gradient coastal plain. The tectonic influence on depositional patterns was episodic, but had a pronounced influence on distribution patterns of a large part of the succession in the upper Bryne Formation.

The Lulu Salt Structure, which is oriented parallel to the basin axis may also have influenced sedimentation in the basin (Møller, 1986), although it is not considered to have seen significant activity during the Middle Jurassic (Korstgård et al., 1993). The Lulu-1 well which is the only one of the wells included in this study, which is situated directly on that salt structure, has the HST of the Baj-1B sequence sitting directly on Permian salt. This may be due to salt structure uplift during deposition of the lowermost part of the Bryne Formation. The upper part of the Middle Jurassic succession in Lulu-1 shows no variations in thickness or facies distribution, that may be attributed to salt movements. The Lulu-2 well, which is not included in this study, sits directly on the salt structure and lacks all of the Middle Jurassic succession. The depositional associations, that are characteristic for the upper or lower hanging-wall dip slope, respectively, seem to change close to the Lulu Salt Structure. This may be due to the activity of salt-related faults enhancing the differences between the upper and the lower dip slope.

# Palaeogeography

## Terrestrially dominated coastal plain (Aalenian - Bathonian)

The palaeogeography of the lower Bryne Formation is presented in figs. 21 and 22. During the Aalenian? or Early Bajocian to the Middle or Late Bathonian the study area was dominated by an alluvial plain environment with laterally migrating, sinuous rivers as the most characteristic element in periods with a relatively low base-level (fig. 21). Stacked, amalgamated channel sandstones in wells West Lulu-1 and 3/7-4 in the vicinity of the Lulu Salt Structure and its northward extension suggest, that this area favoured channel occupation. The correlatable deposits of river channels in all wells in the study area show that laterally migrating rivers commonly swept most of the floodplain during their life span. The occurrence of flaser bedding and abundant mud drapes in some channel sandstones suggest that deposition took place on a coastal plain, where upstream effects of tidal processes were occasionally felt in the river channels.

Rising base level during this period resulted in abandonment of the large river channels. The area changed into a wet floodplain environment dominated by ponds and minor channels. At the time of maximum flooding topographic lows were occupied by lakes, and brackish waters may occasionally have entered the basin. With a decreasing rate of base level rise sediment wedges began to prograde into the lakes and ponds as of lacustrine deltas and crevasse splays (fig. 22). Deltas and splays were fed by non-migrating river channels, probably anastomosed channels (cf. Smith and Smith, 1980). Renewed base-level fall saw the re-establishment of laterally migrating rivers.

## Tidally dominated coastal plain (Bathonian - Callovian)

The palaeogeographic development in the upper Bryne Formation is presented in fig. 23, 24 and 25. The incised valley, forming the base Cal-1A SB, is depicted in fig. 23. The incised valley system was upstream dominated by laterally migrating river, or upper estuary channels (cf. Allen and Posamentier, 1993) and downstream by bayhead delta, central basin and tidal sand bar deposits of the inner estuary and estuary mouth. The extent of the interfluve area, which has only been located in West Lulu-4, is uncertain.

Fig. 24 represents the late transgressive phase of both the Cal-1A, -1B and -1C sequences. The coastal plain was dominated by barred lagoons and estuaries, that were no longer confined to incised valleys. A transgressive shoreface environment was sourced with sand from destruction of the barrier coast by wave action. A part of the eroded sand was deposited by washover fans and flood tidal deltas in the lagoon. A transgressive sand sheet was left seaward of the transgressing barrier coast. Landward of the barrier coasts were lagoons and estuaries with tidal deltas, bayhead deltas, tidal flats and marsh environments.

The regressive phases of the upper Bryne Formation are represented by fig. 25. Estuaries were filled during the initial phases of regression, when the rate of relative sea level rise began to decrease. A strandplain was created by shoreface progradation. Sea-level fall forced regression of the shoreline to the deepest parts of the basin and possibly out of the study area. Vegetated swamps covered the area during maximum regression and the initial phase of a new transgression.

# Conclusions

By integrating sedimentological studies with high resolution sequence stratigraphic methods has it been possible to achieve a good understanding of the depositional history of the Middle Jurassic succession in the Søgne Basin, to explain some of the mechanisms that controlled depositional patterns, and to determine facies and sequence architecture even in the absence of high resolution seismic data.

Deposition of the Bryne Formation took place during the early phases of rift related subsidence in the Søgne Basin. Asymmetrically distributed accommodation space was created during periods of active subsidence at the main boundary fault, that alternated with periods of tectonic quiescence. The asymmetric distribution of thickness variations across the basin and facies distribution patterns with dominance of lacustrine and distal floodplain deposits in the eastern part of the basin closest to the main boundary fault and dominance of fluvial channel and proximal floodplain deposits in the western part of the basin are diagnostic for deposition of alluvial plain or fluvial dominated coastal plain successions during active half-graben subsidence. In the paralic to shallow marine succession in the upper Bryne Formation depositional units showing reciprocal distribution patterns with estuarine dominated TST deposits closest to the western margin of the basin and shore and shoreface dominated HST and FRST deposits to the east indicate deposition on a sloping surface; in this case the hanging-wall slope of a half-graben. Coal beds, that were deposited on a low-gradient coastal plain, separate depositional units with reciprocal sediment distribution patterns, thus indicating that periods characterised by tectonic quiescence and slow uniform subsidence alternated with episodes of faulting at the main boundary fault, when the hanging-wall slope was re-established and the newly created accommodation space was filled.

An overall, gradual change from alluvial plain or fluvially dominated coastal plain deposits with relatively few indications for marine or tidal influence in the lower Bryne Formation to dominantly tidal and shallow marine deposits in the upper Bryne Formation and the backstepping stacking pattern of the uppermost three sequences of the Bryne Formation indicate that not only rift related subsidence but also eustacy or regional subsidence controlled the creation of accommodation space. The important SB at the base of the Cal-1A, which probably formed in latest Bathonian time, is cut deeply both into upper hanging-wall slope deposits and into successions from the lower hanging-wall slope and the vicinity of the main boundary fault. This suggests that a regional fall in relative sea-level rather than rift related tectonics is responsible for the formation of the SB.

Besides the reciprocal distribution patterns of systems tracts in the upper Bryne Formation also estuarine and shoreface depositional systems show a systematic distribution pattern, which is related to the half-graben geometry of the basin and therefore potentially predictable. Shore and shoreface sandstones of the HST and FRST in the uppermost sequences occur as strike parallel laterally extensive sheet-sandstones. They can be correlated with negligible changes in thickness, grain-sizes and facies for at least 15 km in the Danish Søgne Basin. In contrast thick estuarine channel deposits of the TST in the uppermost sequences mainly occur in dip-parallel incised valleys.

Deposition of paralic and shallow marine sandstones of the Bryne Formation was terminated when the basin entered the rift climax phase. The sediment supply was no longer sufficient to keep pace with the increased rate of subsidence, and deposition of the Lola Formation shelf mudstones took over.

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# Figure captions

**Fig. 1:** Map of the North Sea and Central Graben. Location of map in fig. 2 inset.

**Fig. 2:** Map of the study area; the Søgne Basin, easternmost subbasin of the Central Graben.

**Fig. 3:** East - west section of the Bryne Formation in the western and central part of the Søgne Basin. Major incised valley marked by yellow.

**Fig. 4:** North - south section of the Bryne Formation in the eastern and central part of the Søgne Basin. Major incised valley marked by yellow.

**Fig. 5:** Cross-section through the lower part of the Bryne Formation dominated by alluvial deposits.

**Fig. 6:** Core log and gamma ray log of fluvial channel, floodplain and lacustrine deposits from the lower part of the Bryne Formation; West Lulu-3.

**Fig. 7:** Core log and gamma ray log of fluvial channel and vegetated floodplain deposits from the lower part of the Bryne Formation; West Lulu-2.

**Fig. 8:** Channel fill deposits of the upper Bryne Formation, sequence Cal-1A. (A) Channel base at base of major incised valley in West Lulu-3 (3711m), intraformational mud-clast conglomerate above channel base overlain by well-sorted sandstone showing large-scale cross-stratification. (B) Large-scale cross-bedded sandstone with a few mud laminae; uppermost amalgamated channel complex in major incised valley, West Lulu-3 (3685.6m). (C) Well sorted sandstone with mud-laminae and flaser-lamination; channel deposit of major incised valley, West Lulu-2 (3842.6m). (D) Well sorted sandstone showing climbing ripple cross-lamination; channel deposits of a bay head delta or tidal delta complex, West Lulu-3 (3654.5m).

**Fig. 9:** Shoreface and back-barrier deposits of the upper Bryne Formation. (A) Thoroughly bioturbated sandstone (*Diplocraterion*, *Teichichnus*?) of estuary channel or estuary sand bar; Cal-1B, West Lulu-3 (3647.5m). (B) Transgressive sandstone and conglomerate in sequence Cal-1C at the top of the Bryne Formation in West Lulu-2 (3782.2m). Clast supported pebble conglomerate with pebbly sandstone and matrix supported conglomerate deposited by wave-reworking of shorezone during transgression. (C) Very well sorted sorted sandstone showing HCS/SCS-bedding. Lower shoreface/ offshore transition deposit; Cal-1B sequence, Lulu-1 (3575.6m). (D) Wave ripple cross-laminated sandstone with siltstone laminae. *Teichichnus* and *Planolites* burrows. Offshore transition zone of prograding shoreface; Cal-1A sequence, Lulu-1 (3593.6m).

**Fig. 10:** Cal - 1A sequence in the western part of the Søgne Basin. The major part of the sequence fills the large valley, which is cut into the alluvial deposits of the lower Bryne Formation. The valley fill consists of fluvial and estuarine channel deposits with subordinate floodplain and fine grained estuary deposits. A regionally extensive coal seam act as a cap over the incised valley. The uppermost part of the sequence are estuary channel and tidal delta deposits.

**Fig. 11:** Core and gamma logs of Cal - 1A incised valley fill deposits; West Lulu-1 and West Lulu-3. Total thickness of valley fill deposits is more than 40 metres in West Lulu-3. The thickness of one amalgamated channel unit is 15 metres.

**Fig. 12:** Cal - 1A sequence in the eastern and central part of the Søgne Basin. The largest, lower part of the sequence occur as a thick incised valley fill succession with up to 25 metres thick amalgamated channel units in Amalie-1 and as a somewhat thinner valley fill section of interbedded channel sandstones and fines in 3/7-4 and Lulu-1. The coal seam which caps the incised valley fill shows significantly smaller thicknesses in the eastern part of the study area. Above the coal seam the estuarine deposits which dominated in the western part of the Søgne Basin are substituted by progradational shoreface deposits.

**Fig. 13:** Uppermost part of Cal - 1A sequence, western and central part of Søgne Basin. Core and gamma logs of estuarine deposits in West Lulu-1 and West Lulu-3 and progradational shoreface deposits in Lulu-1. The estuarine deposits are situated below the surface of transgressive erosion and the maimum flooding surface, whereas the shoreface deposites are situated above these surfaces.

**Fig. 14:** Cal - 1B sequence in the western part of the Søgne Basin. The lower boundary shows some incision in West Lulu-2 and West Lulu-3. This may represent a minor incised valley or a channel base diastem. The interval between the basal SB and the coal seam is dominated by estuary channel deposits. The interval above the coal seam is dominated by tidal channel and tidal delta deposits.

**Fig. 15:** Cal - 1B sequence in the central and southeastern part of the Søgne Basin. No incision is evident at the basal SB, which is situated at the transition from shoreface to beach and backbarrier deposits. Above the coal seam are the offshore mudstones of the HST separated from shoreface and foreshore deposits of an FRST by a regressive surface of erosion.

**Fig. 16:** Core and GR logs of the Cal - 1B sequence, western and central part of Søgne Basin. The sequence is represented by estuary deposits and coals of the TST in West Lulu-2. In Lulu-1 the sequence is dominated by shelf and shoreface deposits belonging to the HST and FRST. In this well a relatively thin TST consists of retrogradational shoreface and shelf deposits.

**Fig. 17:** Cal - 1C sequence in the western part of the Søgne Basin. Some incision may be present in the two westernmost wells. The thick TST in this area consists of estuary channel and nearshore deposits overlain by a retrogradational shelf interval, that continues into the HST. A thin TST in West Lulu-1 (partly due to faulting) and 3/7-4 is overlain by a progradational HST of offshore and lower shoreface deposits.

**Fig. 18:** The lower part of sequence Cal - 1C in the western part of the Søgne Basin. Core and GR logs depict estuary channel and bay-head delta deposits overlain by nearshore gravels and sands.

**Fig. 19:** Cal - 1C sequence in central and southeastern part of the Søgne Basin. The thin TST of estuarine and coastal sediments is overlain by an HST of mainly offshore deposits that thin progressively towards the southeast.

**Fig. 20:** Palaeogeographic map, lower Bryne Formation. Laterally migrating river channels of a LST/ lower TST.

**Fig. 21:** Palaeogeographic map, lower Bryne Formation. Distal floodplain, lake and lacustrine deltas of maximum flooding or HST. In the upper part of the lower Bryne Formation the large lake may have been replaced by brackish bay or lagoon.

**Fig. 22:** Palaeogeographic map, lowermost upper Bryne Formation. Major incised valleys with estuary and tidally influenced rivers of lower TST.

**Fig. 23:** Palaeogeographic map, upper Bryne Formation. Transgressive shoreface, barrier coast and coastal plain of TST.

**Fig. 24:** Palaeogeographic map, upper Bryne Formation. Progradational shoreface. beach ridge plain and alluvial plain of HST/FRST.

**Fig. 25:** Idealized east - west section of the sequences of the upper Bryne Formation (A), the most complete sequences of the lower Bryne Formation (B), and a schematic representation of the evolving half-graben and salt-dome which may have influenced sedimentation patterns (C).

**Tab. 1-3:** Facies descriptions.

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 1 | massive and laminated silt- and claystone | massive or mm to cm-scale interlaminated silt- and claystone | thick less than 50cm beds | | offshore, fairweather deposition and suspension fall-out after storms |
| 2 | interbedded siltstone and sandstone | cm-scale interbedded silt- and sandstone; sharp based, normal graded sand laminae show parallel lamination and wave ripples | beds max. 10cm | weak to moderate bioturbation; *Anconichnus.*, *Planolites.*, *Palaeophycus* and *Teichichnus.* | offshore, near storm wave base |
| 3 | bioturbated siltstone and sandstone | bioturbated siltstone, vf. sandstone beds with sharp bases may show wave or combined flow ripples, parallel lamination and HCS | siltbeds less than 3m, sand-beds up to 10cm, rarely 50cm | moderate to intense bioturbation; *Teichichnus.*, *Thallas.*, *Skolithos.*, *Planolites.* | offshore and offshore transition, storm activity alternating with long periods dominated by fair-weather conditions |
| 4 | HCS dominated sandstone | vf. and f.grained sandst. with siltstone laminae; sharp based sandstone beds with HCS and subordinate wave ripple lamination | beds from 10 to 30cm | weak bioturbation | offshore transition, storm- and waning storm deposition |
| 5 | SCS dominated sandstone | f.grained sandstone, SCS, low-angle planar x-bedding and scour structures | beds from 20 to 50cm | trace fossils are rare | lower and middle shoreface, above fair-weather wave base |
| 6 | trough and planar x-bedded sandstone | f. to c.grained sandstone, occasionally pebbly; trough x-bedding, planar x-bedding and subordinate current- and wave ripples | 20 to 50cm beds in units up to 3m thick | bioturbation in the most fine grained intervals as *Diplocraterion* and *Skolithos* | upper shoreface; rip channels, nearshore bars and troughs |
| 7 | horizontally laminated and planar x-bedded sandstone | f. to m.grained sandstone, and more coarse grained laminae; horizontal lamination with low-angle erosion surfaces and low-angle planar x-bedding | 5 to 15cm thick beds in units up to 50cm thick | trace fossils are rare; roots and *Skolithos*? may occur | foreshore |
| 8 | conglomerate and pebbly sandstone | clast-supported pebble and granule conglomerate, less common matrix supported conglomerate and pebbly sandstone; clast-supported conglomerate may show bedding or x-bedding; conglomerate veneers on erosion surfaces | conglomerate beds max. 10cm; pebbly sandstone beds up to 30cm thick | | beach and breaker zone deposits; may represent a transgressive lag |
| 9 | poorly sorted, bioturbated muddy sandstone and heterolith | poorly sorted sandstone with subordinate siltstone; soft-sediment deformation structures and bioturbation dominate, some wave and current ripples may occur | 5 to 10cm beds in up to 1m thick units | often thoroughly bioturbated; *Teichichnus* and *Diplocraterion.* may occur | transgressive marine sandstone deposited below fair-weather wave base during a rising sea-level |

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 10 | horizontally laminated and current rippled sandstone | erosively based fu. units of vf. to m.grained sandstone; horizontal or gently inclined lamination and current ripples, locally soft-sediment deformation structures or high-angle x-bedding may occur | 5 to 20cm thick beds | moderate bioturbation, roots may occur | wash-over sediments |
| 11 | structureless rooted sandstone | various sandstones and heteroliths fully or partly homogenized by root burrowing | 50cm to 3m | thoroughly bioturbated by roots | beach ridge plain |
| 12 | fu. x-bedded sandstone with muddrapes | fu. units of c.-f. grained sand; planar and trough x-bedding with ripple x-lamin., flaser and wavy bedding in upper parts of units, abundant clay laminae, clay clasts and coal debris, interbedded sandstone and mudstone may occur | fu. units from 4 to 10m | moderate, rarely intense bioturbation; *Teich.* | major tidal channel or active tidal inlet |
| 13 | fu. interbedded mudstone and sandstone | f. and vf.grained sandstone and heteroliths with mud clasts; ripple x-lamin., horiz. lamin., flaser, lentic. and wavy bedding, x-bedding | fu. units typically from 50cm to 2.5m | moderate to intense bioturbation | tidal creek or inactive major tidal channel |
| 14 | cu. sandstone with abundant mud laminae | vf. to f.grained sand; bioturbated with mud laminae mud flasers and ripple x-lam. | cu. units up to 2m thick | moderate to intense bioturbation, *Teich.* | tidal sand bar/flat |
| 15 | cu. x-bedded sandstone with mud laminae | vf. to m.grained sand and heteroliths; x-bed., x-lam., flaser bed. and mud laminae | cu. units up to 4m thick | generally moderate bioturbation, *Teich.* and *Diplo.* | proximal flood tidal delta or estuary sand bar |
| 16 | fu. heterolithic sandstone and mudstone | thinly interbedded sandstone, mudstone and heteroliths; ripple x-lam., horiz.lam., flaser bed. | units less than 1m thick | moderate to intense bioturbation, *Diplocraterion* and *Planolites* are common | tidal flat and distal flood tidal delta |
| 17 | cu./fu sandstone and heterolith | vf. to m.grained cu. sandstone units with planar x-bedding, horiz. x-lam. current and wave ripple x-lam. and small scale HCS/SCS; commonly assoc. with fu. channel units | up to 5m thick units | moderately bioturbated; *Teich., Diplo.* | bay head delta/bay shoreface |
| 18 | massive or laminated mudstone and bioturbated sandstone | horizontally laminated or massive mudstone with interbeds and laminae of sandstone; horizontal lamination, wave ripples, flaser and lenticular bedding. | units less than 2m thick | moderate to intense bioturbation | low energy outer estuary, estuary central basin or lagoon |
| 19 | organic rich rooted mudstone | organic rich mudstones with plant fragments, thin coals and with abundant rootlets | less than 50cm | moderate to intense bioturbation by roots | marsh or vegetated coastal swamp |
| 20 | coal | | max. 5m | | mire |

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 21 | fu. interbed. sandstone and fines | sharp based fu. and ungraded x-bed. and x-lam. sandstone with abund. heterolithic beds and mud lam., beds with abund. coal or mud clasts occur | max. 12m thick units | upper part of channel units may be bioturbated with *Diplo.* and *Teich.* | tidally influenced fluvial channel |
| 22 | fu. and ungraded sandstone | sharp based fu. x-bed. and x-lam. sandstone, heterolithic sandst. may dominate upper part of units, some beds may have abund. coal and mud clasts; large amalgam. units may be ungraded | max. 8m thick units | | major fluvial channel |
| 23 | intraformational conglomerate | pebble- to cobble sized, matrix- or clast-supported conglomerate in sand matrix. Clasts are angular mud- or siltstone. Conglomerate beds at base of fu. sandstone units are parallel- or x-bedded. | beds are up to 75cm thick | | channel lag deposits |
| 24 | fu. thin- bedded or x-bedded sandstone | sharp based fu. sandstones; thin-bedded with current ripple x-lam., horiz. lam., or x-bedded. Intraform. clasts and coal fragm, soft sedim. def. | units less than 2m | | crevasse channel or minor fluvial channel |
| 25 | chaotic bedded sandstone | poorly sorted sandstone wtih mud laminae; laminae deformed and overturned, coal and mud clasts scattered throughout | beds typically 20 to 50cm thick | | channel margin deposits of fluvial channels |
| 26 | sideritic siltstone and mudstone | siltstone and mudstone with siderite bands and nodules, and abundant plant remains and roots, indistinct patches of sandst. may occur | typically from 0.5 to 2m | | abandoned channel fill |
| 27 | cu-units of deformed siltstone sandstone | stacked cu-units of siltstone and sandstone dominated by soft-sediment deformation structures with current-, wave-, and climb. ripple lam. in sandst. units, and parall. and climb.ripple lam. and wavy and lent. bedding in siltst. units. Mudstone clasts and coal fragments may locally be abundant. Thinner, sharp based fu-sandstones with deformed x-bedding may occur at top of cu-intervals. | 2 - 5 m thick units may be stacked in 10 - m thick cu-successions | | lacustrine delta; stacked minor cu-units topped by channel sandstones may represent delta lobes in a larger lacustrine delta |
| 28 | cu. units of sharpbased sandstones and siltstone | cu. units of vf. to m.grained sandstone with silt- and mudstone; horizontal or current-ripple lamination, root traces and soft-sediment deformations are common, base gradational to floodplain mudstones | units up to 2m thick, single beds 10 to 50cm | | levee and crevasse splay |
| 29 | disturbed silty mudstone | mud- and siltstone, subord. sandstone, coal debris; horiz. lam., sediments disturbed by roots, soft-sediment def. and pedogenesis | generally less than 1m thick | thoroughly bioturbated, mainly by roots | floodplain fines |
| 30 | organic rich, laminated mudstone | organic rich mudstone with sand and silt laminations | up to 8m thick | | lake and pond |

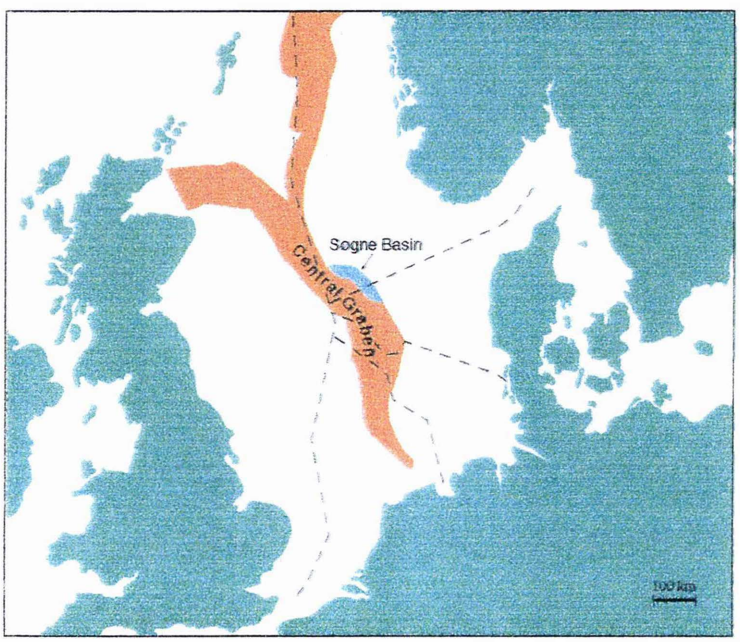



Fig. 1

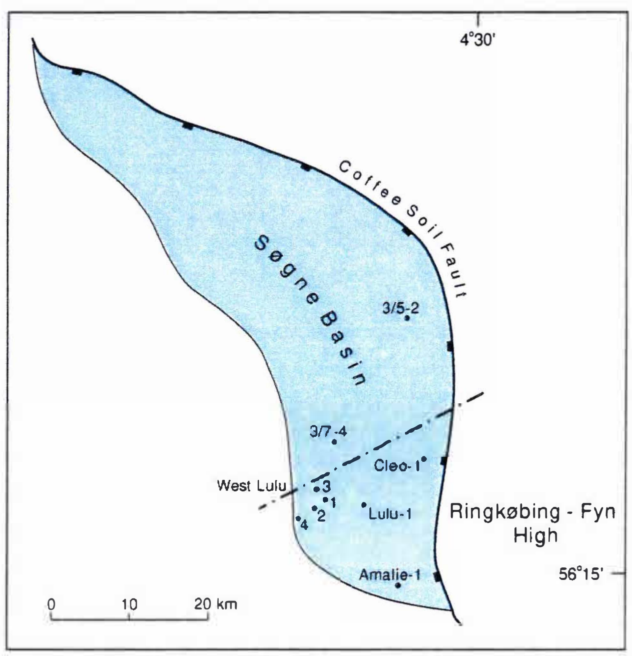

4°30'
Coffee Soil Fault
Søgne Basin
3/5-2
3/7-4
Cleo-1
West Lulu
3
1
2
4
Lulu-1
Ringkøbing - Fyn
High
Amalie-1
56°15'
0
10
20 km

Fig.2

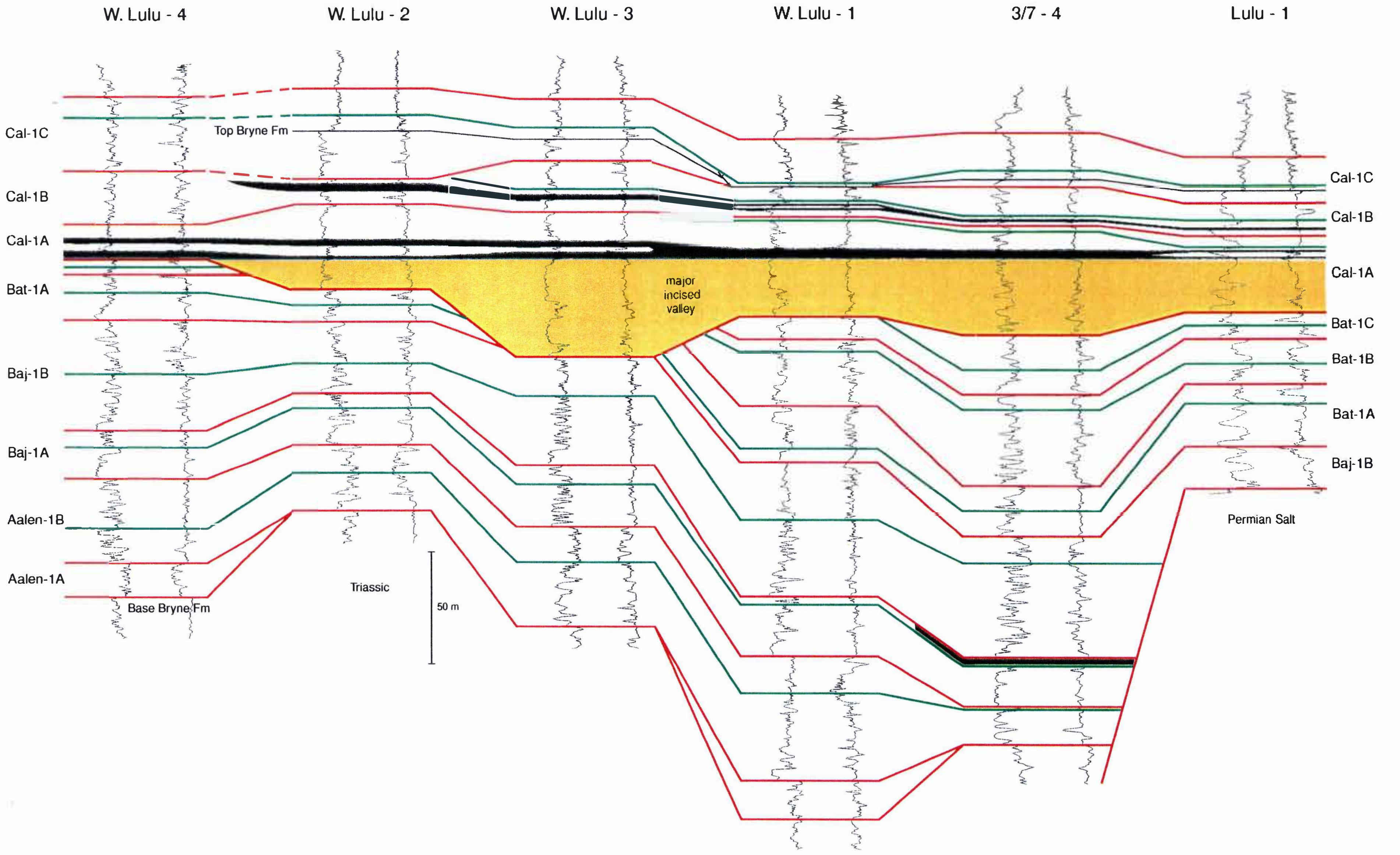

W. Lulu - 4
W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
Lulu - 1
Cal-1C
Cal-1B
Cal-1A
Bat-1A
Baj-1B
Baj-1A
Aalen-1B
Aalen-1A
Top Bryne Fm
Base Bryne Fm
major incised valley
Triassic
50 m
Permian Salt
Cal-1C
Cal-1B
Cal-1A
Bat-1C
Bat-1B
Bat-1A
Baj-1B

Fig.3

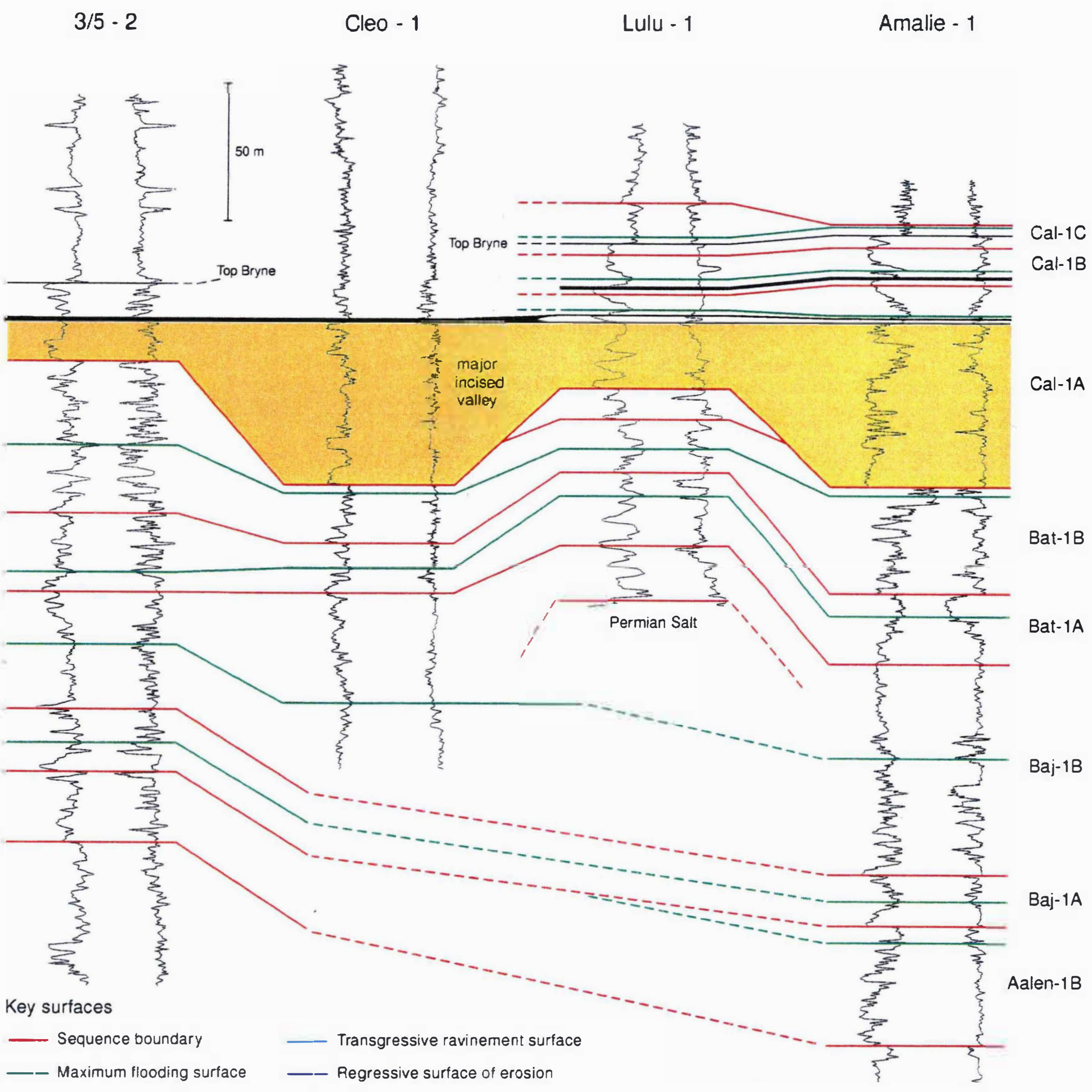

3/5 - 2
Cleo - 1
Lulu - 1
Amalie - 1
50 m
Top Bryne
Top Bryne
major
incised
valley
Permian Salt
Cal-1C
Cal-1B
Cal-1A
Bat-1B
Bat-1A
Baj-1B
Baj-1A
Aalen-1B
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig.4

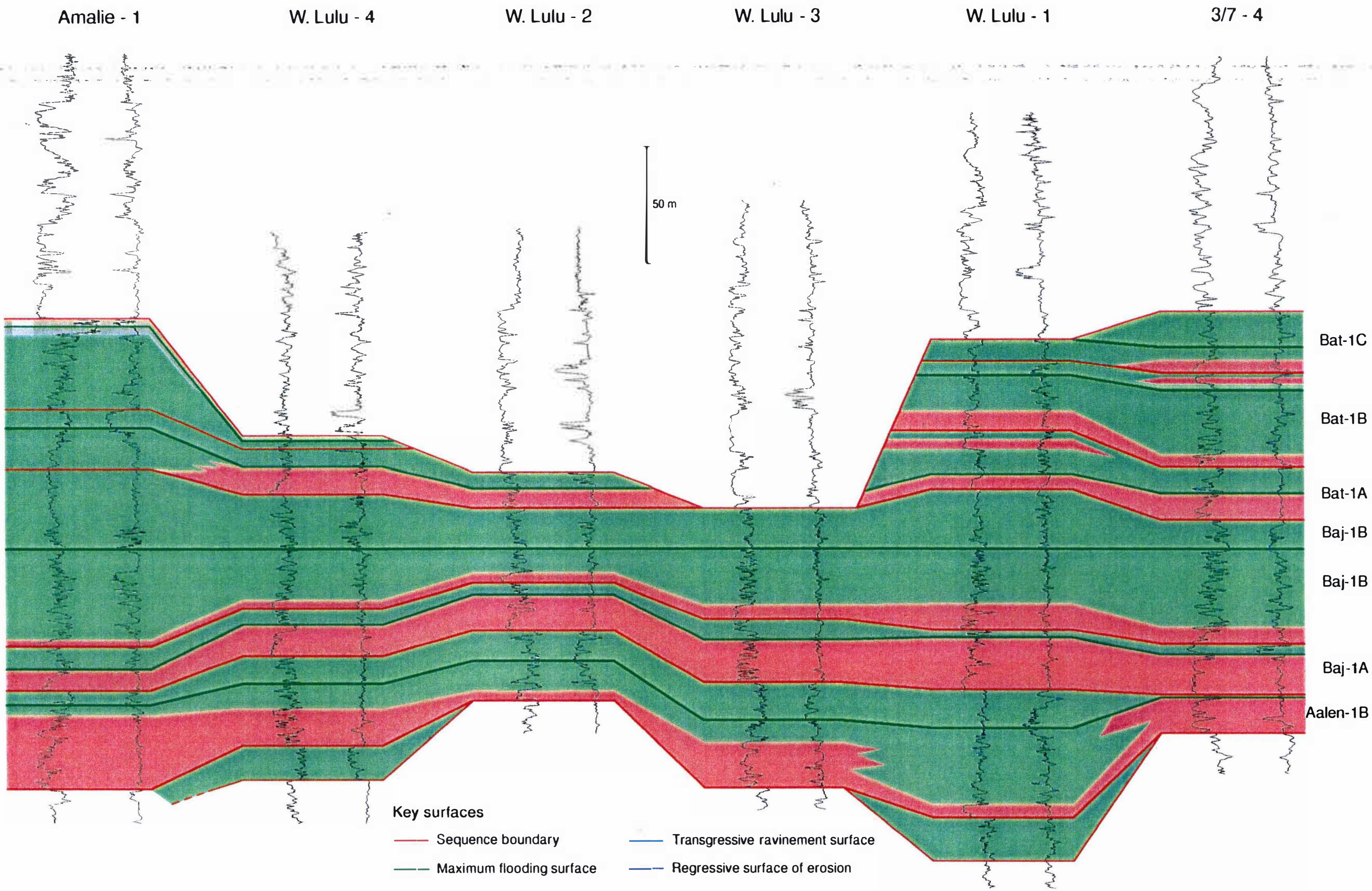
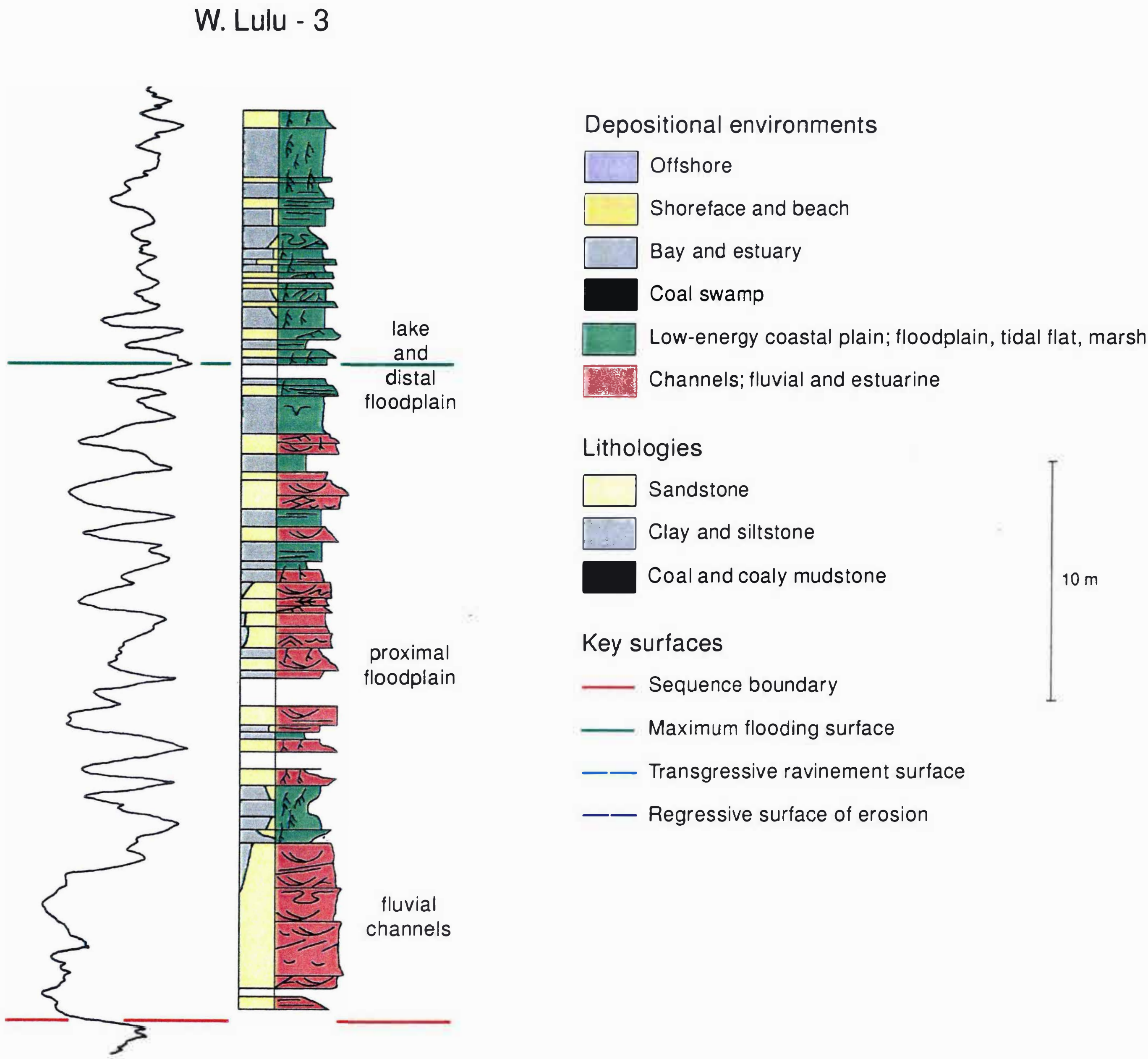
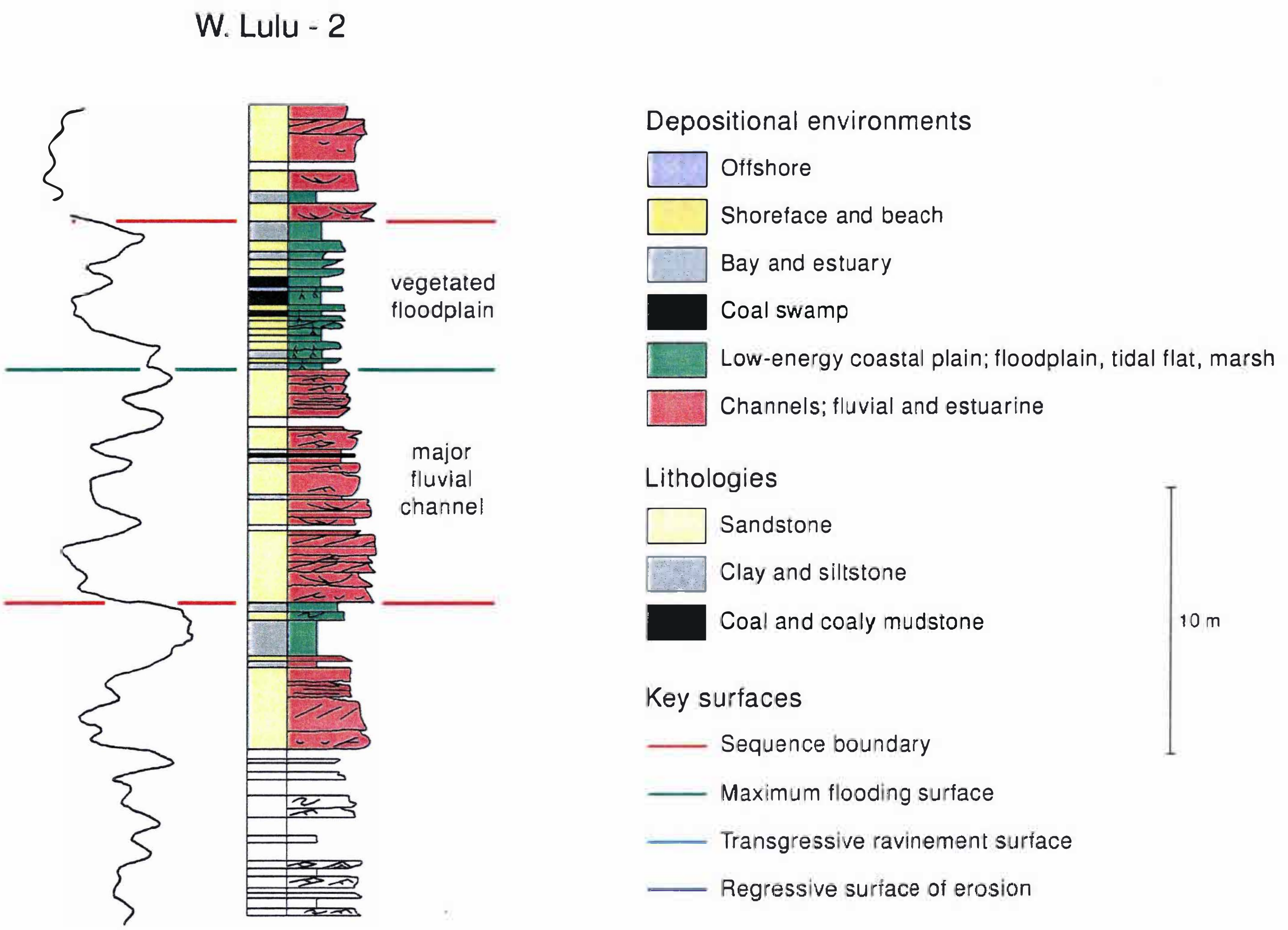

Amalie - 1
W. Lulu - 4
W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
50 m
Bat-1C
Bat-1B
Bat-1A
Baj-1B
Baj-1B
Baj-1A
Aalen-1B
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig.5



W. Lulu - 3
lake
and
distal
floodplain
proximal
floodplain
fluvial
channels
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion
10 m


Fig.6



W. Lulu - 2
vegetated floodplain
major fluvial channel
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
10 m
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig.7

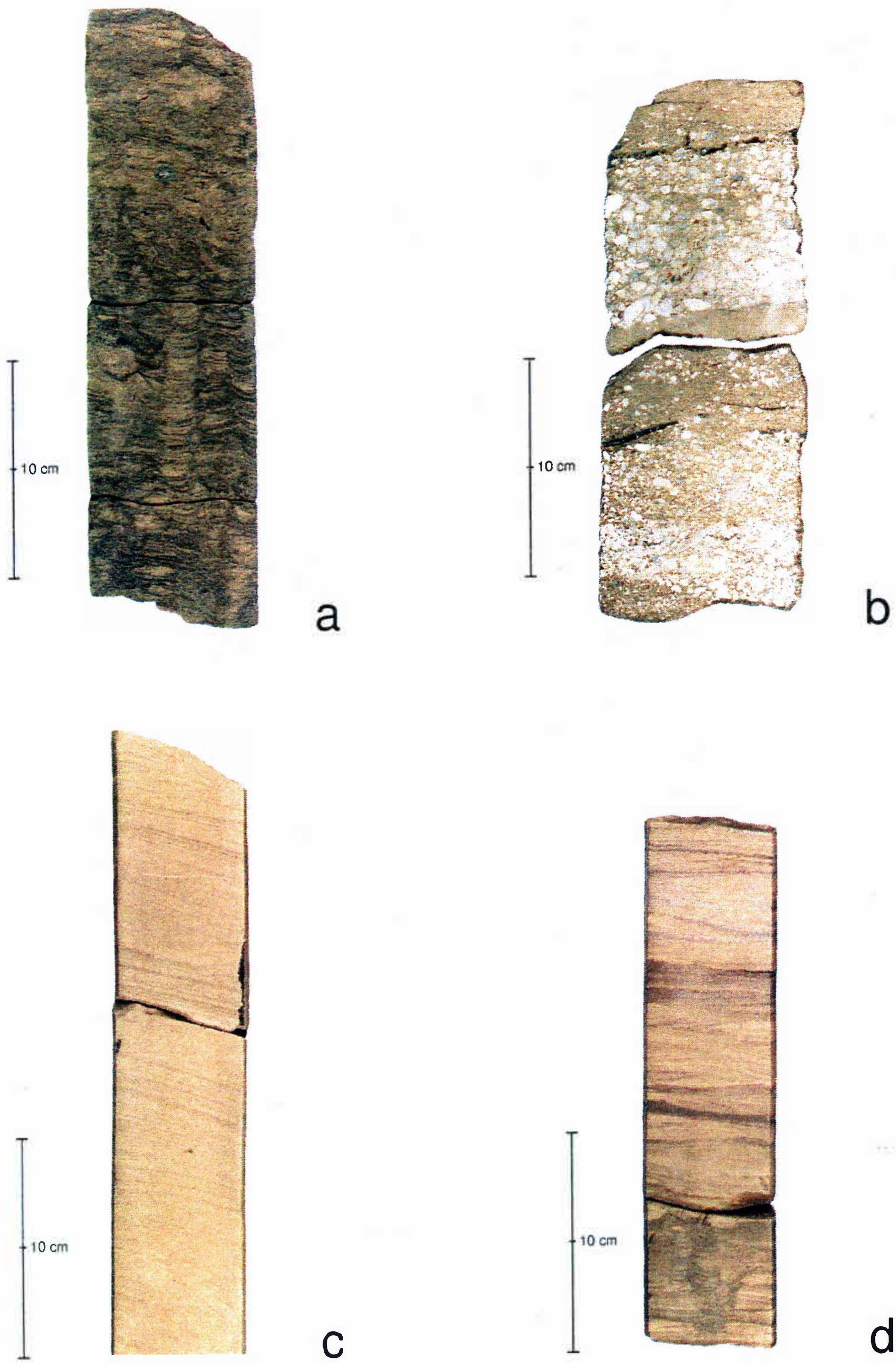



Fig.8

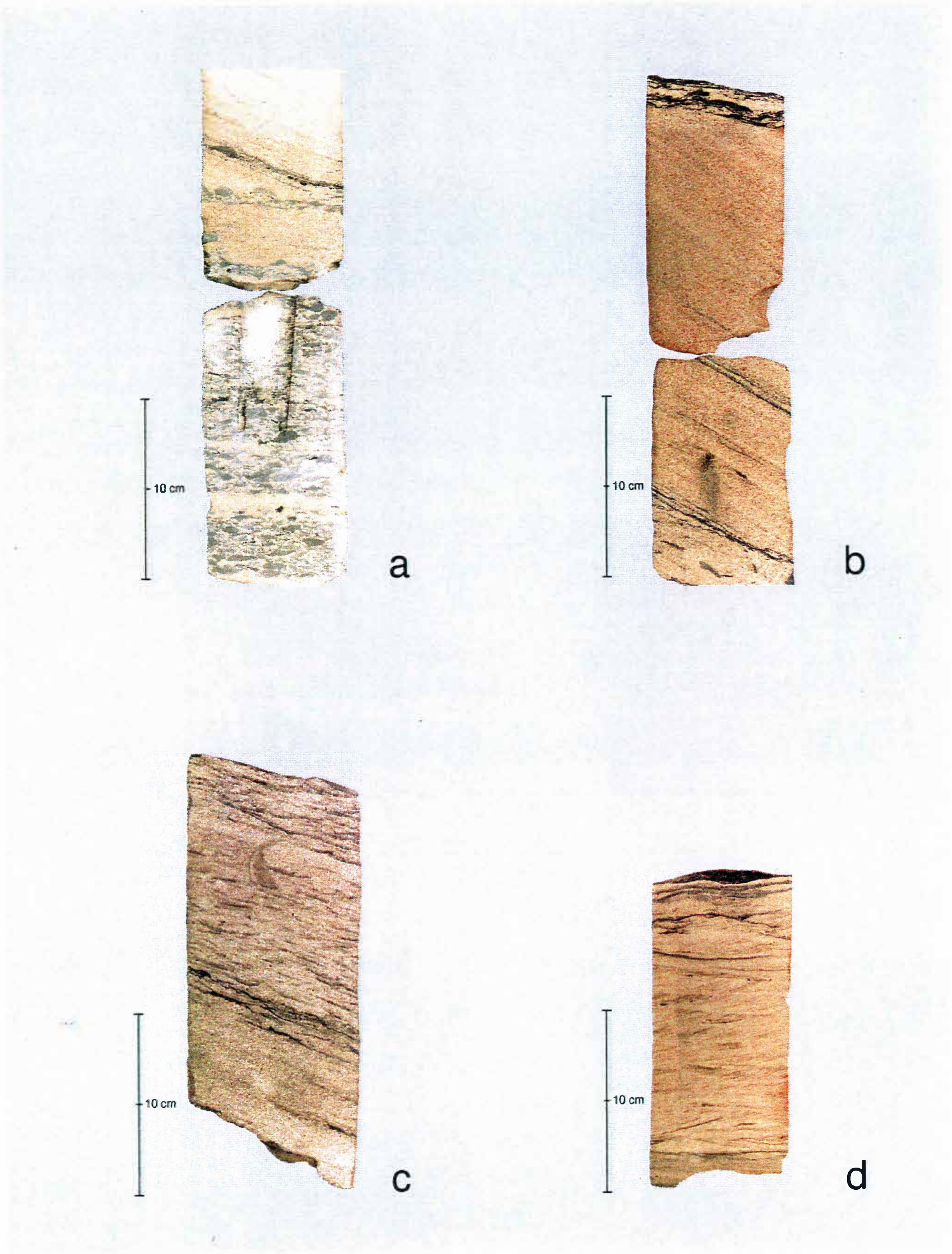
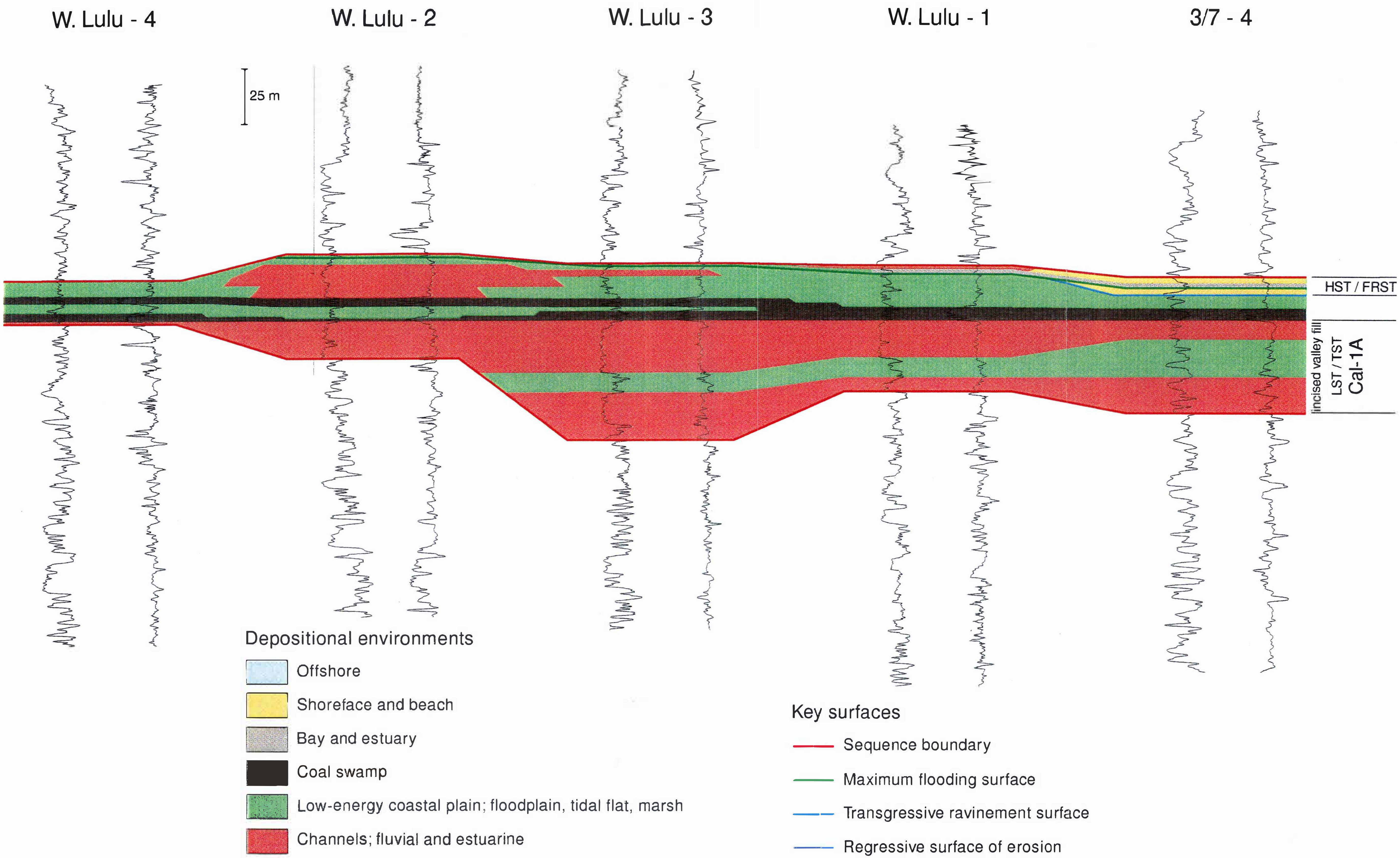
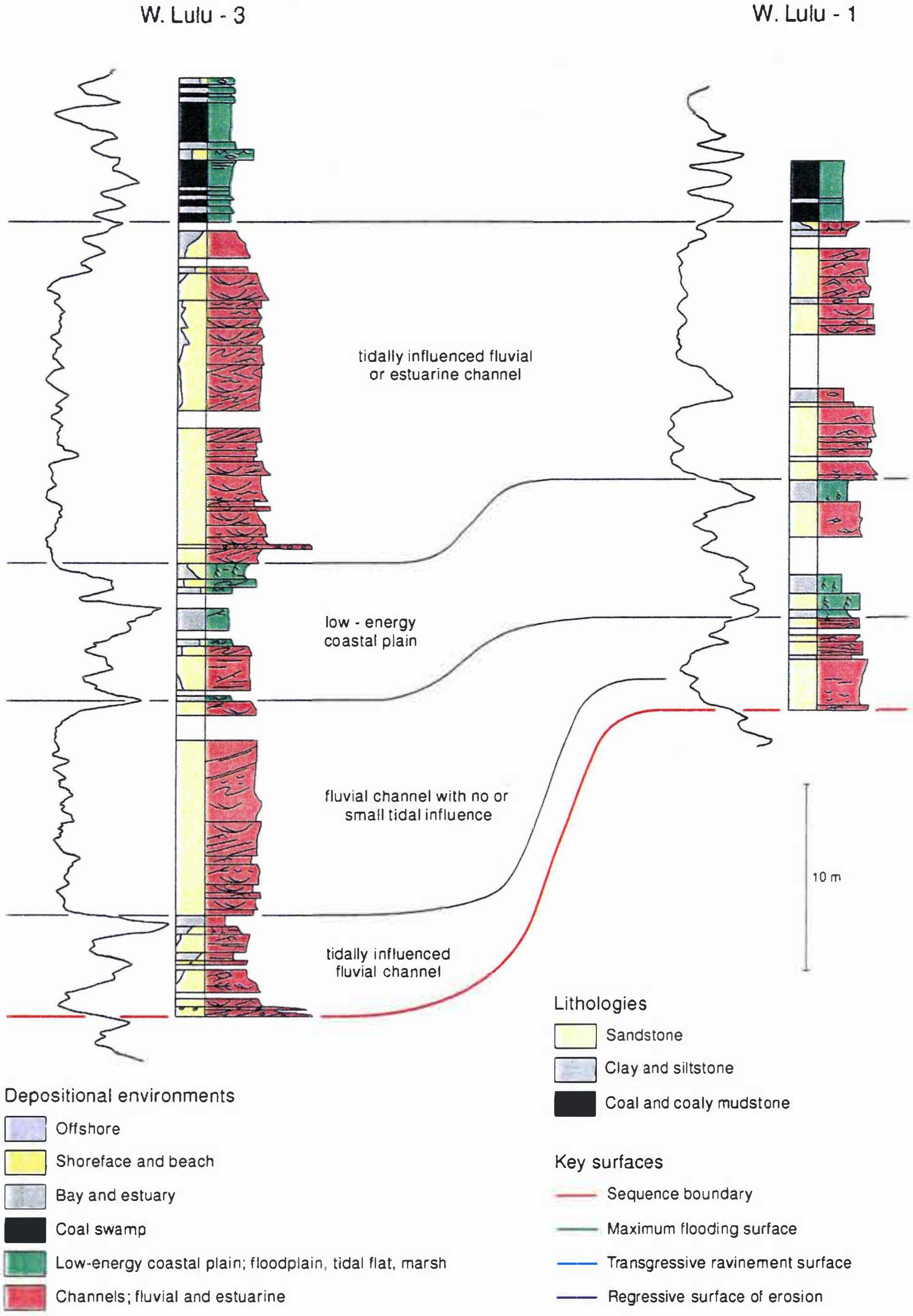



Fig.9



W. Lulu - 4
W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
25 m
HST / FRST
incised valley fill
LST / TST
Cal-1A
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig.10



W. Lulu - 3
W. Lulu - 1
tidally influenced fluvial or estuarine channel
low - energy coastal plain
fluvial channel with no or small tidal influence
tidally influenced fluvial channel
10 m
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig. 11

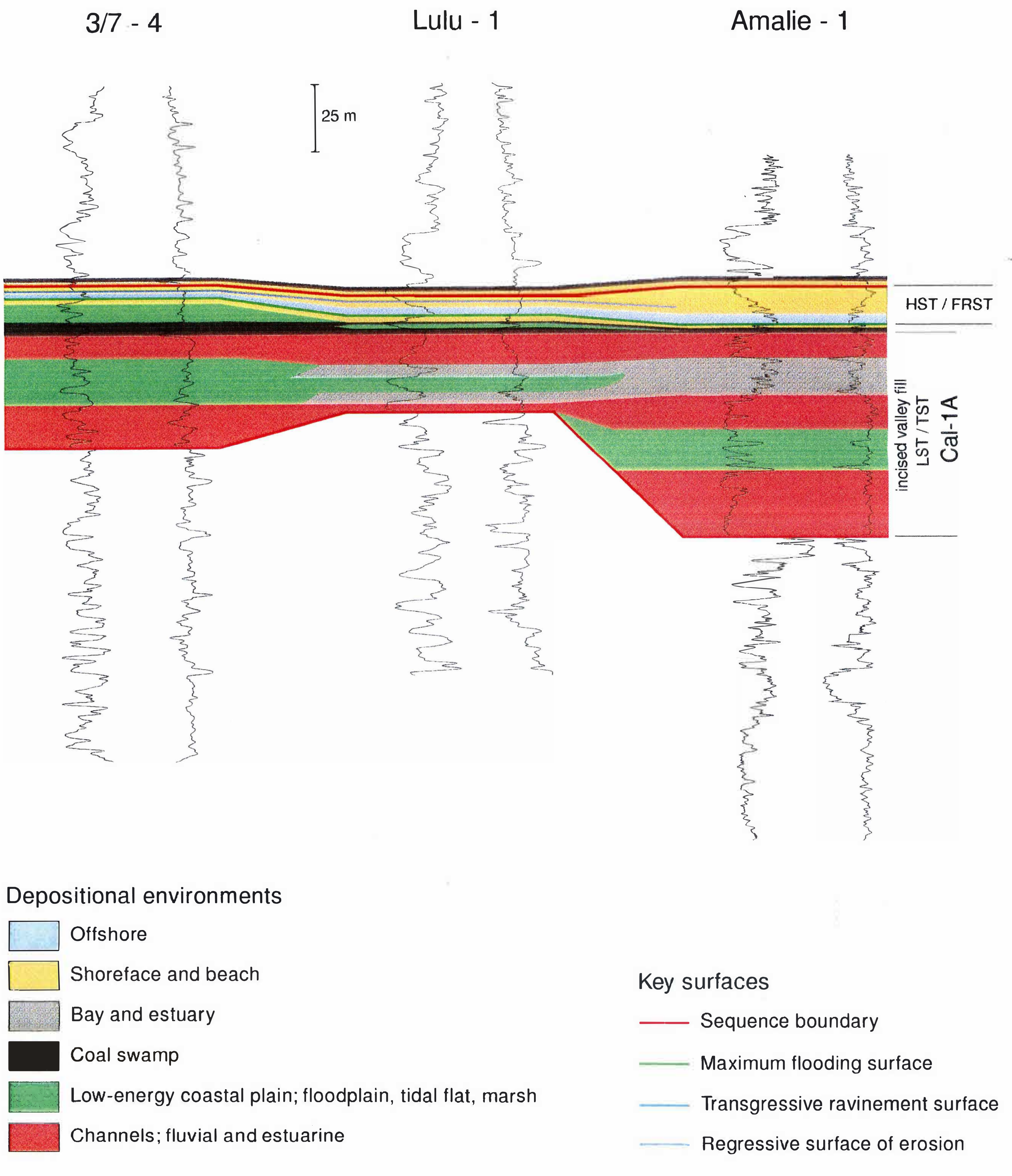

3/7 - 4
Lulu - 1
Amalie - 1
25 m
HST / FRST
incised valley fill
LST / TST
Cal-1A
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig.12

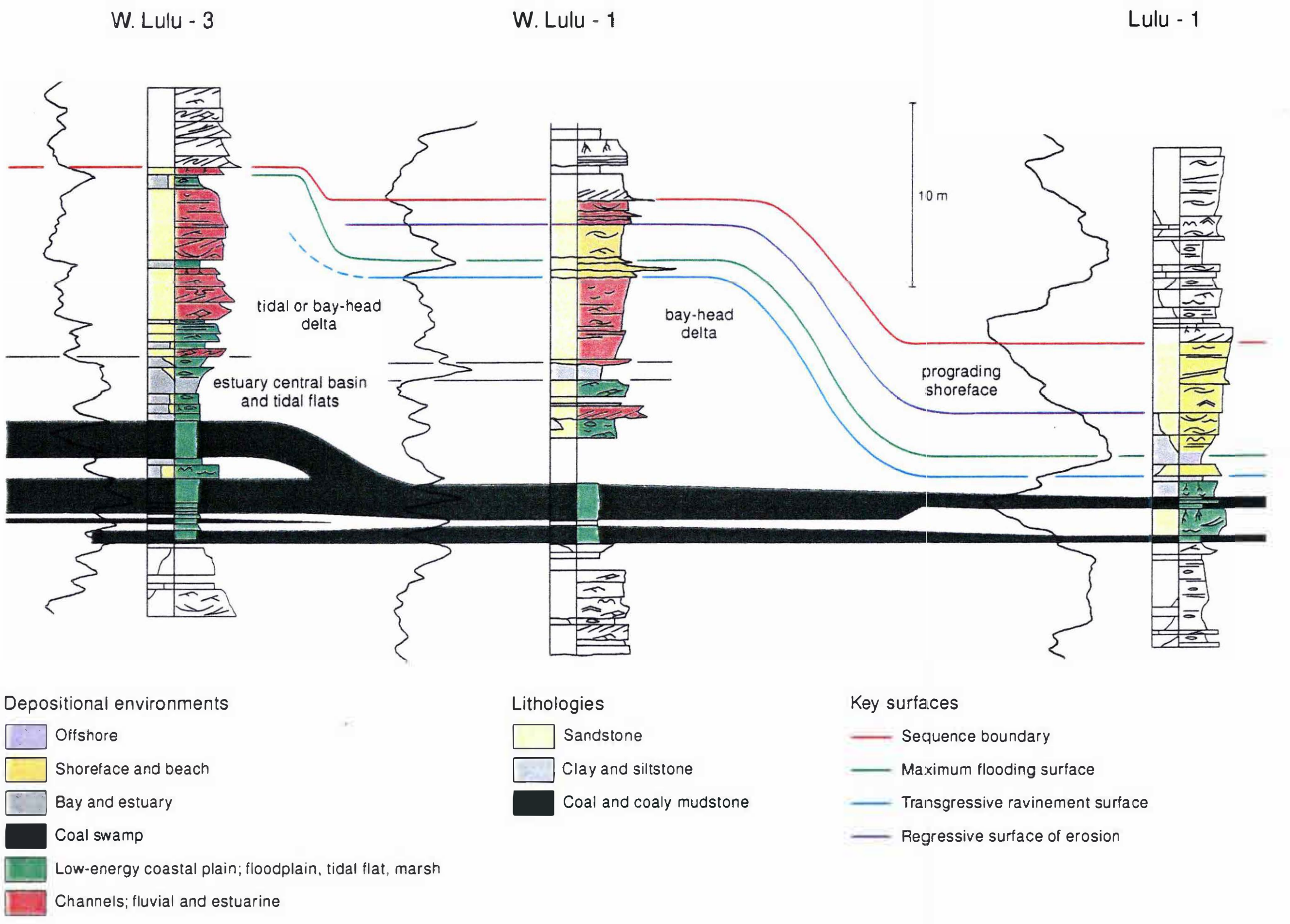

W. Lulu - 3
W. Lulu - 1
Lulu - 1
10 m
tidal or bay-head delta
estuary central basin and tidal flats
bay-head delta
prograding shoreface
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig.13

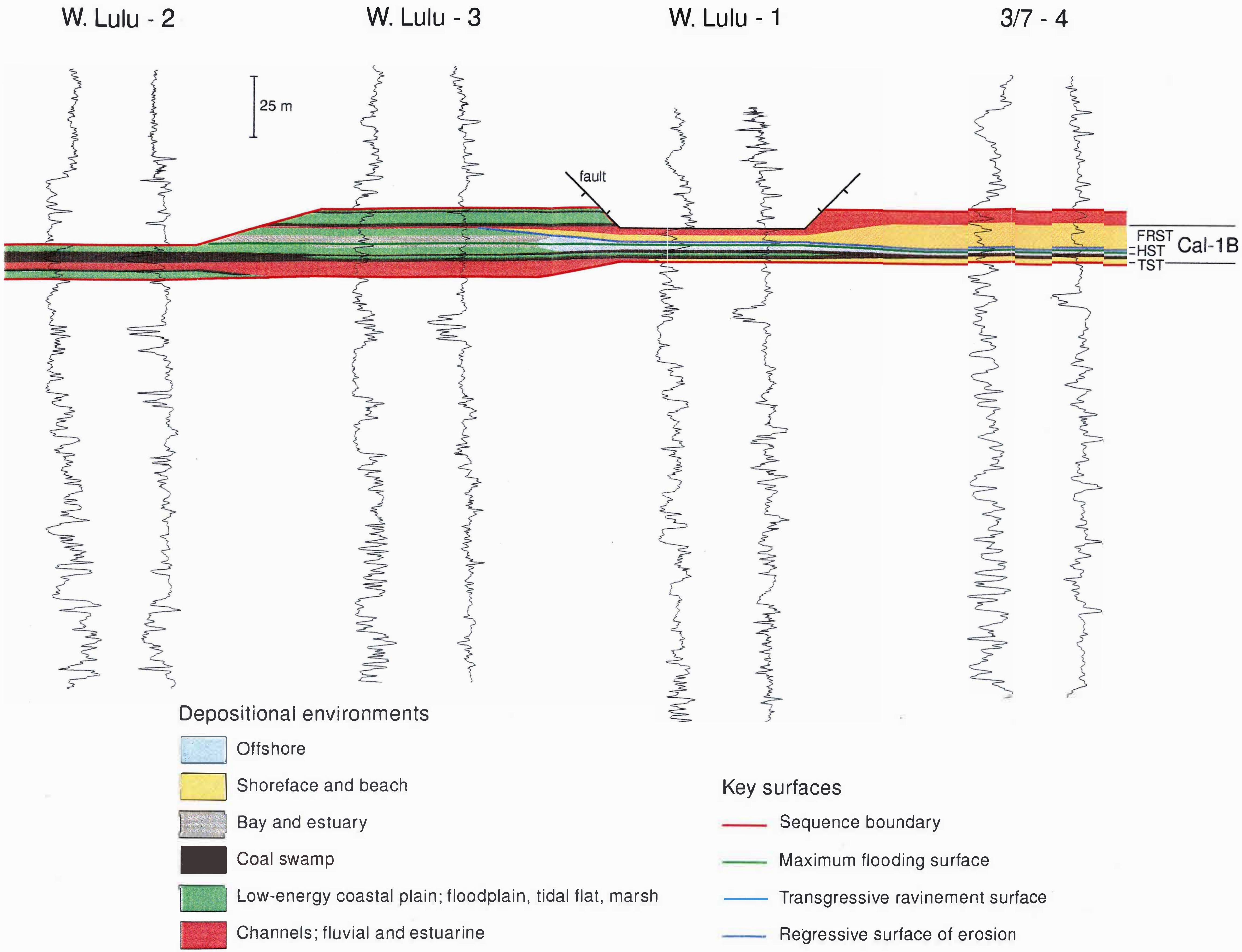
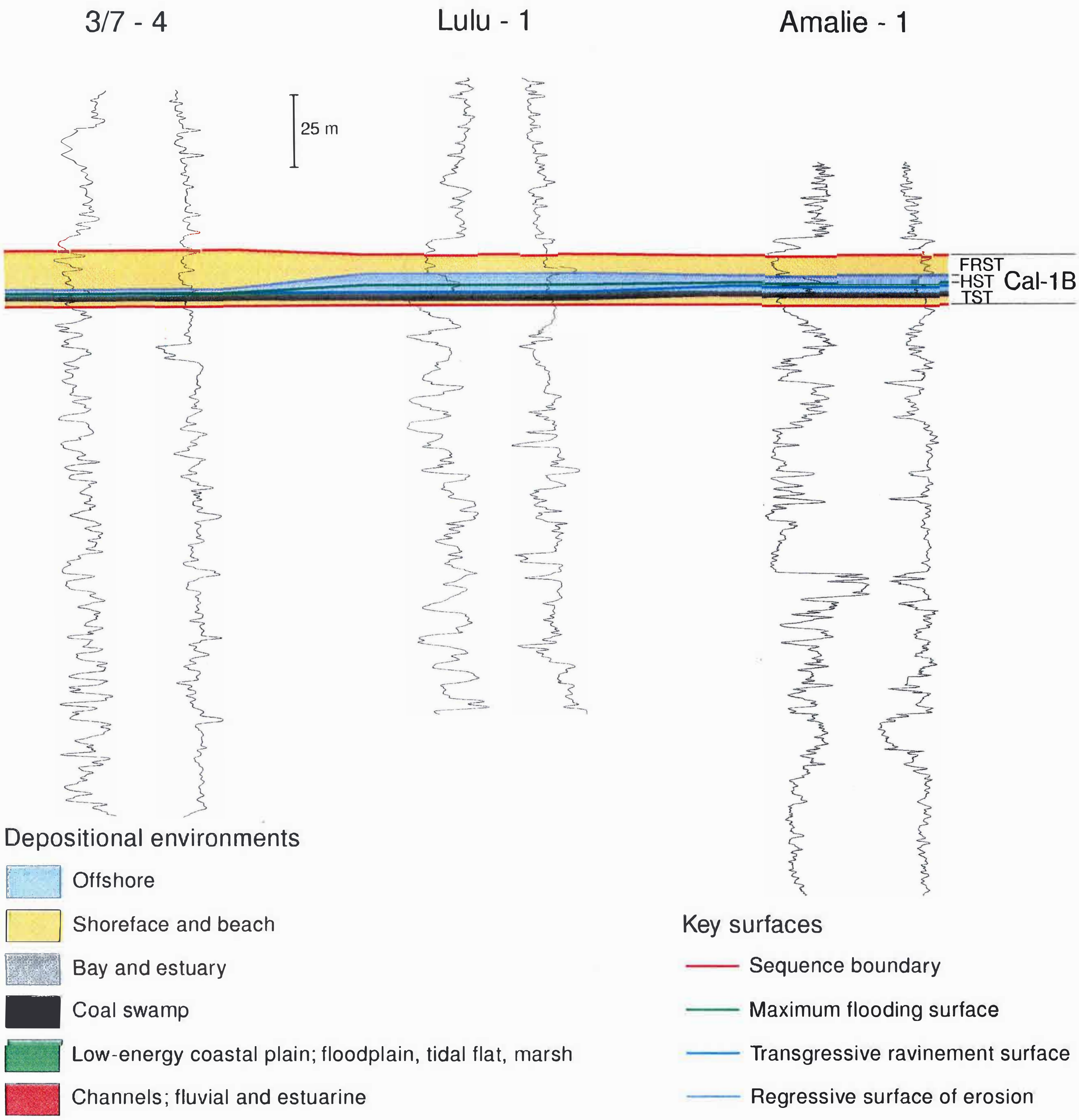
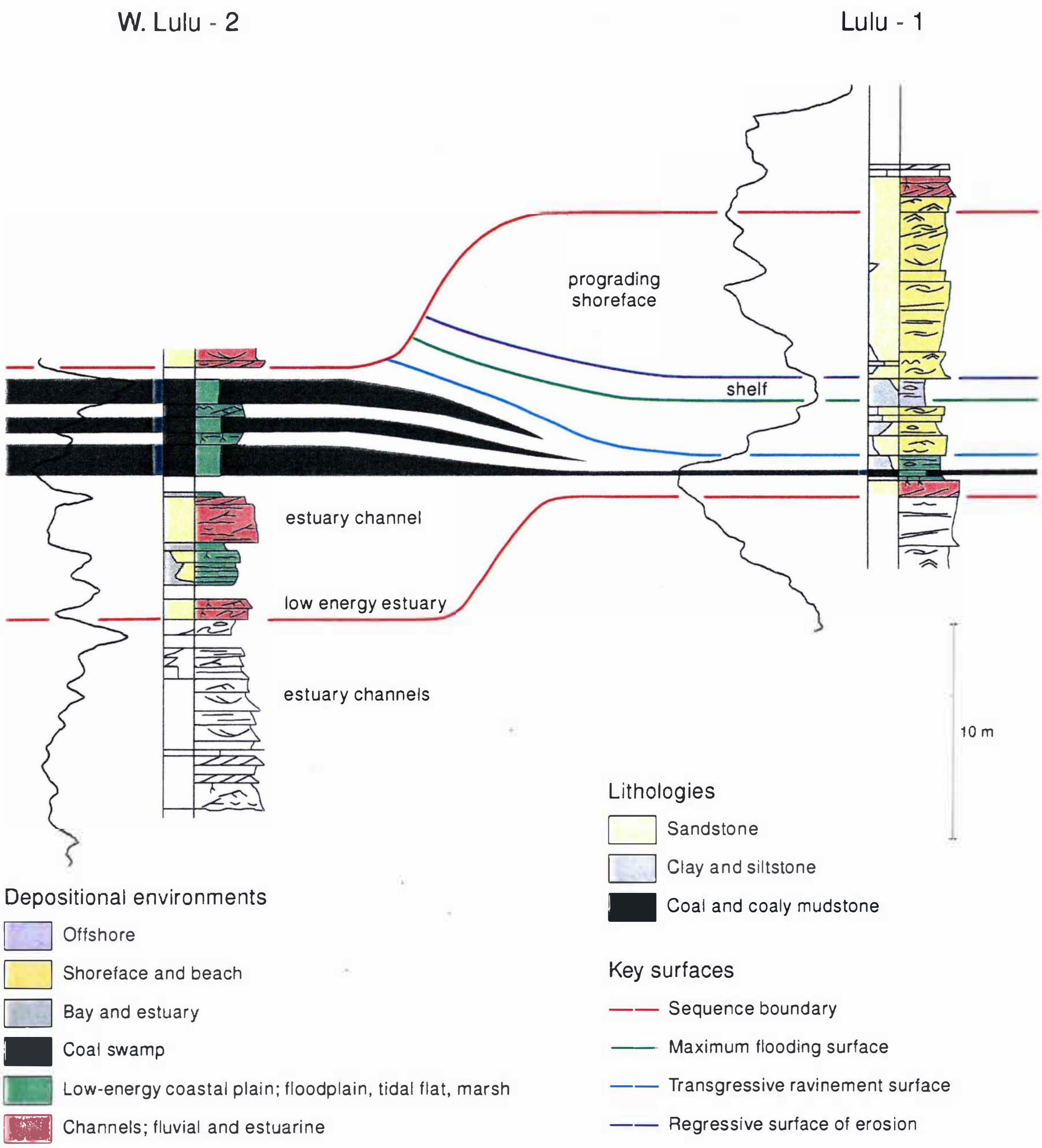

W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
25 m
fault
FRST
HST
TST
Cal-1B
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 14



3/7 - 4
Lulu - 1
Amalie - 1
25 m
FRST
HST
TST
Cal-1B
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig.15



W. Lulu - 2
Lulu - 1
prograding
shoreface
shelf
estuary channel
low energy estuary
estuary channels
10 m
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig.16

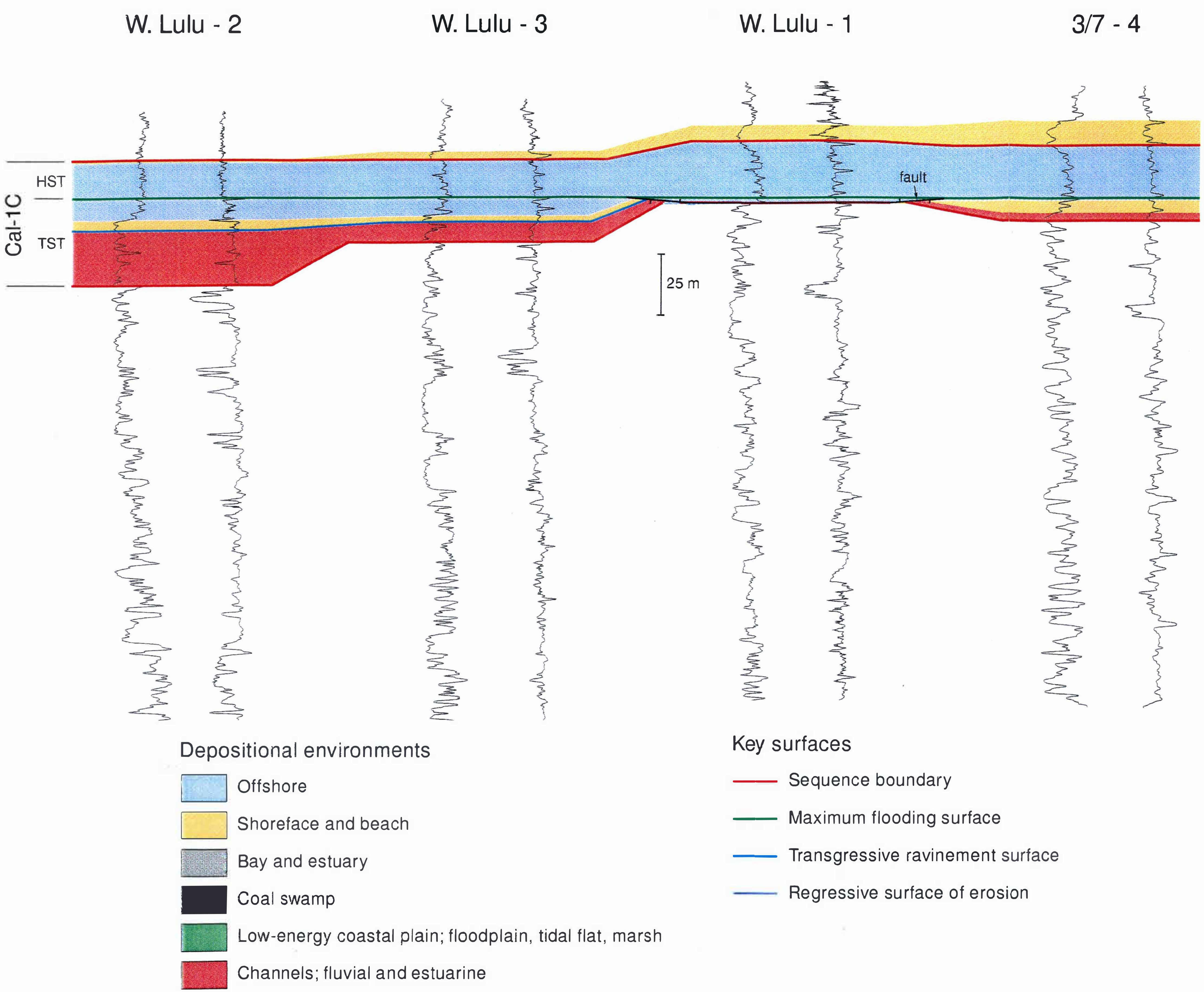
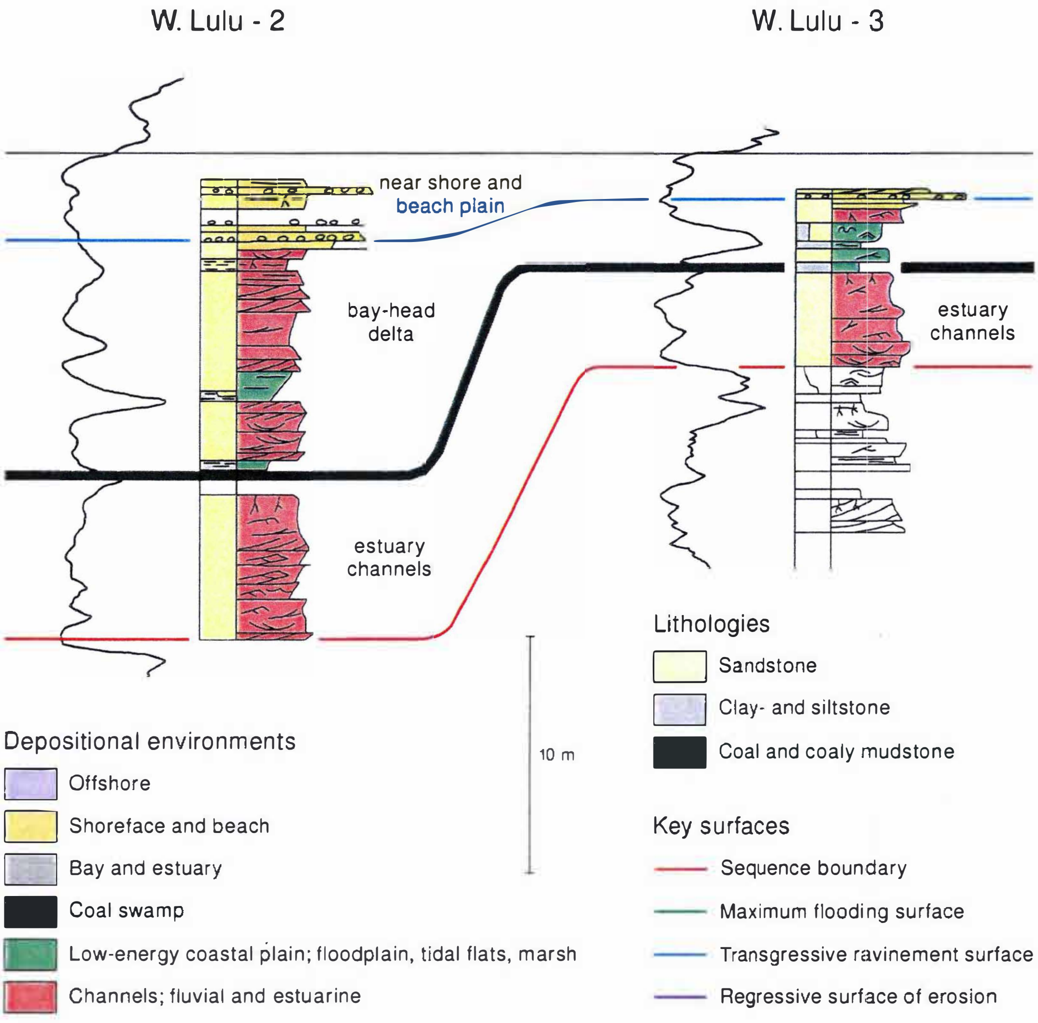

W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
Cal-1C
HST
TST
fault
25 m
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 17



W. Lulu - 2
W. Lulu - 3
near shore and
beach plain
bay-head
delta
estuary
channels
estuary
channels
10 m
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flats, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay- and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion


Fig. 18

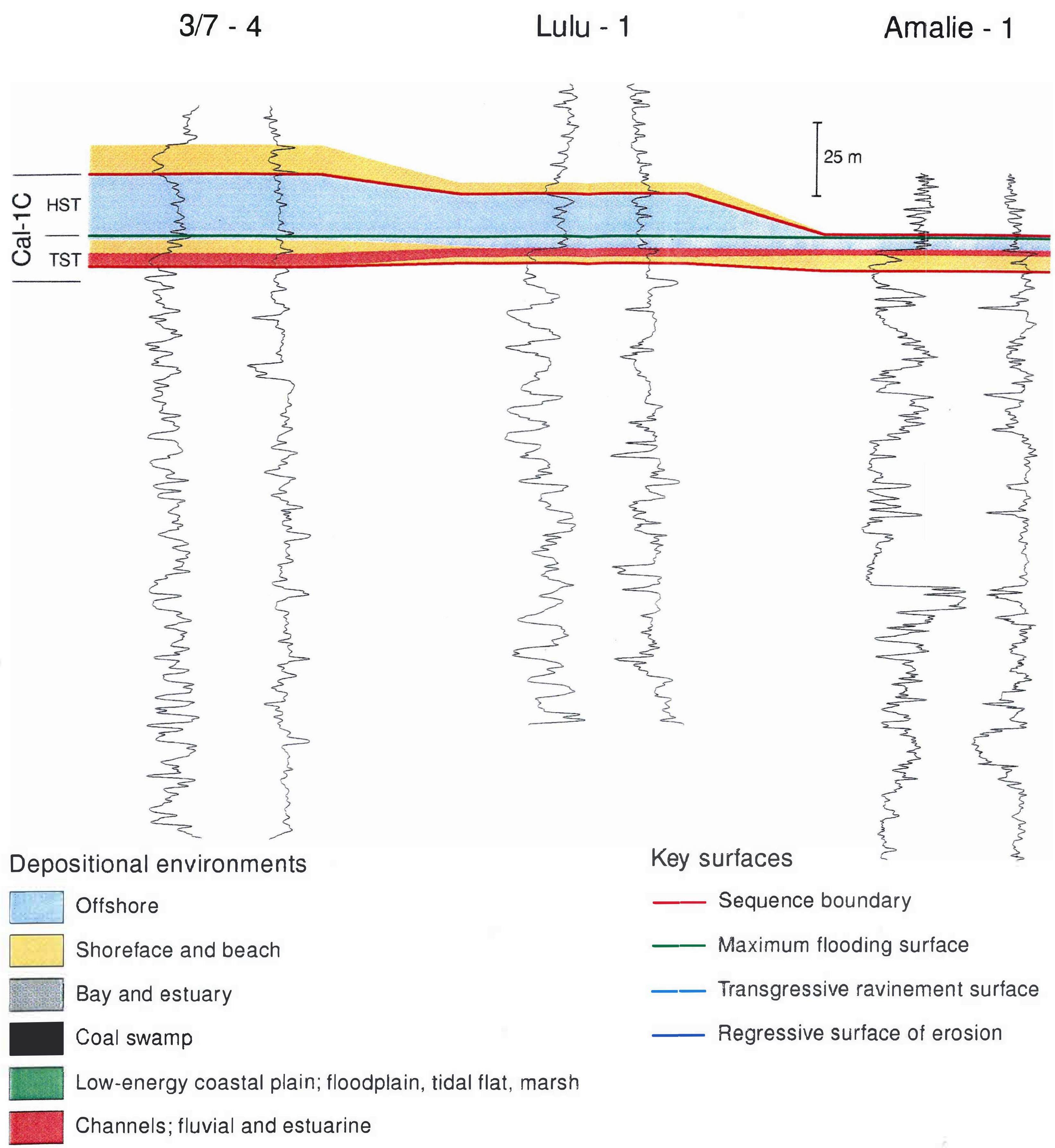

3/7 - 4
Lulu - 1
Amalie - 1
25 m
Cal-1C
HST
TST
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig.19

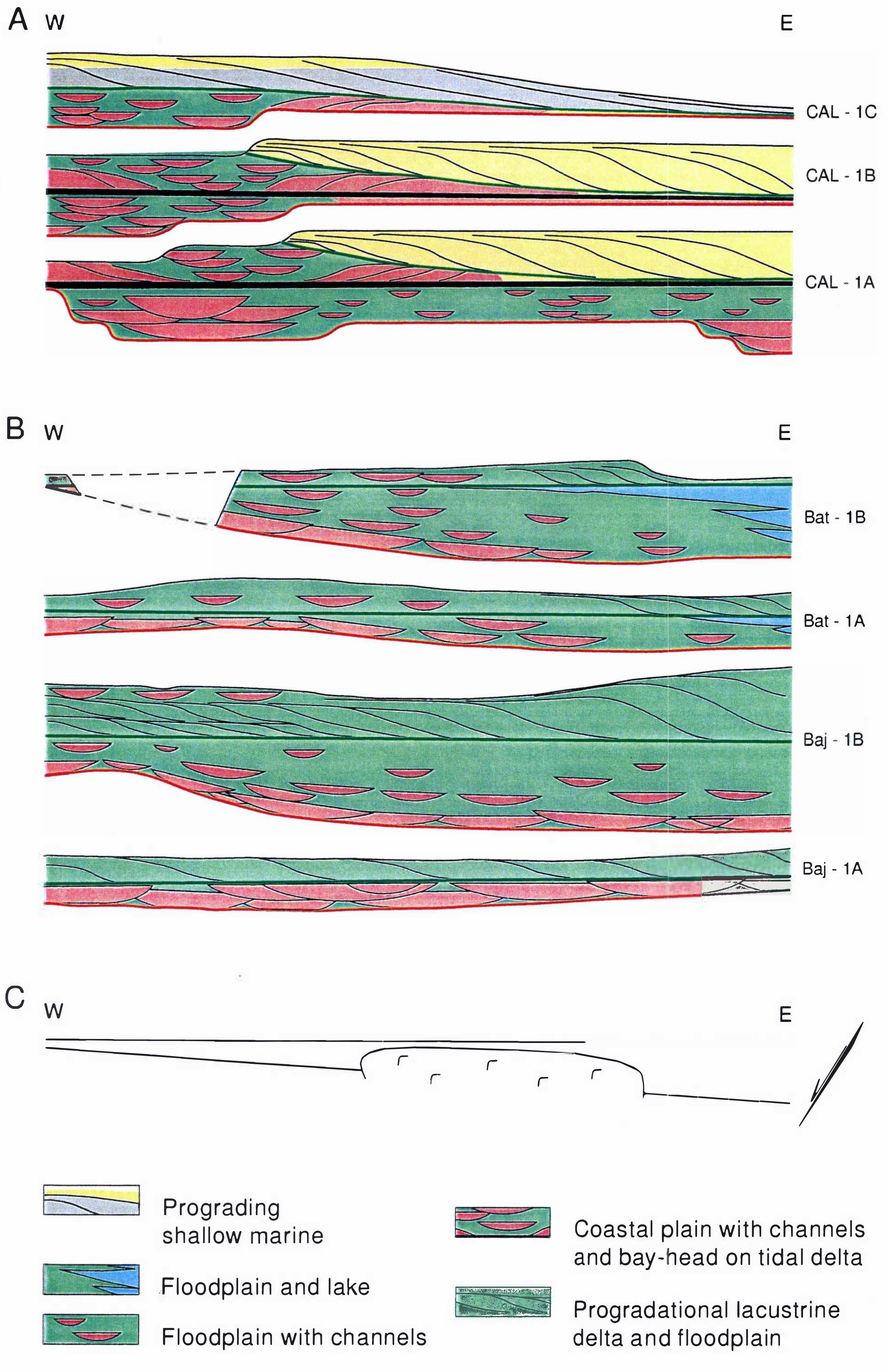

A W
E
CAL - 1C
CAL - 1B
CAL - 1A
B W
E
Bat - 1B
Bat - 1A
Baj - 1B
Baj - 1A
C W
E
Prograding shallow marine
Floodplain and lake
Floodplain with channels
Coastal plain with channels and bay-head on tidal delta
Progradational lacustrine delta and floodplain

Fig.20

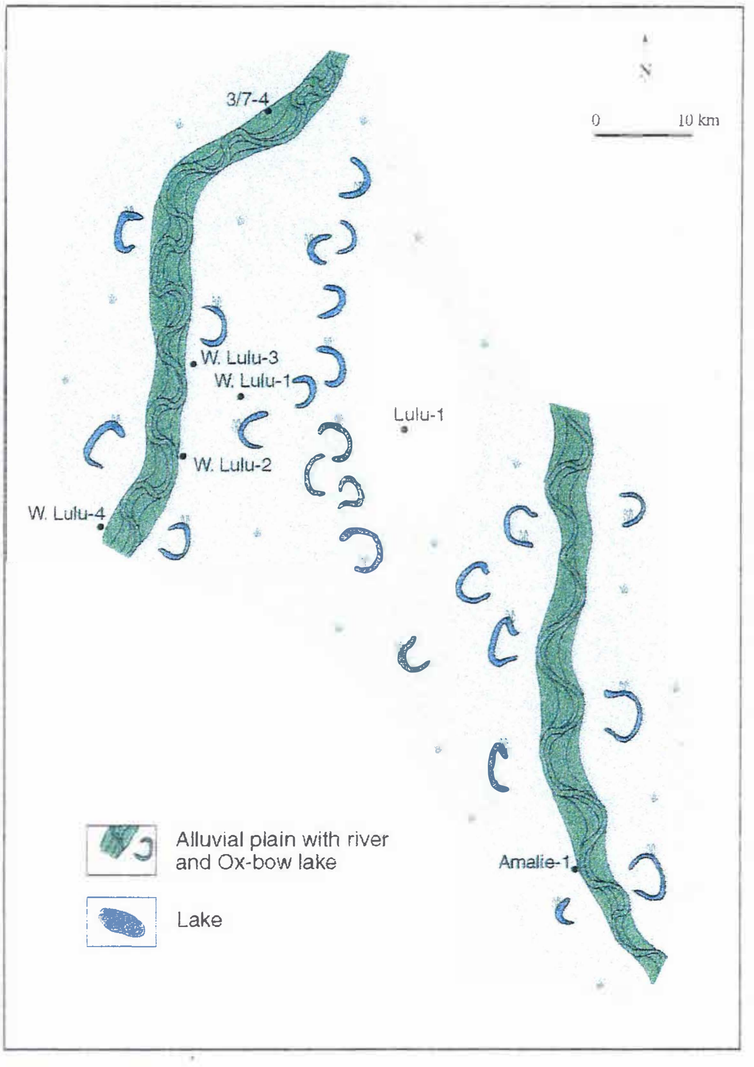

N
0
10 km
3/7-4
W. Lulu-3
W. Lulu-1
Lulu-1
W. Lulu-2
W. Lulu-4
Amalie-1
Alluvial plain with river and Ox-bow lake
Lake

Fig.21

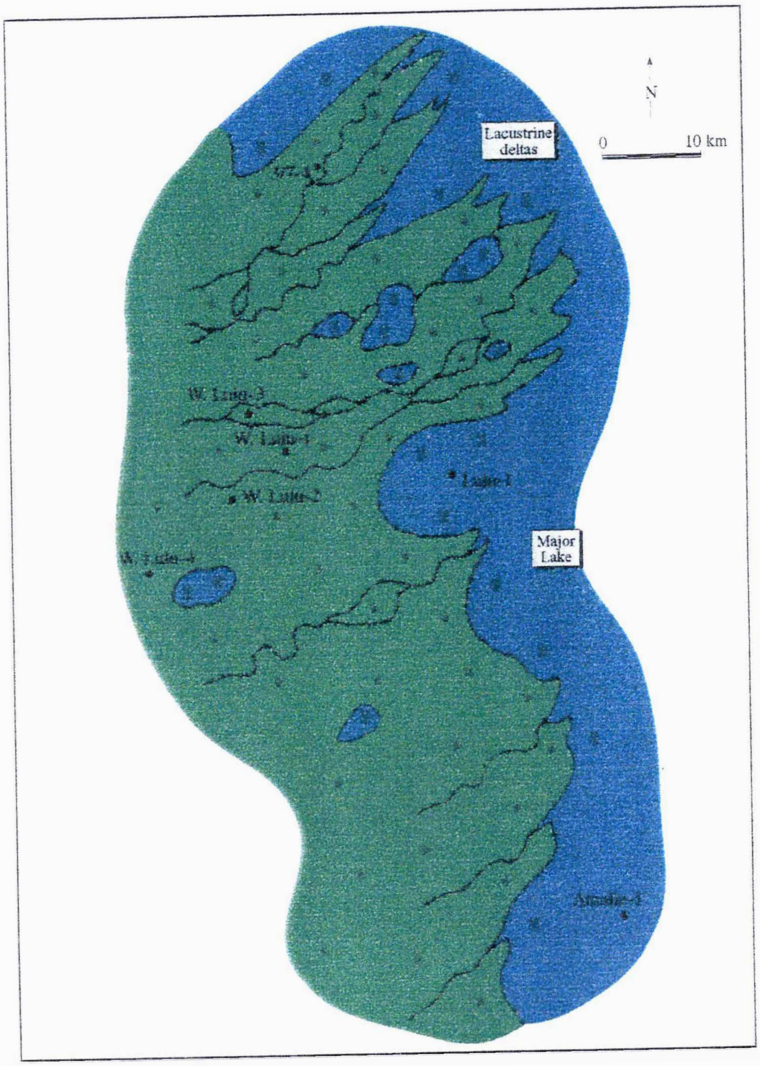
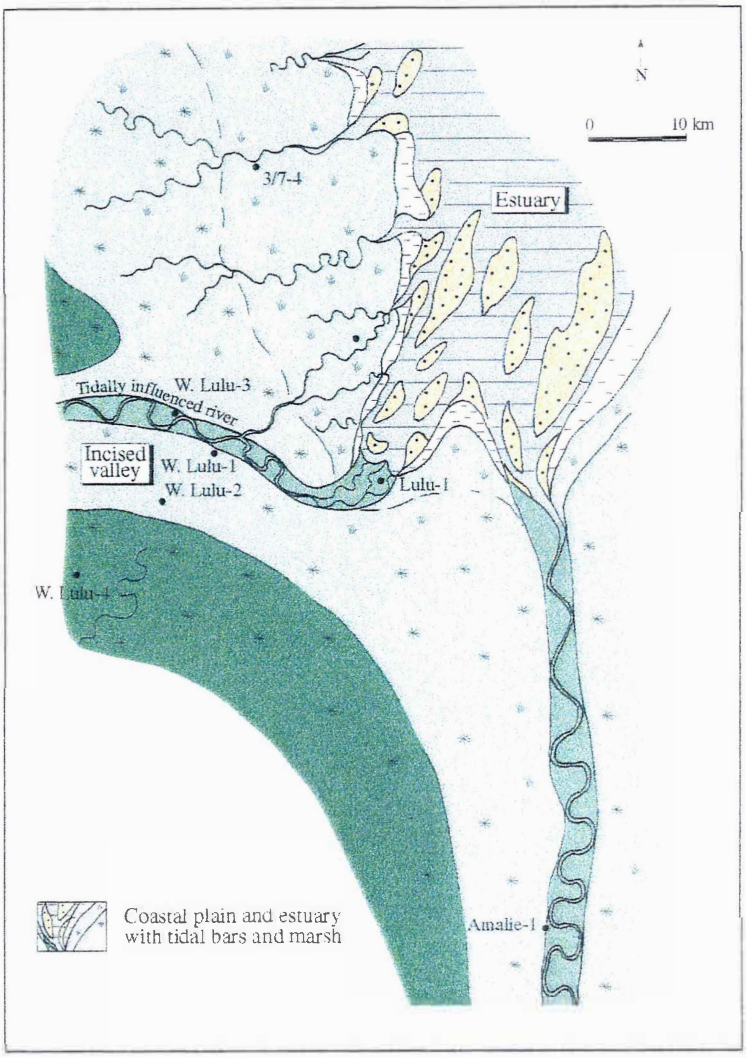



Fig.22



N
0 10 km
Estuary
3/7-4
Tidally influenced river
W. Lulu-3
Incised valley
W. Lulu-1
W. Lulu-2
Lulu-1
W. Lulu-4
Coastal plain and estuary
with tidal bars and marsh
Amalie-1


Fig.23

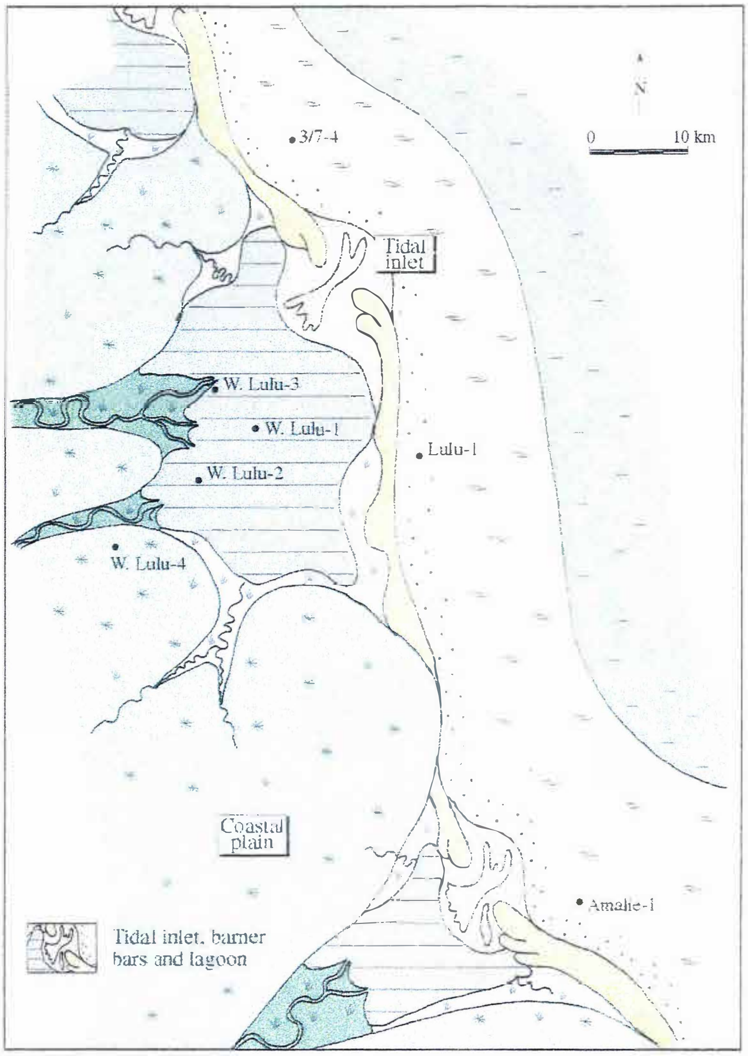

N
0
10 km
3/7-4
Tidal inlet
W. Lulu-3
W. Lulu-1
Lulu-1
W. Lulu-2
W. Lulu-4
Coastal plain
Amalie-1
Tidal inlet, barrier bars and lagoon

Fig.24

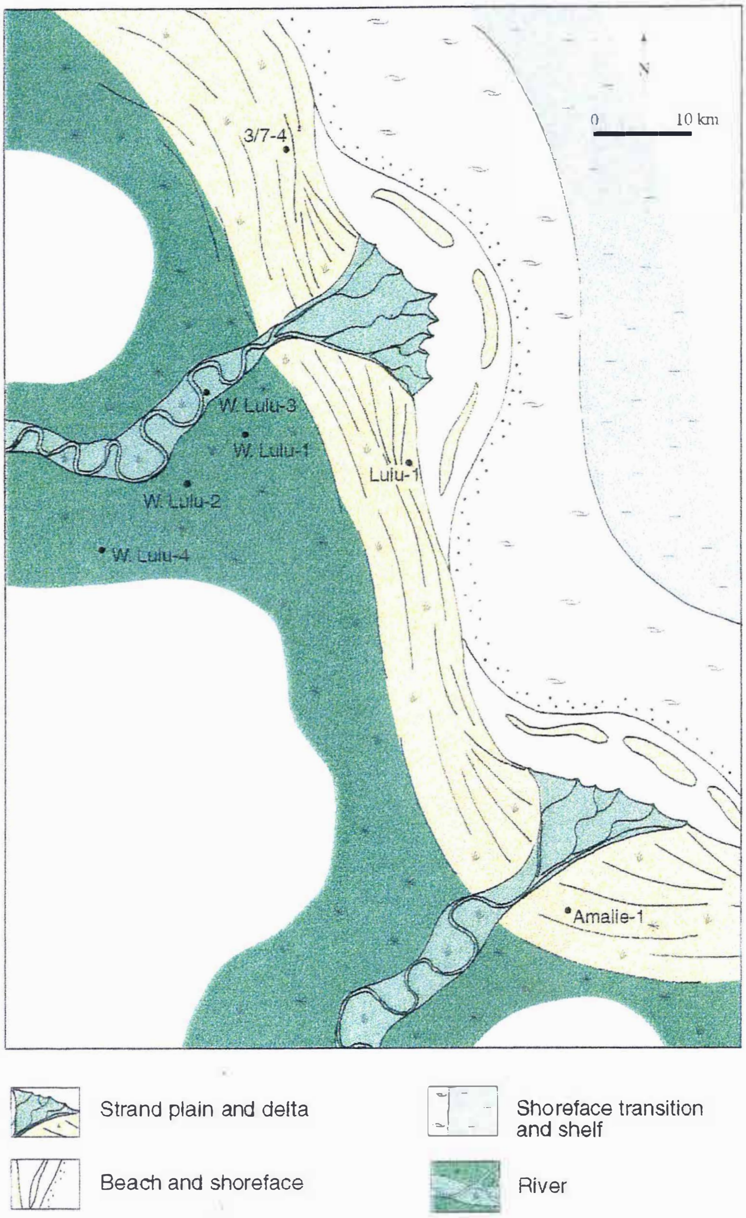

N
0
10 km
3/7-4
W. Lulu-3
W. Lulu-1
W. Lulu-2
W. Lulu-4
Lulu-1
Amalie-1
Strand plain and delta
Shoreface transition and shelf
Beach and shoreface
River

Fig.25

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Sedimentology and sequence stratigraphy of Middle Jurassic deposits

## Danish and Norwegian Central Graben
## Part 3

Jan Andsbjerg

Ph.D. Thesis, University of Copenhagen, Geological Institute

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Incised valleys and reciprocal architecture in coastal plain deposits of a half-graben basin

## Middle Jurassic of the Central Graben, Danish North Sea

Jan Andsbjerg

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

# Incised valleys and reciprocal architecture in coastal plain deposits of a half-graben basin; Middle Jurassic of the Central Graben, Danish North Sea.

Jan Andsbjerg

GEUS

# Contents

## Abstract

Cores and well logs from 9 wells in the southern part of the Søgne Basin form the basis for a sedimentological and sequence stratigraphic analysis of paralic and shallow marine deposits from the upper part of the Middle Jurassic Bryne Formation. Both sea-level changes and half-graben tectonics influenced the development of the upper Bryne Formation. Detailed log correlation shows that an up to 50 m deep system of incised valleys was cut into the alluvial plain deposits of the lower Bryne Formation. Incision was caused by a fall in sea-level, but the location and orientation of valleys and the depth of incision was influenced by tectonically controlled topography. Valley fill took place during an overall rise in sea-level. The complexity of valley-fill deposits suggests that high-frequency sea-level changes influenced deposition in the incised valley. A major peat cap developed in coastal plain mires on top of the filled valley and interfluves. Peat-forming coastal mires developed behind coastal barriers before transgression resumed. Transgression continued after faulting had generated a higher gradient on the coastal plain. The large amount of accommodation generated below the steep shoreline trajectory was filled by TST deposits that show a thickening trend in a landward direction. The HST/FRST deposits of the same sequence could only accumulate further downdip where they developed a seaward-thickening succession, thus creating a reciprocal sedimentary architecture. Two or three faulting events each created a sedimentary unit characterised by reciprocal architecture.

## Introduction

### Regional setting and structural development

The Danish Central Graben is part of the Central Graben (Fig. 1), a complex N - S trending Mesozoic intra-cratonic rift basin. It was initiated in the Triassic and was most active during the Middle and Late Jurassic (Møller, 1986). The Central Graben separates the Mid North Sea High to the west from the East North Sea Block of the Ringkøbing -Fyn High to the east. The development of the Danish Central Graben was determined by differential subsidence of grabens along N - S and NW - SE trending faults. The Søgne Basin and Tail End Grabens began to subside as separate half-grabens during the Middle Jurassic (Gowers and Sæbøe, 1985; Møller, 1986). Initiation of rift-associated subsidence was probably related to domal uplift and subsequent dome collapse in the North Sea area (Ziegler, 1982, 1990; Underhill and Partington, 1993). Most authors agree that asymmetric subsidence was initiated in the Søgne Basin in connection with fault activity at the Coffee Soil Fault (Fig. 2) during the Middle Jurassic (e.g. Gowers and Sæbøe, 1985, Møller, 1986; Cartwright, 1991; Michelsen et al., 1992; Mogensen et al., 1992; Korstgård et al., 1993). It has been suggested, however, that no syndepositional rotation took place in the Søgne Basin until Volgian time (Sundsbø and Megson, 1993).

Salt structures were generated in the Søgne Basin in the Triassic. Middle Jurassic subsidence and faulting initiated the development of boundary fault salt pillows and updip salt structures, that may have influenced depositional patterns in the southern Søgne Basin (Mogensen et al. 1992).

## The Bryne Formation

Middle Jurassic sandstones with interbedded mudstones and coals were encountered by the first exploration well in the Danish part of the Søgne Basin, Lulu-1 (Fig. 2). Similar deposits encountered in the Norwegian part of the Central Graben were included in the Bryne Formation established by Vollset and Doré (1984). The Bryne Formation was extended to the Middle Jurassic deposits of the northern part of the Danish Central Graben by Jensen et al. (1986) (Fig. 3). Similar and coeval deposits of the southern part of the Danish Central Graben were referred to the Central Graben Group of NAM and RGD (1980) by Jensen et al. (1986) (Fig.3).

In the Søgne Basin, the Bryne Formation unconformably overlies Triassic and Permian deposits and is conformably overlain by marine mudstones of the Upper Jurassic Lola Formation (Jensen et al., 1986) and unconformably by Cretaceous deposits on structural highs (Fig. 3). The Bryne Formation shows thicknesses from 130 to 300 m in the wells of the Søgne Basin (Figs 4, 5). It may be absent from the top of structural highs, and it may attain slightly larger thicknesses in deeper parts of the basin.

Based on sedimentological analysis of cores the Middle Jurassic of the Lulu-1 well has been interpreted as deltaic interdistributary bay deposits overlain by coastal sediments (Frandsen, 1986). Middle Jurassic deposits further south in the Danish Central Graben were previously interpreted as alluvial plain and delta plain deposits by Koch (1983). Damtoft et al. (1992) suggested a fluvial channel and floodplain environment for the Bryne Formation, whereas Johannessen and Andsbjerg (1993) and Andsbjerg (in prep.) interpreted the Bryne Formation as an alluvial plain succession overlain by tidal and shallow marine deposits.

The first clastic hydrocarbon reservoirs to be put into production in the Danish North Sea are the Bryne Formation sandstones of the Harald Field in the Søgne Basin. The best reservoir sandstones and most of the hydrocarbons are found in the upper part of the Bryne Formation, which is the subject of this study. These are interpreted as estuarine and fluvial incised valley fill deposits overlain by interfingering shallow marine and estuary deposits by (Andsbjerg, in prep.). The estuarine and other back-barrier sediments commonly deposited during transgressive intervals and regressive shoreface deposits occur within the same 15 to 25 metres thick successions between correlatable coal beds (Andsbjerg, in prep.). Within these successions, shallowing upward sections of shallow marine deposits dominate in locations close to the basin axis, whereas back-barrier intervals, frequently showing a deepening upward trend, become increasingly important towards the basin margin on the hanging-wall slope. In wells where both types of sections can be recognised, the regressive shoreface deposits overlie the transgressive estuarine deposits, and are separated from them by a maximum flooding surface. This differential distribution of the two main elements of the succession is an example of "reciprocal deposition" described by Kidwell (1988) and by Nummedal and Molenaar (1995). However, in order to distinguish this concept from reciprocal deposition as introduced for mixed carbonate-siliciclastic systems by Meissner (1972) and adapted to sequence stratigraphy by Sarg (1988) the term "reciprocal architecture" introduced by Catuneanu et al. (1997) is preferred. Although the "reciprocal architecture" of Catuneaunu et al. (1997) describes the differential distribution of regressive and transgressive successions, it differs as a concept from the reciprocal deposition or architecture of Nummedal and Molenaar (1995) and the present paper by the occurrence of synchronous regressive and transgressive deposits in different parts of the basin.

In the present paper focus is on the Cal-1A sequence (Andsbjerg, in prep.), which shows both the best developed incised valley in the Middle Jurassic of the Danish Central Graben and a good example of reciprocal architecture. The sediments, key surfaces, and architecture of that sequence is treated in the following as basis for further discussion of the development of incised valleys and reciprocal architecture in an active half -graben.

## Well database and datings

Data from 9 of the 12 wells penetrating the Bryne Formation in the Søgne Basin are used in the present study (Fig. 2). Approximately 700 m of core has been examined and described. Graphic core logs are matched to gamma ray (GR) and sonic logs supplemented by density, neutron and resistivity logs, in order to gain an improved interpretation of the cored successions. The observed core to log relationships are used in the interpretation of well logs from uncored intervals, where sedimentological interpretations of cores are extrapolated to the uncored sections. The well logs are used to construct cross-sections. Well-to-well correlations of key surfaces and characteristic units form a framework that guide correlations of other units and form the basis for the construction of palaeogeographic maps.

Stratigraphically useful microfossils are rare in the studied succession. The sparse biostratigraphic information available for this study comes from unpublished reports from the Geological Survey of Denmark and Greenland (GEUS), reports from service companies, and the results of new investigations prepared for the study and presented by Andsbjerg and Dybkjær (in prep.). Only palynomorphs were used for the datings of that study, and the events are presented mainly as last occurrence datums (LOD) of dinoflagellate cyst species. The events used and their relation to boreal standard chrons are presented in Andsbjerg and Dybkjær (in prep., their table 2).

Age specific microfossils have not been found in the lower part of the Bryne Formation. However, the occurrence of the LOD of *Kekryphalospora distincta* in a supposedly correlatable section in Alma-1 further south in the Danish Central Graben indicates an Aalenian or earliest Bajocian age. The occurrence of *Adnatosphaeridium caulleryi* in the upper part of the Bryne Formation in West Lulu-1 indicates an age not older than the Bathonian, and the LOD of *Impletosphaeridium varispinosum* in the same interval indicates a latest Bathonian to early Callovian age. The LOD of *Ctenidodinium continuum* higher in the succession indicates an Early Callovian - earliest Oxfordian age for the uppermost part of the Bryne Formation. The LOD of *Liesbergia scarburghensis* in the basal part of the Lola Formation in several wells (Andsbjerg and Dybkjær, in prep.), indicates a mid Oxfordian age for the final transgression of the major part of Søgne Basin. The uppermost unit of coal-bearing sandstones and mudstones in West Lulu-4 cannot be correlated to the Bryne Formation in other wells of that area. This may indicate that a sand-prone paralic environment lasted somewhat longer at the western fringe of the basin.

# Sequence stratigraphic framework

## Sequence stratigraphic nomenclature and definitions

Sequence stratigraphic principles and nomenclature in this study follow Van Wagoner et al. (1988), Posamentier et al. (1988), Posamentier and Vail (1988), Van Wagoner et al. (1990) and Hunt and Tucker (1992, 1995). The subdivision and naming of sequences in the study area have been presented by Andsbjerg (in prep.). Unless explicitly stated as eustatic sea-level, the term sea-level is used in the sense "relative sea-level".

### Key surfaces

Sequence boundaries (SB) in the lower Bryne Formation commonly are represented by the erosive bases of major, laterally extensive channel sandstones. Maximum flooding surfaces (MFS) in the lower Bryne Formation are located in lacustrine mudstones overlying fining upward channel sandstones or located at the inflection point between fining upward and coarsening upward floodplain deposits.

In the marine and marginal marine deposits of the upper Bryne Formation sequence boundaries can be seen as erosional bases of estuary channel sandstones or as more subtle shifts from shoreface to beach plain deposits. In this setting surf zone erosion may have caused amalgamation of SB and transgressive surface of marine erosion (TSE) (ravinement surface). In some units, a regressive surface of marine erosion (RSE) separates offshore transition zone and lower shoreface sediments deposited during sea-level highstand, from upper shoreface and foreshore sandstones deposited during falling sea-level above. In this setting the MFS is commonly picked at a laterally extensive offshore or lagoonal mudstone. Flooding surfaces (FS) separate terrestrial or more proximal marine deposits from marine or more distal marine deposits. The first FS above a SB usually is taken as the boundary between sediments of the lowstand and the transgressive systems tract.

### Systems tracts

A systems tract is defined as a linkage of contemporaneous depositional systems defined by stratal geometries at bounding surfaces, position within the sequence, and internal stacking patterns (Posamentier et al., 1988). Sequences are subdivided into lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and forced regressive systems tract (FRST) following Hunt and Tucker's modifications of the EXXON system (Hunt and Tucker, 1992, 1995). Identification of systems tracts is based on the identification of their bounding surfaces, stacking patterns and their position within sequences. The link between sequence development and sea-level changes is direct in the marine and marginal marine deposits, but more circumstantial in the non-marine realm. However, the sporadic occurrence of tidal indicators in the non-marine deposits of the lower Bryne Formation suggests that deposition took place on a coastal plain, where sea-level changes may have had a pronounced influence on variations in accommodation space and on sedimentation patterns.

### Lowstand systems tracts

In accordance with Hunt and Tucker (1992, 1995) the sediments deposited during falling relative sea-level are referred to the FRST so that the lowstand systems tract (LST) consists of deposits formed at the lowest relative sea-level stand. These deposits are bounded below by the mainly subaerial sequence bounding unconformity (SB) and above by the first transgressive surface (TS). In the paralic and marginal marine deposits of the upper part of the Bryne Formation, the LST may be represented by massive channel sandstones in the incised valley fills that show little or no evidence of tidal processes. However, the majority of the channel sandstones in the incised valley fill deposits that show clear evidence for tidal processes, are interpreted as TST deposits, and unquestionable LST-deposits are not identified in this succession. During the lowest sea-level stand, incised valleys acted as conduits for sediment by-pass, and most deposition is inferred to have taken place further basinward. It must be emphasised that the transition from fluvial LST-deposits to tidally influenced TST-deposits is diachronous, and that this change inland may be marked by a change in fluvial style or by the development of a coal bed (Miall, 1996).

### Transgressive systems tracts

Sediments of the TST are deposited under increasing rates of rising sea-level. A large proportion of the sediment will be trapped on the coastal plain where new accommodation space is generated. The lower boundary of the TST is the first TS and the upper boundary the maximum flooding surface (MFS). The MFS is represented by a bed of shelf or lagoonal mudstone which is recognised as a GR spike on the well logs. The deposits of the TST belong to two separate depositional systems (Thorne and Swift, 1991; Nummedal and Molenaar, 1995): a backbarrier wedge, between the top of the lowstand valley fill and the TSE, consists of estuarine, tidal flat, marsh and lagoon deposits; and between the TSE and the MFS a backstepping shelf wedge that consists of a fining upward succession of shoreface and shelf deposits. A large part of the backbarrier wedge may have been deposited in incised valleys, which are sometimes capped by a coal bed or coal zone. The backstepping shelf wedge normally wedges out in a basinward direction.

### Highstand systems tract

Deposition in the HST commences when a decreasing rate of sea-level rise brings transgression to an end. A continued slow sea-level rise creates some accommodation space on the coastal plain, but sediment surplus will cause a gradual progradation to begin. The HST is characterised by a progradational stacking pattern which may be interrupted by transgressive events. The systems tract is bounded at the base by the MFS and at the top by the SB or by a RSE if it is overlain by a forced regressive systems tract (FRST).

In the marine and paralic successions, the HST occur basinwards as a coarsening upward succession dominated by shelf, shoreface or tidally influenced delta deposits. In the paralic to shallow marine deposits of the upper Bryne Formation, the HST typically wedges out in a landward direction, where it overlies gradually thicker estuarine deposits of the TST, and is cut from above by an incised SB. Farther landward in the study area, the HST is mainly represented by ebb- or flood tidal delta, bay-head delta or other deposits, that reflect a rapid, progradational infilling of estuaries or bays.

**Forced regressive systems tract**
A significant erosional break within the coarsening upward succession suggests that the upper shoreface and foreshore deposits above the break may belong to the forced regressive systems tract (FRST) (Hunt and Tucker, 1992, 1995). The erosional break typically separates SCS-sandstones above from interbedded HCS-sandstone and mudstone below the surface. The basal, erosional boundary of the FRST is a regressive surface of marine erosion (RSE), which formed as a result of wave erosion of shelf deposits in response to the falling relative sea-level. The formation and preservation of the FRST depends on the balance between relative sea-level change and sediment input. The FRST consists of coarsening upward shoreface, estuary mouth, foreshore and beach deposits that prograded during falling relative sea-level (Plint, 1988).

**Sequences of the lower Bryne Formation**
The fluvially dominated coastal plain deposits of the lower Bryne Formation have been subdivided into 7 sequences, which are named Aalen-1A, Aalen-1B, Baj-1A, Baj-1B, Bat-1A, Bat-1B, and Bat-1C (Andsbjerg, in prep.) (figs 4, 5). Sequence boundaries have been picked at the base of regionally extensive channel units, some of which can be traced to the southern part of the Danish Central Graben (Fig. 6). Sequences below the Baj-1B sequence do not show significant thickness variations except for those caused by onlap on the pre-Middle Jurassic surface. In the upper part of the lower Bryne Formation the Baj-1B and Bat-1B sequences are strongly asymmetric with the largest thicknesses in the eastern part of the basin, where distal floodplain facies and thick lacustrine deposits are concentrated. The asymmetric distribution of deposits and facies may have been caused by the first rift-related faulting episodes along the Coffee Soil Fault at the eastern margin of the Søgne Basin (Fig. 2). The Bat-1A sequence shows only small thickness variations across the basin, possibly reflecting a pause between two faulting episodes. Thickness variations in the Bat-1C sequence cannot be evaluated as the sequence is missing from many wells due to intensive down-cutting at the base Cal-1A SB.

**Sequences of the upper Bryne Formation**
The succession has been subdivided into three sequences; Cal-1A, Cal-1B, and Cal-1C (Andsbjerg, in prep.), of which the lowermost Cal-1A sequence is the main subject of this study (figs 4, 5). The possibility of subdividing the Cal-1A sequence further into sequences of a higher hierarchical order is discussed below. The sequences of the upper Bryne Formation show a much more heterogeneous facies distribution than the sequences of the lower Bryne Formation. The Cal-1A SB has been picked in most wells at the base of deeply incised channels. The sequence boundaries of Cal-1B and Cal-1C are located in beach deposits overlying progradational shoreface successions in the central and eastern part of the basin and at the base of estuarine channels in the western part of the basin (figs 4, 5). The imprint of faulting on the development of these sequences is discussed below.

# Facies and facies associations

## Facies associations

The sedimentary facies recognised within the upper part of the Bryne Formation are grouped into 8 facies associations: (1) estuary channels and bars; (2) flood tidal delta and washovers; (3) bay-head delta; (4) low-energy estuary and lagoon and marsh; (5) swamp; (6) offshore; (7) prograding shoreface and beach; and (8) transgressive shelf and shoreface. Facies are presented in Tables 1a, 1b and 1c.

**Facies association 1: estuary channel and bar deposits**

The estuary channel and bar association occurs as 4 - 10 m thick fining upward, massive, or occasionally coarsening upward sandstone dominated units, and as 0.5 - 4 m thick, fining upward, fine- to very fine-grained sandstones and heteroliths. Channel fills occur both as single fining upward successions up to 13 m thick (Fig. 7) and as multiple ungraded or fining upward sandstones separated by erosional contacts (Fig. 8). The channel sandstones consist mainly of fine- to medium-grained sand, with common planar and trough cross-bedding in the lower part of fining upward units and in ungraded sandstones (Figs 9a, 10b). Coal fragments and mudstone clasts occur in some beds, notably above erosional bases of fining upward sandstone units (Fig. 10a). Cross-bedded sandstones may display superimposed current ripples and mud drapes (Figs 9a, b, 10a, b). More fine-grained sandstones, occurring in the upper part of fining upward units or interbedded with more coarse-grained sandstones in multiple sandstone successions, show current and climbing ripple lamination, frequently with mud flasers and thin mud drapes (Fig. 10c). In more heterolithic units wavy bedding and parallel lamination are common. Heterolithic strata, 5 - 20 cm thick, showing an angular contact with other strata, most commonly in the upper part of fining upward channel sandstone units may represent beds of inclined heterolithic stratification (Thomas et al., 1987) (Fig. 11a). Mudstone and siltstone beds occur at the top of a few fining upward channel units. They are heterolithic with common lenticular bedding and parallel lamination (Fig. 9b). Bioturbation in channel deposits varies from moderate to intense with common *Teichichnus* (Fig. 12a). Coarsening upward units, commonly about 2 m thick, occur as progressively thicker and coarser grained sandstone beds separated by thin mudstone and siltstone beds (figs 13, 14). These sandstone beds may show cross-bedding, ripple cross-lamination, and mudstone flasers and laminae, but may also be massive except for a few inclined mudstone laminae and mudstone flasers. Bioturbated coarsening upward sandstones may also be seen. In contrast to coarsening upward sandstones of the bay-head delta association wave-generated structures are not found.

Several metres thick, erosively based, fining upward units are interpreted as the deposits of tidally influenced large fluvial channels in the upper estuary. These units are dominated by cross-bedded sandstone in the lower part, and ripple cross-laminated and flaser bedded sandstone beds interbedded with heterolithic and siltstone beds in the upper part. The thickest up to 5 m thick fining upward sandstone units can be traced between several wells. This indicates that they were deposited by laterally migrating channels. The abundance of mudstone laminae, double mud-drapes and flaser bedding suggests deposition in an environment with a strong tidal influence. Multiple ungraded or fining upward sandstones separated by erosion surfaces represent deposition in rapidly migrating tidal creeks or minor fluvial channels and distributaries. The coarsening upward sandstone units may represent bars in major tidal channels.

**Facies association 2: flood tidal delta and washover deposits**

The flood tidal delta and washover fan association consists of up to 3 m thick, generally coarsening upward units of sandstones and heteroliths, that may be overlain by fining upward units of well-sorted sandstone (Fig. 15). In the coarsening upward units fine-grained heterolithic beds show lenticular and wavy bedding. The most fine-grained sandstones are commonly strongly bioturbated, but may show flaser bedding and parallel lamination. Coarser grained sandstone facies include trough cross-bedded, parallel laminated and ripple cross-laminated sandstone. The coarser grained sandstones may have erosional surfaces overlain by thin conglomerates. The fining upward units are dominated by well-sorted, fine- or very fine-grained sandstone, showing parallel lamination, low-angle planar cross-bedding, ripple cross-lamination, and soft-sediment deformation structures.

The fine-grained heterolithic beds characterised by wavy and lenticular bedding and the coarsening upward sandstones with abundant mudstone laminae and flaser bedding, frequently interbedded with lagoonal mudstones, are interpreted as the deposits of flood tidal deltas and tidal sand flats. The coarsening upward trend and the association of physical structures correspond well with the description of recent flood-tidal deltas (e.g. Nichol and Boyd, 1993). This interpretation is further supported by the interbedding with lagoonal sediments. The well-sorted, erosionally based, fining upward units, that occasionally overlie flood tidal delta and tidal flat deposits show a close likeness to washover deposits described by Schwartz (1982).

**Facies association 3: bay-head delta and bay-fill deposits**

Sandstones and heteroliths may occur in overall coarsening upward successions up to 8 metres thick (figs 14, 16). The sediments are dominated by current-generated structures, but wave-generated structures are common. Climbing-ripple and current-ripple lamination dominate the finer grained sandstones in the lower part of the succession (Fig. 10d), whereas trough cross-bedding is common in the upper, more coarse grained units. Soft-sediment deformation structures may occur throughout. Sandstones with current-generated structures may occur as erosively based channel units in the coarsening upward successions. Double mud-drapes in some beds may be indicative of varying tidal influence. Beds of well-sorted sandstone and heterolith may show low-angle planar cross-bedding, swaley and hummocky cross-bedding, and wave ripple cross-lamination. The sandstones of this association frequently overlie fine-grained lagoon deposits.

The coarsening upward successions of this association are interpreted as bay-head deltas, that prograded into estuaries, lagoons, or bays. The dominant sedimentary structures suggest deposition by unidirectional currents. The abundance of climbing ripple lamination indicates a high proportion of suspended load sedimentation (Reineck and Singh, 1980). Depending on the amount of wave influence, the deposits were either slightly modified by small-scale wave activity, or reworked into bay shorefaces by storm wave activity.

**Facies association 4: low-energy estuary and lagoon deposits**

The low-energy estuary and lagoon association is represented by organic-rich mudstones, siltstones and heterolithic sandstones. Heterolithic sandstones are dominated by ripple cross-lamination, flaser bedding, and wavy bedding (Fig. 11a, b). Silt- and mudstone dominated heterolithic beds show parallel lamination, and wavy and lenticular bedding which may be partly obliterated by biogenic activity (Fig. 11c). Units of this association vary in thickness from a few decimetres to several metres (Fig 7).

Deposits of this association represent various environments of lagoon, estuary central basin and marginal tidal flats in the lower energy part of an estuary.

**Facies association 5: marsh and swamp deposits**

Coals, mudstones and associated rooted heteroliths are grouped in the marsh and swamp association. Successions of this association may attain thicknesses of up to 7 m. Mudstones and rooted heteroliths have a dark grey to black appearance, reflecting the high organic content (Fig. 11d). Both vitrinite-rich and inertinite-rich coals are present. The vitrinite-rich coals represent deposition in a waterlogged, anoxic, mire environment. The inertinite-rich coals represent a somewhat drier environment, with periodically oxic conditions in a swamp or mire (Petersen and Andsbjerg, 1996). Pyrite in some coal beds suggests the occasional influx of marine water. The indications of persistent marine water influx, and the association of coals and rooted sediments with lagoonal deposits suggest that deposition took place in backbarrier swamps and marshes.

**Facies association 6: offshore deposits**

The offshore association consists of up to 50 cm thick units of massive and laminated siltstone and claystone, and cm-scale interbedded, heterolithic siltstone and sandstone (figs 12d, 17b, c). Sediments of this association frequently occur as the lower part of coarsening upward shelf to shoreface successions. Massive mudstone in the basal part is overlain by siltstone and sandstone laminae and beds that show an upward increase in thickness. The sandstone beds are commonly sharp-based. Laminae may be normally graded, and show parallel lamination and wave and combined flow ripple lamination. The sandstone-dominated upper part of coarsening upward units may grade into HCS-dominated deposits of the prograding shoreface and beach association. Bioturbation in the offshore association varies from weak to intense, but mudstones are commonly completely bioturbated with few remaining physical structures. *Anconichnus, Planolites, Palaeophycus* and *Teichichnus* occur in the sandstone beds.

Mudstones with rare laminae of silt- or sandstone indicate that deposition took place below storm wave-base. The thorough bioturbation of the mudstones suggests that they were deposited on a shelf with oxic bottom conditions. A higher content of siltstone and sandstone laminae suggests the occasional influence of oscillatory currents near storm wave-base. Sharp-based sandstone laminae are interpreted as storm-sand deposits, and their finer-grained interbeds are fair-weather sediments and suspension fall-out after storms. Deposition took place between storm wave-base and fair-weather wave-base.

**Facies association 7: prograding shoreface and beach deposits**

The prograding shoreface and beach association is represented by up to 12 metres thick coarsening upward, sandstone dominated successions (figs 18, 19). A basal erosion surface commonly separates the coarsening upward successions from underlying fine grained deposits of the offshore association (Fig. 17c). From the base upwards the successions consist of very fine-grained, hummocky cross-stratified sandstone with siltstone interbeds overlain by swaley cross-stratified sandstone (Figs 12c, 17a, b, c). The upper part of the succession is dominated by low angle cross-bedded fine- to medium-grained sandstone and trough and planar cross-bedded fine- to coarse-grained sandstone. Horizontally laminated, low-angle cross-bedded and massive fine- to medium-grained sandstones and pebble conglomerates may occur at the top of the successions. The hummocky and swaley cross-stratification dominated sandstone forms sharp-based, laminated sandstone beds ranging between a few decimetres and a few metres in thickness, separated by centimetres to decimetres thick siltstone beds. Laminae may be gently undulating and typically intersect and truncate at low angles (Fig. 17b). Individual hummocky cross-stratified units may grade into wave-rippled heterolithic silt- and sandstone. Swaley cross-stratified sandstones typically occur as larger amalgamated units that lack the heterolithic subunits and the silty interbeds (Fig. 12c). The cross-bedded sandstones occur in poorly defined sets usually a few decimetres thick.

The coarsening upward successions are interpreted as the deposits of prograding shelf, shoreface and shoreline systems. Minor, 2 to 4 metres thick, coarsening upward units of typical shoreface deposits may represent wave influenced mouth bars or ebb tidal deltas. The hummocky cross-stratification dominated units, commonly lowermost in the successions, were deposited by storm wave activity below fair-weather wave-base in the offshore transition zone. The swaley cross-stratified deposits represent more continuous wave activity on the lower shoreface, whereas the cross-bedded of the upper part of the succession represent migrating dunes on the upper shoreface.

Beach and backshore deposits occur as rather inconspicuous units between coarsening upward shoreface deposits and regional coals. Characteristic sediments are fine- to medium-grained, horizontally laminated or low-angle planar cross-bedded sandstone. The sandstones may occasionally include laminae and thin beds of coarse sand and granules and interbeds of sandstones and heteroliths thoroughly bioturbated by roots and *Skolithos* burrows.

**Facies association 8: transgressive shelf and shoreface deposits**

Deposits of the transgressive shelf and shoreface association consist of bioturbated muddy sandstones and sandy silt- and mudstones, poorly sorted pebbly sandstones, and conglomerates (Fig. 12b). Transgressive sandstones typically occur as one or more 0.5 to 2 m thick coarsening or fining upward sandstone beds situated between beach or back-barrier deposits below and offshore deposits above (figs 18, 19). The bioturbated deposits are characterised by intense burrowing and a diverse ichnofauna.

These sediments were deposited in a shoreface or shallow shelf environment during a transgression, partly by reworking of previously deposited coastal plain deposits. Physical structures, reflecting the high energy level on the upper shoreface, were partly or completely obliterated by burrowing organisms under more quiet conditions.

# Incised valleys

## Recognition of incised valleys in the Bryne Formation

An incised valley has been defined as a "fluvially-eroded, elongate topographic low that is typically larger than a single channel form, and is characterised by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base. The fill typically begins to accumulate during the next base-level rise and may contain deposits of the following highstand and subsequent sea-level cycles" (Zaitlin et al., 1994). The following important criteria for the identification of incised valleys are listed by Zaitlin et al. (1994). (1) The valley is a negative (i.e.) palaeotopographic feature, the base of which truncates underlying strata. (2) The base and walls of the incised valley system represent a sequence boundary that may be correlated to an erosional (or hiatal) surface outside the valley (i.e. on the interfluve areas). (3) The base of the incised-valley fill exhibits an erosional juxtaposition of more proximal facies over more distal deposits (basinward shift of facies). (4) Depositional markers within the deposits of the incised-valley fill will onlap the valley walls. Of the four points listed above three have been evaluated in the present study. However, no seismic study with a resolution sufficiently high to discern onlap of seismic markers on valley walls has been made in the study area so far.

Detailed sequence stratigraphic correlations in the lower Bryne Formation show that most key surfaces are easily correlated across the Søgne Basin (figs 4, 5). However, a number of units and surfaces belonging to the Bat-1B and Bat-1C sequences in the uppermost part of the lower Bryne Formation are missing from the West Lulu-2 and West Lulu-3 wells in the western part of the basin, where a distinct erosional channel base form the base of the Cal-1A sequence (Fig. 4). The sequence boundaries and maximum flooding surfaces of Bat-1A, -1B and -1C, which are all present in Lulu-1 and the Norwegian well 3/7-4, are missing from West Lulu-3, where they are interpreted to have been truncated by the basal erosion surface. Similarly the sequence boundaries and maximum flooding surfaces of Bat-1B and -1C are inferred to be truncated in West Lulu-2 and the maximum flooding surface of Bat-1C is truncated in West Lulu-1 (Fig.4). Both the sequence boundary and the maximum flooding surface of Bat-1C is missing in Amalie-1 (Fig. 5). In all these wells the erosion surface is characterised by a marked contrast between relatively fine-grained floodplain deposits below and more coarse-grained channel deposits above. It has not been possible to identify Bat-1C in West Lulu-4 (Fig. 4). The thick coal seams which in other wells cap the interpreted incised valley fill here sit directly on top of Bat-1B and possibly very condensed Bat-1C deposits. No direct evidence for major down-cutting at the Cal-1A sequence boundary has been observed in West Lulu-4, and the surface most likely represents an interfluvial area overlying a condensed uppermost lower Bryne Formation succession. The Cal-1A sequence boundary is correlated out of the Søgne Basin to wells in the central and southern part of the Danish Central Graben, where in most places it erosively separates floodplain and lacustrine (or lagoonal) deposits below from a succession dominated by channel units and coals above (Fig. 6).

The truncated succession is unconformably overlain by stacked fluvial and estuary channel deposits in West Lulu-1, -2 and -3 and in Amalie-1 and by interbedded channel sandstones and more fine-grained, tidally dominated deposits in 3/7-4 and Lulu-1. The presence of structures such as flaser bedding and bi-directional ripple cross-lamination commonly interpreted as tidally generated in some sandstones in the succession below the erosion surface (e.g. 3/7-4, 3535-3574.5 m), suggests that the succession was deposited on a tidally influenced coastal plain (Andsbjerg in prep.). With tidally influenced coastal plain deposits below the erosion surface and interbedded estuarine and fluvial deposits above it, and with sometimes several sequences of the uppermost part of the lower Bryne Formation removed by erosion in most wells it is difficult to test for a basinward shift of facies across the surface. Due to the missing section below the erosion surface in many wells and the lack of cores from the mudstone dominated unit below the erosion surface in the assumed most distally positioned well Amalie-1 it is not possible to determine how strong the marine or tidal influence was in distal areas immediately prior to truncation (Fig. 5).

The succession that is missing from West Lulu-2 and West Lulu-3 attains a thickness of more than 50 m in neighbouring West Lulu-1. However, due to local thickness variations the succession actually removed from West Lulu-2 and West Lulu-3 may have been somewhat thinner.

The thickness of the channel deposits unconformably overlying the lower Bryne Formation is 44 m in West Lulu-3 compared to 26 m in West Lulu-1. The channel deposits of West Lulu-1, -2 and -3 are directly overlain by a series of laterally correlatable coal beds. The coal beds can be traced to the westernmost well in the Danish Søgne Basin, West Lulu-4, where there is no evidence for incised channels. However, the succession missing from West Lulu-2 and -3 is rather condensed in west Lulu-4 (Fig. 4). The coal beds thin towards the east, but can still be traced to 3/7-4 in the Norwegian part of the Søgne Basin and to Lulu-1 and Amalie-1. In these wells, the coal beds overlie a succession of interbedded channel deposits and more fine-grained tidal and lagoonal sediments, that are separated from the underlying floodplain and lacustrine deposits by an erosion surface, which is particularly pronounced in Amalie-1 (Fig. 5). The stacked channel deposits and interbedded channel and fine-grained tidal deposits between the basal unconformity and the coal beds is interpreted as the sedimentary fill of a system of incised valleys. The lack of such deposits in West Lulu-4 indicates that an interfluve area was present at that location. The presence of the coal beds in West Lulu-4 suggests that the coal-forming peat swamps capped the incised valleys and covered interfluvial areas.

With the sparse well coverage, and rather poor seismic resolution, the incised valleys cannot at present be mapped in details. However, the constraints given by the presence of an interfluve at West Lulu-4 combined with lateral facies variations in the valley fill deposits give some clues as to the extent of the incised valley system. Facies and thickness variations, which are treated in more detail later, indicate the presence of the most proximal fluvial and estuarine deposits in the deeply incised channels of West Lulu-3 (Fig. 20a). The smaller amount of incision and thus thinner valley-fill deposits in West Lulu-1 and -2 suggests that these wells were situated in a more marginal position in the valley. Further to the east and north-east, 3/7-4 and Lulu-1 show more tidal and marine influence and are clearly in a more distal position. Amalie-1 to the south-east shows, at the lower levels of the incised valley fill, fluvial influence equal to that seen in West Lulu-3, but at higher levels tidal influence equal to that seen in Lulu-1. However, with its position south-east in the Søgne Basin, clearly off the proximal - distal axis of the West Lulu - Lulu area, Amalie-1 probably occupies a position in a different branch of the incised valley system.

# Valley fill deposits

## Valley fill unit 1

Two of the studied wells, West Lulu-3 and Amalie-1 show a depth of incision of more than 40 m. The lowermost unit in these wells, unit 1, which consists of channel deposits from the deepest, axial parts of the incised valleys, does not have correlatable equivalents in the other wells (Fig. 20a, b). In West Lulu-3, unit 1 is a 6 m thick, fining upward channel sandstone with a 1 m thick basal conglomerate of intraformational mudstone clasts (Fig. 10a). The channel sandstone show trough cross-bedding and bi-directional ripple cross-lamination in the lower part, whereas the more heterolithic upper part is dominated by soft-sediment deformation and poorly defined lamination with root traces. Uppermost is a 75 cm organic-rich mudstone and coal bed. In Amalie-1, unit 1 is a 14 m thick fining upward channel unit of which only the uppermost 8 m are cored (Fig. 20b). Lowermost in the cored part of the unit are cross-bedded sandstones with scattered mud clasts (Fig. 9a). The upper part of the unit becomes increasingly heterolithic with ripple cross-lamination and flasers in the sandstone dominated lower part and wavy and lenticular bedding with scattered current rippled laminae in the siltstone bed at the top of the unit (Fig. 9b). *Planolites* and *Diplocraterion* trace fossils increase upwards in frequency in the channel sandstone.

In both wells unit 1 is interpreted as estuarine or tidally influenced fluvial channel deposits. The uninterrupted fining upward trend in both wells suggests that they represent large laterally migrating channels. Tidal influence seems to be greater in Amalie-1 than in West Lulu-3. Amalie-1 probably represents a main estuary channel, whereas West Lulu-3 may have been deposited in a tidally influenced fluvial channel upstream from an estuary. As the two wells may be positioned in different branches of the incised valley system, there is not necessarily a direct proximal - distal relationship between the two wells (Fig. 21). The presence of the thin coal bed at the top of the West Lulu-3 channel unit suggests that channel activity for a time was transferred to another area, or that a minor sea-level rise caused cessation of channel activity for a period, allowing peat growth in the lower reaches of the valley behind a protecting barrier.

## Valley fill unit 2

In Amalie-1 and West Lulu-3, unit 1 is overlain by the erosional base of unit 2 channel sandstones. This surface represents the basal surface of the incised valley in West Lulu-1, 3/7-4 and Lulu-1 (Fig. 20a, b). Unit 2 consists of 11 m of stacked, cross-bedded or structureless sandstones in West Lulu-3, while in 3/7-4 three cross-bedded channel sandstones with double mud-drapes and abundant mud clasts and coal debris are separated by organic rich mudstones and coal beds; the unit is revealing a 3 m thick cross-bedded, cross-laminated or bioturbated sandstone with mud-drapes in West Lulu-1. Unit 2 is uncored in Lulu-1 and only a 0.7 m thick core piece is available from the base of the unit in Amalie-1. However, log patterns from the two wells closely comparable to those of 3/7-4 (Fig. 20b), except that the basal sandstone in Amalie-1 which shows cross-bedded sandstone with subordinate current-ripple lamination in the core piece at its base (Fig. 9b) is thicker with a more massive lower part than in 3/7-4.

Unit 2 can be subdivided into three subunits; 2A, 2B, 2C (Fig. 20a,b). The 5 to 10 m thick subunit 2A is found in West Lulu-3, 3/7-4, Lulu-1 and Amalie-1. The fining upward sandstone beds in West Lulu-3 are dominated by trough and planar cross-bedding. There is a stepwise, upward increase in grain-size from bed to bed which are separated by erosion surfaces. A 1 m thick bed with abundant coal fragments shows chaotic bedding. In 3/7-4 subunit 2A is represented by two 2 m thick, cross-bedded channel sandstones separated by a 0.7 m thick bed of disturbed organic-rich mudstone and siltstone. The sandstones are characterised by slightly disturbed cross-bedding with some double mud-drapes and abundant coal debris and mud clasts. Subunit 2A is interpreted as the deposits of large fluvial channels with little or no tidal influence in West Lulu-3 and in the lower part of the subunit in Amalie-1, and as the deposits of smaller tidally influenced channels interbedded with marsh and lagoonal sediments in 3/7-4, Lulu-1 and the upper part of the subunit in Amalie-1.

Subunit 2B is absent from West Lulu-3, and core material is only available from the uppermost part of the subunit in 3/7-4. Based mainly on log-data, subunit 2B is dominated by organic-rich mudstones interbedded with 1 to 2 m thick sandstones and coals (Fig. 20a,b). The sandstones uppermost in subunit 2B in 3/7-4 show ripple cross-lamination and common double mud-drapes. Subunit 2B is interpreted as mainly lagoon and marsh sediments with subordinate tidal channel and tidal flat deposits. In West Lulu-3 subunit 2C consists of a 5 m thick sandstone with a weakly fining upward profile. This sandstone has a more massive appearance than the sandstones of subunit 2A with only a few cross-bedded sets distinguishable due to the occurrence of mud drapes on bedding surfaces. A 1 m thick bed shows abundant intraformational mud clasts. At the top of the subunit in West Lulu-3, a 30 cm thick, more fine-grained silty sandstone with disturbed bedding and abundant coal fragments is overlain by organic-rich mudstones of unit 3. Subunit 2C is 3 m thick in West lulu-1, where it consists of a sandstone which passes up from a basal ripple cross-laminated bed with mud flasers into a coarsening upward, massive sandstone with mud flakes showing an upwards increase in bioturbation. The 3 m thick channel sandstone in subunit 2C of 3/7-4 has a massive appearance with weakly defined cross-bedding and some double mud-drapes. It is overlain by organic-rich mudstones of unit 3. Unit 2 is not cored in Lulu-1 but it shows a close similarity to 3/7-4 on well logs, although more coal beds may be present. Furthermore, although Amalie-1 has poor core coverage in unit 2, the well log patterns are similar to 3/7-4 and Lulu-1(Fig. 20b). The upper boundary of unit 2 in Amalie-1 is an erosional channel base probably representing the base of unit 4. Subunit 2C is interpreted as the deposits of large fluvial channels with little tidal influence in West Lulu-3, and as the deposits of smaller, probably more marginal channels with more tidal influence in the other wells.

The thick, stacked channel sandstones with very little evidence for tidal influence in unit 2 of West Lulu-3 probably represents the main channel of a river, upstream from an estuary (Fig. 21). The somewhat thinner channel sandstones with more evidence for tidal influence in West Lulu-1, 3/7-4 and Lulu-1 are interpreted as minor distributary channels with less fluvial and more tidal energy. In West Lulu-1, the sandstones were deposited in secondary channels positioned off the main axis of the incised valley. In 3/7-4 and Lulu-1 the channels are both in a more lateral and a more distal position than the channel of West Lulu-3 (Fig. 21). The fine-grained beds and coals of unit 2 in 3/7-4 and Lulu-1 may represent channel switching or short-lived lagoonal floodings. The lower channel sandstone in Amalie-1 was deposited in a major channel of a different valley branch (Fig. 21). The dominance of fine-grained sediments and coals in subunits 2B and 2C in Amalie-1 suggests that the main channel had migrated to a different part of the valley, or that a minor base-level rise had forced the mouth of the main channel further up in the valley leaving only minor distributaries in a more distal setting in the Amalie-1 area.

## Valley fill unit 3

The mudstone and coal dominated deposits of unit 3 are found in West Lulu-1, West Lulu-3, Lulu-1 and 3/7-4. Unit 3 deposits have probably been removed by channel base erosion in Amalie-1, although alternative correlations may transfer some of the fine-grained deposits from subunit 2C to unit 3 (Fig. 20a, b). In West Lulu-1 and -3 and in 3/7-4, unit 3 consists of a lower, 2 - 3 m thick heterolithic unit (subunit 3A), a 1 m thick coal in West Lulu-1 and -3 and a correlative 3 m thick, organic-rich mudstone in 3/-4 (subunit 3B), and an upper sandstone-dominated unit in West Lulu-1 and -3 (subunit 3C) (Fig. 20a, b). The heterolithic sandstone of subunit 3A in West Lulu-1 shows parallel lamination, climbing ripple, current ripple, and wave ripple cross-lamination, and a bioturbated sandstone with root traces uppermost in the subunit, which is overlain by organic-rich mudstone and coal of subunit 3B. The heterolithic subunit 3A in West Lulu-3 consists of thinly interbedded sandstone and siltstone disturbed by soft-sediment deformation, faulting and bioturbation. Parallel laminations are the only visible physical structures. In 3/7-4, the subunit 3A consists of a 1 m thick, coarsening upward, laminated and disturbed heterolithic siltstone with an erosionally based, cross-bedded sandstone at the top. Above is a 1 m thick strongly disturbed siltstone. The organic-rich mudstone of subunit 3B in 3/7-4, that correlates with the coal bed in West Lulu-1 and -3, is disturbed and bioturbated, but does show some lamination. The uppermost heterolithic subunit 3C in West Lulu-3 consists of disturbed, parallel laminated siltstone overlain by interbedded siltstone and sandstone. Above is a rooted organic-rich siltstone overlain by an erosionally based, coarsening upward, cross-bedded sandstone with abundant coal fragments. Subunit 3C in West Lulu-1 is a fining upward heterolithic sandstone with abundant mud-laminae and flasers. Uppermost is a 35 cm siltstone with abundant root traces, which is cut by the erosional base of valley fill unit 4. Subunit 3C is missing from 3/7-4 due to erosion, but is represented by parallel-laminated and lenticular bedded siltstone in Lulu-1.

Unit 3 represents regional flooding of the incised valley. Tidal flats developed in the upper reaches of the incised valley and lagoons in the lower reaches as a response to the initial flooding (Fig. 22). While the lagoonal areas expanded in the lower reaches, coal-forming peat swamps developed in the upper reaches. The sandstone and heterolithic beds of subunit 3B is evidence for a renewed regression, which caused estuarine channels to be re-established throughout the valley.

## Valley fill unit 4

The channel sandstone-dominated unit 4 is present in all studied wells (Fig. 20a, b). It is the only unit of the incised valley-fill in West Lulu-2. This unit consists almost exclusively of channel sandstones and fills all remaining accommodation in the incised valley in the proximal wells West Lulu-1, -2 and -3. The unit is 17 m thick in West Lulu-3, where it consists of two subunits of stacked channel sandstones separated by a 20 cm thick bed of heterolithic sandstone. In West Lulu-1 and -2 unit 4 also consists of two sandstone subunits separated by a heterolithic subunit. Unit 4 has a much more heterolithic appearance in 3/7-4 and Lulu-1 than in the West Lulu wells. In both 3/7-4 and Lulu-1 a lower subunit 4A is separated from an upper subunit by a fine-grained, -bearing unit. Although it cannot be established with certainty whether this fine-grained unit correlates to subunit 4B, it is tentatively assigned to it, and the lower and upper subunits to 4A and 4C respectively. Unit 4 is approximately 11 m thick in Amalie-1. Most of it is referred to subunits 4A and 4B. In West Lulu-3, the lower subunit 4A has a 10 cm basal conglomerate of quartz clasts and intraformational mudstone clasts. Above are three fining upward channel sandstones dominated by trough cross-bedded sandstone with abundant coal fragments (Fig. 10b). The sandstones also show mud-laminae including double mud-drapes, and flaser bedding. In West Lulu-2, the 4 - 5 m thick subunit 4A is dominated by almost massive sandstone with scattered mudstone clasts, but vaguely defined trough cross-bedding can be discerned. In the upper part of the subunit are thin beds of chaotically bedded sandstone with abundant coal debris. Subunit 4A has a basal, cross-bedded sandstone with scattered mudstone clasts in West Lulu-1. Above, the subunit is dominated by current ripple cross-laminated sandstone with some double mud-drapes. Subunit 4A is only partly cored in 3/7-4. It consists of an erosionally based, cross-bedded sandstone, which is overlain by a current ripple-laminated sandstone. In Lulu-1 subunit 4A consists of a 2.5 m thick coarsening upward sandstone. Much of the sandstone has a massive appearance but in places shows low-angle cross-bedding with abundant mud-drapes and ripple cross-lamination. Towards the top of the subunit are several beds with abundant mudstone clasts or coal debris separated by beds with abundant mud-drapes of which many are paired. Only the upper part of the 8 m thick subunit 4A is cored in Amalie-1. Well logs suggest that the lower part of subunit 4A in Amalie-1 consists of a 3 m thick erosively based channel sandstone (Fig.20b). A thin siltstone bed dominated by lenticular and wavy bedding separates the lower part of the subunit from the 4 m thick erosively based upper channel sandstone. This channel sandstone has a massive appearance, but vaguely defined cross-bedding, ripple cross-lamination, and flaser bedding can be discerned (Fig. 9c).

Subunit 4B of West Lulu-3 is represented by a 20 cm heterolithic sandstone with rip-off mudstone clasts. In West Lulu-2, subunit 4B consists of two sandstones overlain by two mudstone beds. Lowermost is a 0.5 m thick fining upward, parallel laminated, heterolithic sandstone, which is overlain by a 0.6 m thick lenticular and wavy bedded, organic rich mudstone. Above is a 0.6 m thick sandstone bed dominated by ripple cross-lamination and flaser bedding (10c).Uppermost is a 0.2 m organic rich mudstone. Subunit 4B is only partly cored in West Lulu-1. The cored lower part of the subunit consists of lenticular bedded mudstone. Log patterns are similar to those of West Lulu-2 and -3 (fig 20a). Well logs show that the lower part of subunit 4B in 3/7-4 fines upwards from the uppermost sandstone of subunit 4A to a mudstone dominated unit with a coal bed (Fig. 20a, b). The uppermost, cored part of subunit 4B consists of a strongly disturbed fining upward bed dominated by organic rich mudstone, which is cut by the erosional base of subunit 4C. In Lulu-1, subunit 4A is overlain by the 2 m thick subunit 4B dominated by siltstone with thin sandstone beds and sand laminae and a thin coal bed. In Lulu-1, subunit 4B is cut by the basal erosion surface of a channel sandstone from subunit 4C.

The subunit 4C of West Lulu-3 consists of stacked, 0.5 - 2 m thick, mainly fining upward channel sandstones. In the basal part of the subunit, sandstones are typically massive; elsewhere they show trough and planar cross-bedding with abundant mud-laminae, flaser-bedding, and chaotic bedding with abundant coal debris. The upper part of the subunit becomes increasingly heterolithic with the generally fining upward sandstones interbedded with increasingly dominant bioturbated siltstones.

Subunit 4C appear very similar in West Lulu-1 and -2, but it is only completely cored in West Lulu-2. The subunit has a varied appearance with cross-bedded sandstone with double mud-drapes, beds dominated by mud flasers, strongly disturbed heterolithic sandstone beds, and climbing ripple cross-laminated sandstone. At the top of the unit in West Lulu-2 is a chaotically bedded sandstone with abundant coal debris, which is overlain by lenticular bedded mudstone. The 10 m thick subunit 4C in 3/7-4 consists of several stacked, 1 - 3 m thick, fining upward sandstones and, near the top, a siltstone dominated heterolith which may represent the time-equivalent unit 5 in Lulu-1 and Amalie-1. The lowermost channel sandstones are strongly deformed, but vague cross-bedding with siltstone interbeds can be discerned. The upper part of the subunit shows trough cross-bedding, brecciated beds, siltstone beds with wavy bedding, and disturbed beds with water escape structures. Uppermost is an erosionally based, cross-bedded sandstone with root traces. In Lulu-1, the 3.5 m thick subunit 4C has a heterolithic appearance. It consists of cross-bedded and laminated sandstone with abundant mud-laminae. Uppermost in the subunit a bioturbated sandstone fines upward to the siltstone dominated unit 5. Subunit 4B in Amalie-1 is represented by the fining upward succession of heterolithic sandstone and siltstone which separates the lower part of unit 4 from unit 5 in Amalie-1 (Fig. 9d). At the base of the subunit is an intraformational conglomerate of brecciated siltstone laminae (Fig. 20b).

Unit 4 is interpreted to represent mainly large estuary channels in West Lulu-1, West Lulu-2, West Lulu -3, and Amalie-1. The stacked, fining upward sandstone bodies with both current generated structures and structures typical of tidal environments suggest that they originated in large, laterally migrating, estuary channels. The thick succession of stacked channel sandstones in West Lulu-3 indicates that the well also at this level is close to the axis of the western branch of the incised valley. West Lulu-1 and West Lulu-2 show slightly higher degrees of tidal influence, but represent approximately the same energy level as the deposits of West Lulu-3. They are interpreted as have been deposits in the main axis of the estuary but in the same zone as West Lulu-3. The more heterolithic channel fill deposits in 3/7-4 and Lulu-1 indicate that these wells represent a more distal position in the incised valley estuary. Amalie-1 also represents a main estuary channel but in a different branch of the incised valley system. *Teichichnus* and *Diplocraterion* burrows that occur uppermost in the unit in all wells may indicate flooding, albeit possibly diachronous, of the incised valleys. The unit show many similarities to unit 2 but exhibits a somewhat higher degree of tidal influence.

## Valley fill unit 5

The fine-grained and heterolithic unit 5, which is probably time equivalent to the upper part of unit 4 in West Lulu-1, -2, -3, and 3/7-4, is found in Lulu-1 and Amalie-1. The unit is approximately 6 m thick in Lulu-1 and 10 m in Amalie-1. In both wells it forms an overall fining upward succession of siltstone, interrupted by thin, sharp-based sandstone beds. The thin sandstone beds show flaser and wavy bedding and occasionally current ripple cross-lamination. The siltstones show parallel lamination and lenticular bedding and are locally burrowed. The unit is overlain by thin coal beds in both wells.

Unit 5 represents a lagoonal environment with minor tidal flats, that developed at the beginning of the final flooding of the incised valley system. The occurrence of this unit in Amalie-1 and Lulu-1, and possibly also uppermost in 3/7-4 suggests that the flooding was initiated in the north-eastern part of the Søgne Basin.

## Valley fill history

The Middle Jurassic deposits of the Danish Central Graben are generally difficult to date due to the scarcity of palynological dating material. However, a few datings based on dino-flagellate cysts have been presented by Andsbjerg and Dybkjær (in prep.). On the basis of an observation of the *Nannoceratopsis gracilis* LOD (Discus ammonite zone) in unit 2 of 3/7-4 and the LOD of the *Cleistosphaeridium varispinosum* (Calloviense ammonite zone) in unit 2 of West Lulu-3 and unit 4 of West Lulu-1 the incised valley fill has been dated to the latest Bathonian and Early Callovian with unit 2 probably not younger than latest Bathonian.

The incised valley was probably cut to its deepest level before deposition began. Lateral incision and shallow incision into older valley fill deposits was caused by migrating channels during the valley fill process (Fig. 23b). Estuarine conditions were established in large parts the valley when deposition was resumed after incision (Fig. 24a). The channel sandstones of the deepest part of the incised valley penetrated in West Lulu-3 and Amalie-1 are strongly influenced by tidal processes suggesting that they originated in tidally influenced fluvial channels in the upper estuary. A thin coal bed on the top of the West Lulu-3 channel unit suggests that channel activity was transferred to another area for a sufficient period of time to allow growth of coal forming peat swamps or alternatively that a minor sea-level rise forced channel and delta deposition upstream in the valley allowing coal peat growth behind the protection of a barrier coast.

Renewed channel activity extended to a larger area including the West Lulu-1 and 3/7-4 locations when deposition of the unit 2 sandstones began (Fig. 20a). Unit 2 channel sandstones appear to have been less influenced by tidal processes in West Lulu-3 and Amalie-1 than the unit 1 sandstones. The thick, massive channel sandstones of West Lulu-3 and Amalie-1 were probably deposited in fluvially dominated main channels in the axial part of two separate valleys (Fig. 21). West Lulu-1 and 3/7-4 probably represent deposition in tidally influenced secondary channels alternating with sedimentation in tidal flats or in lagoonal areas after channel avulsions.

Deposition of unit 2 channel sandstones was terminated by a major flooding event. Heterolithic sandstones and siltstones of unit 3 were deposited on extensive tidal flats. Continued flooding changed the more distal parts of the valley into a lagoonal environment while coal forming peat swamps developed on the tidal flats in the more proximal parts of the valley system in the West Lulu area (Fig. 24b). Lagoons and coastal swamps may have been protected against marine flooding by a coastal barrier. The change to a tidal flat environment represented by the sandstones and heteroliths uppermost in unit 3 in the wells West Lulu-1, West Lulu-3 and Lulu-1 may indicate the beginning of a minor sea-level fall which eventually caused some fluvial incision at the base and margins of the first unit 4 channels.

The incised valley expanded by lateral channel erosion to include the West Lulu-2 site at the beginning of unit 4 deposition (Fig. 20a). The axis of the western valley branch was still located near West Lulu-3 as shown by the succession of stacked estuarine channel sandstones that constitutes unit 4 in that well (Fig. 20a). The estuarine channels also dominated in the area around West Lulu-1 and -2. Both 3/7-4 and Lulu-1 show evidence of a more distal, and probably more marginal estuarine environment (Fig. 20b). A minor tidal channel which initiated unit 4 deposition in 3/7-4 and a tidal flat or tidal delta environment in the Lulu-1 was succeeded by a lagoonal environment. In the south-eastern branch of the incised valley system, the Amalie-1 location was dominated by large estuary channels. An interval with a lower energy level in the West Lulu area is represented by the heterolithic beds of subunit 4 B in West Lulu-1 and -2. Thicker fine-grained lagoonal and swamp deposits were deposited as subunit 4 B in 3/7-4 and Lulu-1. Similar deposits could have been removed from the West Lulu area by erosion at the base of the subunit 4 C channels. Channel activity is recorded from all wells in the incised valley system in connection with the beginning of subunit 4 C deposition. However, whereas channel activity continued in the West Lulu area until regional peat growth began, thick lagoonal mudstones of unit 5 separate the uppermost channel sandstones from the coal cap in Lulu-1 and Amalie-1. This suggests that the lower reaches were submerged somewhat earlier than the upper reaches.

## Higher order sequence stratigraphy

The complex architecture of the incised valley-fill with a systematic distribution of erosively based channel sandstones and laterally extensive lagoonal units suggests that minor sea-level changes influenced deposition in the valley system. However, as the valley-fill deposits and their key surfaces can only be correlated outside the inside valley system with a large measure of uncertainty, "higher-order" sequence boundaries cannot be traced basin-wide, and thus one diagnostic criteria for the identification of sequence boundaries is missing (e.g. Van Wagoner et al. 1988).

## Peat cap

The valley fill deposits are overlain by a correlatable coal seam or zone of coal beds (figs 4, 5). The coal seam, sometimes split into several thinner seams, is up to 5 m thick. It is described from West Lulu-2 as seams R1 and T2, which represents a relatively dry peat-forming environment below (R1) succeeded by a waterlogged peat-forming environment above (T2) (Petersen and Andsbjerg, 1996). The coal seam occurs as one almost massive coal bed in West Lulu-1 and 3/7-4, form 2 or 3 distinct coal beds in West Lulu-2, -3 and -4, and occurs as a zone of interbedded thin coals and lagoon and marsh sediments in Lulu-1 and Amalie-1 (figs 4, 5). The precursor peat swamps to the 5 m thick coal seam in the West Lulu area may have been as much as 50 to 100 m thick, and thus occupied a significant accommodation space for a period without major influx of clastic sediments or the invasion of sea water. A rising groundwater level at this coastal plain setting, probably caused by a rising sea-level, is suggested by the change from a relatively dry peat-forming environment to a waterlogged peat-forming environment (Petersen and Andsbjerg, 1996). The peat swamps thinned towards the east, and the interbedding of thin coals and channel sandstones in Amalie-1 suggests that an axial river system restricted peat growth in that area (Fig. 23).

The coal seam can also be correlated to West Lulu-4 (Fig. 4). In West Lulu-4, however, it does not overlie incised valley deposits but a rather condensed succession representing the sequences Bat-1A and Bat-1B, that are missing from West Lulu-2 and -3. The base of the coal seam in West Lulu-4 thus represents an interfluve area, that saw only limited erosion during formation of the incised valley system.

The peat deposits developed when valley fill was completed after a rising sea-level had reached the level of the valley rim. As sediment transport was dispersed across a low-gradient coastal plain and most sediment was trapped further upstream, mires could develop on the lower coastal plain (Fig. 25). A coastal barrier further to the north-east in the Søgne Basin may have given protection to the coastal plain. Some fluvial sediment transport continued along the basin axis in the Amalie-1 area. This delution by siliciclastics may have contributed to the thinly developed coals in that area. The resulting coal seam exhibits a stepwise increase in marine influence. A relatively dry peat-forming environment was succeeded by a continuously waterlogged environment with occasional salt water incursions (Petersen and Andsbjerg, 1996). The extensive peat-forming environment was terminated when relative sea-level rise began to outpace peat growth followed by the incursion of transgressive coastal sandstones in the east and by the development of a lagoonal environment with clastic influx from bay head and tidal deltas in the west.

## Reciprocal sediments of Cal-1A sequence

### Transgressive systems tract (TST)

The continued transgression after peat generation had stopped caused deposition of further TST-deposits over much of the basin. The deposits overlying the coal seams in West Lulu-2 consist of a 14 m thick succession of stacked, erosionally based, fining upward sandstones interpreted as estuary channels (Figs 14, 26a); this succession is referred to the TST of the Cal-1A sequence (Fig. 26a). The 2 to 5 m thick sandstones vary in maximum grain-size from medium to fine. Trough cross-bedded sandstone with abundant mud-drapes, many of which are paired, is the most common facies. Flaser bedding, current and climbing ripple cross-lamination, and parallel lamination are also common. In a number of beds physical structures are blurred by soft sediment deformation and bioturbation. Coal clasts are scattered throughout the sandstones. Two 0.5 m thick, heterolithic siltstone interbeds in the lower part of the succession may represent passive channel fill. *Teichichnus* burrows occur in the uppermost channel sandstone. The upper part of that unit, which is strongly bioturbated with *Teichichnus*, *Thalassinoides*, *Skolithos*, *Palaeophycus* and *Planolites* burrows, fines upward to a heterolithic siltstone and a thin coal. The succession in West Lulu-2 is interpreted as mainly estuary channel or tidally influenced fluvial channel deposits.

The same succession in West Lulu-3 shows a pronounced coarsening upward trend (Figs 16, 26a). It consists in the basal part of a 3 m thick, coarsening upward, heterolithic mudstone and siltstone overlain by a 10 m thick, coarsening upward succession of stacked, erosionally based sandstones. The lowermost sandstones, which are separated by heterolithic siltstones, are dominated by climbing ripple cross-lamination (Fig.10d). Double mud drapes and mud flasers occur but rarely. The sandstones in the upper part of the succession, which all show a fining upward pattern, are characterised by cross-bedding and current ripple cross-lamination. The uppermost two sandstones are separated by a thin coal. As in West Lulu-2, the upper part of this succession is strongly bioturbated by a *Teichichnus*-dominated ichnofauna (Fig. 12a). The succession is overlain by a 1 m thick heterolithic siltstone and mudstone with abundant roots and a thin coal or coaly mudstone at the top. On the basis of the coarsening upward trend, the dominance of unidirectional current structures and the presence of climbing ripple lamination suggesting a high proportion of suspended load sedimentation, the lack of wave-generated structures suggesting deposition in a protected setting, and the limited presence of tidally generated structures suggesting an environment with a small tidal influence, the succession is interpreted as a progradational bay-head delta with distributaries at the top.

In West Lulu-1, this succession consists of two 5 m thick, coarsening upward sandstone units, separated by a 0.3 m thick siltstone bed (Fig. 26a). The lowermost two metres of the lower unit are not cored. The upper part of the unit coarsen upward from very fine to fine-grained sandstone except for two thin interbeds of medium-grained sandstone. The unit is dominated by poorly defined, somewhat disturbed parallel lamination with subordinate current ripple and climbing ripple cross-lamination. The upper unit has a 0.2 m thick, erosionally based sandstone at the base. Above is a very fine-grained sandstone that coarsens upward to medium-grained sandstone at the top. Cross-bedding with mud-drapes including double-drapes and climbing ripple cross-lamination but most primary structures have been obliterated, probably by bioturbation. *Teichichnus* and possibly *Diplocraterion* burrows are common to abundant within this unit. The unit is overlain by a 10 cm thick, erosionally based pebble conglomerate, which may represent a transgressive surface of erosion (TSE). The TSE is overlain by a 20 cm thick sandstone bed thoroughly bioturbated by *Palaeophycus* ? burrows. The two coarsening upward units in West Lulu-1 are interpreted as distal bay-head delta deposits.

This succession is 6 m thick in 3/7-4, where it consists of a basal fining upward sandstone overlain by a series of stacked, coarsening upward units (figs 15, 26a, b). The 2 m thick basal sandstone consists of a cross-bedded lower unit with abundant mud-drapes and root traces and a thoroughly bioturbated upper unit. A 0.8 m thick heterolithic mudstone with sandstone laminae separates the basal sandstone from the lowermost coarsening upward unit. The three 0.5 to 2 m thick coarsening upward units of heterolithic sandstones and siltstones show parallel lamination, current and climbing ripple cross-lamination and trough cross-bedding. At the top of the uppermost unit is a 20 cm thoroughly bioturbated sandstone bed showing the same ichnofacies (*Palaeophycus* dominated ?) as the sandstone overlying the TSE in West Lulu-1. The succession in 3/7-4 is interpreted as tidal creek overlain by tidal flat and possibly distal tidal delta deposits.

Only a 20 cm thick bed of fining upward, heterolithic sandstone and siltstone represents this succession in Lulu-1 (Figs18, 26b). The bed is thoroughly bioturbated, showing the same ichnofacies as the uppermost sandstone of this succession in West Lulu-1 and 3/7-4. The succession is 3 m thick in Amalie-1, where it consists of a 0.6 m thick basal very fine-grained sandstone overlain by two 1 m thick, coarsening upward units of heterolithic siltstone and mudstone, and a 30 cm thick sandstone bed at the top (figs 19, 26b). The heterolithic basal sandstone shows current ripple cross-lamination, wavy bedding and lenticular bedding in siltstone interbeds. The lower coarsening upward silt- and mudstone unit is dominated by parallel lamination and lenticular bedding, whereas the upper unit is strongly bioturbated. The sandstone bed on top of the upper coarsening upward unit is likewise bioturbated showing the same ichnofacies as the uppermost sandstone in west Lulu-1, 3/7-4 and Lulu-1 (Fig. 17d). The TST succession in Amalie-1 is interpreted as lagoon, tidal flat, flood tidal delta and wash-over and as transgressive shoreface deposits. Only a thin veneer of transgressive shoreface and shelf deposits is present in Lulu-1 (figs 18, 26b).

The TST deposits above the coal seams show both decreasing thickness and a decrease in energy level from the west to the east. The 13 m thick succession of estuary channel and bay-head delta deposits in West Lulu-2 and -3 represents the proximal part of an estuary that developed during a sea-level rise (Fig. 27). Distal bay-head delta deposits in West Lulu-1 and tidal flat deposits in 3/7-4 represents more distal and possibly also more marginal estuary environments. The succession in Amalie-1 represents even more distal estuary deposits. However, the TSE at the top of the succession may have caused erosional removal of more proximal deposits. The thin bed in Lulu-1 probably rests on the TST, and also here may more proximal deposits have been present. The 20 - 30 cm thick thoroughly bioturbated sandstone bed which represents the succession in Lulu-1 and sits on top of the succession in Amalie-1, 3/7-4 and West Lulu-1 marks the final transgression prior to maximum flooding. The thorough bioturbation dominated by *Teichichnus* burrows below the top surface of the uppermost channel unit in West Lulu-2 and -3 is a result of the same flooding event.

## Maximum flooding deposits

Above the bioturbated transgressive sandstone beds are mudstones and heterolithic siltstones that include the maximum flooding surface (Fig. 26a, b). In Amalie-1, Lulu-1 and 3/7-4 the MFS is located in dark, organic rich mudstone and siltstone interpreted as shelf deposits. MFS deposits are missing from West Lulu-1, but the transgressive bioturbated sandstone is erosionally overlain by a heterolithic sandstone interpreted as a lower shoreface deposit, which may have caused the erosional removal of shelf mudstones. The MFS is picked in a bioturbated, organic rich, heterolithic mudstone with abundant root traces in West Lulu-3 and at a thin coal bed encased in soft-sediment deformed, heterolithic siltstone in West Lulu-2. With a terrestrial environment at the West Lulu-2 and -3 locations and a marine environment at Lulu-1 and 3/7-4, and possibly also at West Lulu-1, the most landward position of the coastline must have been east of, but rather close to West Lulu-2 and -3. However, the next sequence boundary (base Cal-1B SB) is located as an erosional channel base right above the picked MFS in those two wells, and it is possible that more distal deposits may have been removed erosionally from these two wells, and thus the MFS may be placed too low.

## Regressive deposits of HST and FRST

With the base Cal-1B SB located right above the MFS, or with the MFS removed by SB erosion, no HST or FRST is present in Cal-1A in West Lulu-2 or -3 (Fig. 26a). In West Lulu-1, the HST/FRST is represented by a 3 m thick succession that shows a stepwise coarsening upward profile (Fig. 26a). At the base is an erosionally based, 1 m thick unit of very fine-grained sandstone consisting of hummocky cross-stratified, heterolithic sandstone overlain by bioturbated sandstone with some visible current ripple cross-lamination. The lower unit is erosionally overlain by a 0.5 m thick very fine-grained sandstone dominated by low-angle cross-bedding or swaley cross-stratification. The uppermost unit consists of an erosionally based 0.5 m thick, medium-grained sandstone with poorly defined cross-bedding overlain by a 1 m thick, bioturbated, fining upward, fine-grained sandstone. The base Cal-1B SB has been picked at the top of this unit. The core immediately above consists of rubble dominated by pebbles and granules. The succession in West Lulu-1 probably represents a strongly condensed shoreface or wave-dominated mouth bar. One or more of the erosional sandstone bases may represent a RSE formed as a result of forced regression.

In 3/7-4, the succession is also 3 m thick and mainly coarsening upward, consisting of a stack of three forward-stepping coarsening upward parasequences (figs 15, 26a, b). In the lower part of the succession are two minor coarsening upward units or parasequences. The lowermost 0.6 m thick parasequence consists of wavy and lenticular bedded siltstones overlain by bioturbated, parallel laminated, heterolithic, very fine-grained sandstones. Above that is a 1 m thick parasequence of lenticular bedded and parallel laminated siltstones overlain by wave ripple cross-laminated and low-angle cross-bedded or swaley cross-stratified fine-grained sandstones. The uppermost parasequence is 2.5 m thick, and shows a basal 0.5 m thick subunit of parallel laminated and lenticular bedded heterolithic siltstone, which is erosionally overlain by a 0.5 m thick unit of bioturbated, probably hummocky cross-stratified, heterolithic sandstones. An erosion surface separates the uppermost 2 m thick, very fine to fine-grained sandstone, which is massive with mud laminae and some bioturbated intervals. Burrows in this succession in 3/7-4 are mainly *Diplocraterion* or *Teichichnus*. The succession is interpreted as a condensed series of progradational shoreface or wave-dominated mouth bar units. A RSE may be located in the uppermost parasequence. The succession is bounded upward by the base Cal-1B SB, which sits at the erosional base of a fining upward, heterolithic sandstone.

The 8 m thick, coarsening upward succession in Lulu-1 can be subdivided into three units separated by erosion surfaces (figs 18, 26b). Lowermost is a 1.3 m thick unit, that shows a coarsening upward development from almost black mudstones at the MFS through thoroughly bioturbated siltstones to parallel laminated and wave cross-laminates siltstones. It is overlain by 4.7 m of coarsening upward, heterolithic, very fine-grained sandstone, which is dominated by wave ripple cross-lamination, parallel lamination and hummocky cross-stratification in the lower part and by hummocky and swaley cross-stratification and poorly defined trough cross-bedding in the upper part (Fig. 12d). A few *Diplocraterion* burrows can be seen in this unit. The uppermost 3 m thick unit rests erosionally on the middle unit. A thin, fine-grained sandstone bed sits directly on the erosion surface. Above the unit shows a coarsening upward profile from very fine-grained sandstone with poorly defined bedding and some current ripple cross-lamination to fine-grained sandstone with low-angle cross-bedding and gently dipping bedding. The base Cal-1B SB has been picked at the top of this unit (Fig. 26b). The succession is interpreted as a progradational shoreface. The erosional base of the middle and possibly the upper unit may represent a RSE formed by forced regression.

The succession in Amalie-1 is very similar to Lulu-1. It is, with a thickness of 12.5 m, somewhat thicker than in Lulu-1 (Fig. 26b). A 6 m thick lower unit of thoroughly bioturbated siltstone shows an upwards decreasing mud content and increasing number of sandstone laminae. The lower siltstone unit is erosionally overlain by a 4 m thick, coarsening upward, very fine-grained, heterolithic sandstone dominated by hummocky cross-stratification and wave ripple cross-lamination (Fig. 17b, c). Scarce *Diplocraterion* or *Teichichnus* burrows are present within this unit. The unit represents the same sedimentary facies as seen in the middle unit of the succession in Lulu-1. Uppermost is a 2.5 m thick, erosional basal unit of very fine- to fine-grained sandstone with a few heterolithic interbeds. This unit is characterised by hummocky and swaley cross-stratification and possibly low-angle cross-bedding (Fig. 17a, b). The base Cal-1B SB has been picked at the top of this unit. As in Lulu-1 the succession is interpreted as a progradational, wave-dominated shoreface. A RSE is present at the base of the middle unit.

The succession everywhere shows evidence for a progradational, wave-dominated environment (Fig. 28). In the most distal wells, Lulu-1 and Amalie-1, deposition took place in a shelf to shoreface environment. The presence of a RSE may suggest that more accommodation space was present originally than that indicated by the pre-compaction thickness of the succession. In West Lulu-1 and 3/7-4 the succession represents a shoreface or wave-dominated mouth bar, that prograded very rapidly into an area with limited accommodation space. The RSE-development caused the removal a larger proportion of the succession in this area.

## Reciprocal architecture of the upper Cal-1A sequence

The main part of the sedimentary succession between the coal seams that act as a cap on the large incised valley at the base and a thin but also regionally extensive coal seam close above the base Cal-1B SB, can be referred to the TST and HST/FRST successions of the Cal-1A sequence described above (Fig. 26a, b). Although bounded by correlatable coal beds, the succession between the coal seams cannot be correlated between proximal and distal areas. In the proximal areas represented by West Lulu-2 and -3 the upper part of Cal-1A is referred to the TST bounded above by the Cal-1B SB (Fig. 26a). Although HST-deposits may have been removed by erosion at the base Cal-1B SB, the limited amount of incision here, as indicated by an only 5 m thick unit present between the SB and the regionally correlatable coal seam above, suggests that the former presence of any significant amount of HST-deposits is unlikely. In the distal wells, Lulu-1 and Amalie-1, the sequence above the incised valley is dominated by HST/FRST-deposits (Fig. 26b). Only 20 cm of transgressive sandstone represents the TST in Lulu-1, whereas 3.5 m are present in Amalie-1 compared to a 12.5 m HST/FRST succession in that well. West Lulu-1 and 3/7-4 occupies an intermediate position with 11 m of TST and 3.5 m of HST/FRST in West Lulu-1 and 7 m TST and 3.5 m HST/FRST in 3/7-4 (Fig. 26a).

While the upper TST interval becomes thicker to the west, and changes from shoreface to mainly estuarine deposits, the HST section wedges out towards the west (figs 26a, b; 29). The TST succession is separated from the HST/FRST succession by the MFS, which is situated close to the lower coal seams in the distal wells, located in an intermediate position in West Lulu-1 and 3/7-4 and is located close below the Cal-1B SB if not cut by it in the proximal wells (Fig. 26a, b). The flooding surface on top of the lower coal seams, the MFS and the base Cal-1B SB thus outlines the reciprocal distribution of systems tracts or the reciprocal architecture of the succession. Similar deepening-upward paralic sections interbedded with shallowing upward regressive sections has been termed reciprocal sedimentation by Kidwell (1988) and Nummedal and Molenaar (1995). Catuneanu et al. (1997) used the term reciprocal architecture for a differential distribution of transgressive and regressive deposits controlled by foreland style tectonics.

## Depositional history of the upper Cal-1A sequence

A flooding that began during infill of the underlying incised valley and temporarily halted during the growth of the extensive peat swamps (Fig. 30a), was continued with termination of peat growth. A lagoonal environment was initially established over much of the study area (Fig. 30b). It received an influx of clastic sediments from point sources such as bay-head deltas and flood tidal deltas. Prograding bay-head deltas and their distributaries and estuary channels came to dominate the proximal western part of the area. Tidal flats and distal tidal deltas dominated intermediate and distal areas. When the distal parts of the area were transgressed, the lagoonal deposits were cut by a transgressive surface of erosion (TSE) and a thin, bioturbated shoreface sandstone was deposited seaward of the coastline. Deposition of bay-head delta and estuary channel deposits continued in proximal parts of the area until intermediate parts of the lagoon were reached by the marine transgression. At the point of maximum flooding, open shelf conditions were established in the central and eastern parts of the Søgne Basin east of the West Lulu-1 and 3/7-4 wells except in a fringe near the eastern boundary fault. More protected shelf conditions were established in an area that included the West Lulu-1 and 3/7-4 sites (Fig. 31a). After an initial flooding and immediately prior to the maximum flooding as indicated by the thorough burrowing of the uppermost estuary channel deposits in West Lulu-2 and -3, a peat forming environment was established in that area at the time of maximum flooding.

HST deposits developed during falling rates of rising relative sea level. In the West Lulu-1 - 3/7-4 area, the HST was deposited as a thin prograding wedge of shoreface and wave-dominated mouth bar deposits. A thick wedge of wave dominated shoreface deposits prograded into the central and eastern parts of the basin. Forced regression due to a fall in relative sea-level caused the erosional removal of both the maximum flooding (at West Lulu-1) and highstand deposits from the central and eastern part of the study area. Above the regressive surface of erosion, most shoreface sediments were deposited in the forced regressive systems tract. Formation of the base Cal-1B SB caused erosion in the western more proximal part of the area, where thin highstand deposits may have been removed. The progradational wedge of shoreface deposits was terminated by deposition of a sheet of beach sandstones, and large parts of the basin, was turned into a beach ridge plain (Fig. 31b). The base of the beach deposits has been picked as the base Cal-1B SB. This SB can traced into the western parts of the basin as the erosive base of estuary channels.

### Cal-1B and Cal-C sequences

The uppermost two sequences in the Bryne Formation show many similarities to the Cal-1A sequence (figs 26a, b; 29). Although much less incision is observable at the base of these sequences, incised channels filled with estuary channel sandstones, that are overlain by coals, are present in the basal part of the sequences in the more proximal wells. Most of the Cal-1B sequence is dominated by the same facies that characterise the reciprocal deposits of Cal-1A. The back-barrier deposits of the TST in Cal-1B do not show the same thicknesses as the equivalent deposits in the Cal-1A sequence, but this may be due to a general backstepping of the depositional system caused by an overall transgression. The progradational shoreface deposits of the HST/FRST show the same asymmetrical development as in the underlying sequence. Only the lowermost part of the TST below the first marine flooding surface in the Cal-1C sequence shows similarities with the Cal-1A and -1B sequences. However, the presence of a coarsening upward shelf to distal shoreface succession in the lowermost Lola Formation may suggest that reciprocally distributed units may be located updip.

## Discussion

### Possible controlling factors

The development of the upper Bryne formation was controlled by a number of factors. Sea-level changes, tectonic movements, climate changes and sediment supply are commonly considered in such a setting. There seems to have been an ample supply of sediment throughout the history of the Bryne Formation and changes in sediment supply are not supposed to have had significant influence on its development. A significant climate change in the Callovian might have influenced coal development and sediment supply, but no such change has been reported. The Late Jurassic spread of the western Pangaea arid zone did not reach north-west Europe until the Late Volgian (Hallam, 1984). However, both tectonic movements and sea-level changes seem to have had a pronounced influence on the development of the Bryne Formation. The Bryne Formation was deposited during the early phases of rift induced half-graben subsidence along the main boundary fault in the Danish Central Graben. In the lower Bryne Formation, a number of units show the asymmetrical geometry and facies distribution characteristic of half-graben settings, suggesting that episodic faulting occurred at the main boundary fault. A major rise in relative sea-level, which to a large degree may have been caused by eustasy, took place from the Middle Jurassic to the late Early Jurassic (Andsbjerg and Dybkjær, in prep.). The overall change from an alluvial or coastal plain with rare episodes of tidal influence in the lower Bryne Formation to the paralic to shallow marine upper Bryne Formation may reflect that sea-level change. Many significant features of the upper Bryne Formation, such as large scale valley incision and the development of reciprocal architecture, may have been influenced or controlled by these factors.

## Controls on valley incision

The formation of the large incised valley at the Bathonian - Callovian transition is so unique in the history of the Bryne Formation that it is reasonable to assume that it was controlled by external forces. The thickness measured between the basal erosion surface of the incised valley and the coal seams that cap the valley fill deposits in West Lulu-1, West Lulu-2, West Lulu-3, and 3/7-4 is a measure of the depth of incision at those locations. The thicknesses in those wells vary from 13 m in West Lulu-2 through 26 m in West Lulu-1 and 35 m in 3/7-4 to 42 m in West Lulu-3 (Fig. 20a). Further to the east and south-east in Lulu-1 and Amalie-1 it is possible that the change in facies from channel or interbedded channel and tidal flat deposits in units 1 to 4 to fine-grained lagoonal deposits of unit 5 uppermost in the supposed incised valley succession reflects completion of valley fill in that area, and that the valley rim should be picked somewhat lower than the coal marker (Fig. 20b). Thus the depth in Lulu-1 and Amalie-1 could either be 34 m and 52 m respectively between erosional base and coal seams or 28 m in Lulu-1 and 40 m in Amalie-1 between the valley base and the base of the lagoonal deposits. In case the unit 5 deposits are located above the valley rim, the pre-incision topographic gradient must account for the gap between coal seams and the valley rim that increases from nil in West Lulu-1 to 6 m in Lulu-1, 4 km down-dip.

The absence of incised valley deposits in West Lulu-4 constrains the extent of the incised valley from the West Lulu-1, -2, and -3 wells towards the south-west. If the deep incision and the thick succession of stacked, almost continuously coarse-grained channel deposits in West Lulu-3 indicates that this well occupies a more axial position in the valley than West Lulu-1 and -2, valley orientation can be constrained further. A valley axis through the West Lulu-3 site that keeps clear of West Lulu-1, -2 and -4 must lie within the sector SW-NE to WNW-ESE. The more distal wells Lulu-1 and 3/7-4, would have been located on different sides of the valley axis in the lower reaches of the valley, unless the valley was strongly sinuous. The deep incision seen in Amalie-1 probably represents an axial part of a different branch of the incised valley system (Fig. 21).

The incised valley did not reach its full extent during the initial incision. Detailed correlations of valley fill units suggest that the valley fill in West Lulu-1 and -2 correlates with the upper part of the valley fill succession in West Lulu-3 (Fig. 20a). The valley was incised to full depth in axial areas during the early stages of development. Laterally migrating channels caused the stepwise extension of the valley further south during the valley fill process. The West Lulu-1 site was cut at an earlier stage than the West Lulu-2 location. There is no evidence available for the exact location of the northern boundary of the valley. However, if it is assumed that the valley was more or less funnel-shaped, with the lower reaches of the valley less constrained than the upper reaches represented by the West Lulu area, the northern valley boundary may be located no more than 2 - 4 km north of West Lulu-3.

A significant lowering of relative sea-level must have taken place to trigger the 40 to 50 metres of incision seen in some wells. A relative sea-level change may have been caused both by tectonic movements and by eustatic sea-level change. In the Middle Jurassic Søgne Basin however, which is characterised by half-graben tectonics, it is unlikely that tectonically induced base-level changes would cause deep incision both in upper hanging-wall slope locations like the West Lulu area and in locations close to the main boundary fault such as Amalie-1. Eustatic sea-level change on the other hand, would have the same effect in all parts of the basin, thus accounting for deep incision both up-dip on the hanging-wall slope and down-dip near the foot-wall. Local topography, which may be strongly influenced by tectonics, may have controlled the extent of incision and influenced the depth of incision. If areas with a steeper gradient than the alluvial plain further updip are exposed by falling sea-level, incision will result (Butcher, 1990; Schumm, 1993; Miall, 1996). Faulting events at the main boundary fault and faulting accompanied by only partial infilling of the deepest part of the half-graben basin may have resulted in higher gradients on the lower part of the hanging-wall slope.

## Controls on valley fill

The valley fill process began in the deepest part of the incised valley. Unit-1, the lowermost unit is only found in the two wells showing the deepest incision, West Lulu-3 and Amalie-1. Unit-1 is influenced by tidal processes, suggesting that sea-level rise had begun after incision of the deepest part of the valley was completed. Deposition of unit-2, that shows little or no evidence for tidal processes, may indicate a temporary halt in sea-level rise. Lateral channel migration may have been responsible for incision at the West Lulu-1 and 3/7-4 locations, where unit-2 is the lowermost unit. The unit-3 flooding event and the re-establishment of the migrating channel-system of unit-4 may be explained by variations in the rate of sea-level rise. Even rather subtle changes in sea-level may have had a dramatic effect in valleys that were conduits for large amounts of sediment. On a low-gradient valley floor, a small rise in sea-level would stop channel activity in the lower reaches of the valley and replace it with low-energy lagoonal or estuarine conditions. On an unconfined coastal plain with a slightly higher gradient the smaller, more dispersed fluvial channels would show a more gradual retreat after a similar rise in sea-level, and cause a more gradual change of facies.

The lagoonal deposits of unit-5 in Lulu-1 and Amalie-1 are probably coeval with the upper part of unit-4 in the more proximal wells. Development of the lagoonal facies may indicate that sea-level had had risen to the valley rim in the valley mouth area, where deposition thus became unconfined by valley walls, or that the upward increase in the width of the funnel-shaped valley mouth prevented the channels from sweeping the full width of the valley mouth until valley fill was completed.

When sea-level reached the valley rim, the coastal plain was not immediately inundated by sea water. Instead thick peat swamps developed in coastal plain mires. The growth of coal-forming peat swamps in the coastal plain environment could only take place when transport of sediment to the area had ceased due to dispersal of sediment conduits and transfer of the main depositional area to a position further updip. At the same time raised coastal mires may have helped to stabilise the coastline by impeding further transgression until peat growth was finally outpaced by sea-level rise (e.g. McCabe and Shanley, 1992). Transgression of the area continued only after a prolonged period of peat growth.

The observed facies distribution may be explained by eustatic sea-level changes alone and there is no need to include tectonic causes. An overall rise in sea-level interrupted by periods of stillstand or small sea-level falls may have controlled sediment distribution patterns within the incised valley. The effect of sea-level changes were largely confined to the incised valleys until sea-level reached valley rim level. Then the development of raised coastal mires prevented further transgression for some time.

## Reciprocal architecture

The reciprocal distribution of systems tracts in the sequences of the upper Bryne Formation is an anomaly when compared with the sequences of the lower Bryne Formation. Both half-graben related subsidence and sea-level changes influenced the lower Bryne Formation, so none of these factors alone explain the development of a reciprocal architecture in the upper Bryne Formation.

A low-gradient coastal plain dominated by peat-forming mires was the starting point for the development of the reciprocal deposits of the Cal-1A sequence (Fig. 32.1). A transgression across such a surface would normally be very rapid and cause significant landward movement of the coastline within a short time-span. Little new accommodation would be created and there would be little time for peat growth and for thick transgressive deposits to develop. On the other hand, a slow sea-level rise with other variables constant would give ample time for peat mires to keep up. In the case under discussion here, change in gradient in combination with a relatively rapid rise in sea-level would be a possible explanation for the development. An increased gradient on the hanging-wall slope caused by faulting at the main boundary fault might might have caused an almost instantaneous drowning of coastal mires on the lower slope, and probably cause the introduction of more clastic sediment in the mires on the upper slope. With the same rate of sea-level rise, a shorter section of the slope would have been transgressed during the same time-span than on the low-gradient plain, but more accommodation space would have been generated at any point (Fig. 32.2). Thus more accommodation and more time was available for the development of a transgressive systems tract. Most deposition was focused in the lagoons, tidal flats and estuaries of a backbarrier environment. Most of the sediment supplied to the area would have been trapped on the landward side of the barrier, leaving a lot of accommodation space seaward of the initial coastline position (Fig. 32.2, 3).

On such a low-gradient coastal plain, deposits of the back-barrier environments are susceptible to surf-zone erosion at the transgressing coastline. In the upper Bryne Formation, significant thicknesses of back-barrier deposits have been preserved even in wells such as West Lulu-1 and 3/7-4, where backbarrier deposits have been cut by a transgressive surface of erosion. This resulted from the relatively steep shoreline trajectory during transgression, which may have caused "accretionary transgression" (c.f. Helland-Hansen and Gjelberg, 1994). The term "accretionary transgression" is used for a situation where the shoreline trajectory during transgression diverges relative to the alluvial landward depositional foundation in existence at the time of onset of transgression (Helland-Hansen and Gjelberg, 1994).

Due to the relatively slow rate of transgression, most of the accommodation space created landward of the initial coastline position during the transgression would have been filled in by deposits of the TST, and very little accommodation space remained when the rate of sea-level rise began to decrease and a regression was initiated. The limited accommodation space above the main part of the TST was soon filled and the coastline moved rapidly seaward until it reached an area with more accommodation space. In that area, a thicker shoreface succession could develop and shoreline regression continued at a slower pace into deeper parts of the basin where only a thin veneer of transgressive sand represents the TST above the incised valley fill (Fig. 32. 4). A sea-level fall may have caused a forced regression and the development of a regressive surface of erosion at the of the sandy shoreface deposits. Shoreface progradation would probably have tended to move in a direction perpendicular to the contours of the hanging-wall slope, resulting in initial progradation from the west to the east in the Lulu - West Lulu - 3/7-4 area and probably from the south in the southern part of the basin. At a late stage of infill, progradation from the south-west towards the north-east might have become dominant.

The presence of a coal bed with a basin-wide distribution right above the Cal-1B sequence boundary shows that infill of the accommodation space generated by a combination of half-graben subsidence and sea-level rise had been completed, and a low-gradient coastal plain was re-established.

Development of the Cal-1B sequence probably followed much the same pattern except that much less incision took place at its sequence boundary. The somewhat thinner TST deposits than seen in the Cal-1A sequence may reflect a step landward of the whole depositional system caused by the overall transgressive development recorded by the upper Bryne Formation. However, the strongly asymmetric development of the HST/FRST succession is clear evidence of a reciprocal facies distribution pattern. Deposition of the Cal-1C sequence may also have followed a similar pattern; but this cannot be evaluated within the study area as the HST, probably due to the continued overall transgression, is only represented by distal shoreface or shelf deposits in the Lola Formation above the first flooding surface.

### Tectonic phases

If a combination of faulting at the main boundary fault and sea-level rise caused the development of reciprocal architecture in Cal-1A, this must also have been the case in Cal-1B and possibly in Cal-1C. In that case successions showing reciprocal architecture in the upper Bryne Formation are evidence of at least two, possibly three tectonic events that influenced depositional patterns in theSøgne Basin. The development of basin-wide coal-forming peat environments is evidence of per iods of tectonic quiescence between the faulting episodes. In addition at least two successions in the lower Bryne Formation show a strongly asymmetric facies and thickness distribution, which may be attributed to fault related half-graben subsidence. This indicates four or five significant phases of faulting at the main boundary fault during a period that probably ranges from the Bajocian through the Callovian.

## Conclusions

The development of a system of up to 50 m deep incised valleys in the Søgne Basin in the latest Bathonian or earliest Callovian and the occurrence of reciprocally distributed TST and HST/FRST successions in the paralic to shallow marine deposits uppermost in the Bryne Formation is in marked contrast to the laterally extensive and homogenous fluvial, floodplain and lacustrine deposits that dominate the lower Bryne Formation

Asymmetrical distribution of thicknesses and facies in two successions in the lower Bryne Formation indicates that half-graben related subsidence had begun before the incised valleys were cut and reciprocal architecture developed in the upper Bryne Formation.

Valley incision was not controlled by faulting related to half-graben subsidence but probably by a major fall in sea-level. The location and orientation of valleys, and the depth of incision may have been influenced by tectonically controlled topography.

The valley fill process was controlled by sea-level variations possibly enhanced by the confined space in the incised valleys. The peat cap on top of the incised valley fill and the surrounding interfluves developed when valley fill was completed and sea-level had reached the valley rim. Sediment transport became dispersed and most sediment was trapped further landward on the low-gradient coastal plain. The raised mires that developed on the coastal plain helped stabilise coastlines and impeded further transgression as long as peat growth kept up with sea-level rise.

A combination of half-graben tectonics and sea-level changes controlled the development of reciprocal architecture. An increased gradient on the coastal plain, which was caused by half-graben subsidence, in combination with an increased rate of sea-level rise led to a relatively slow transgression. The transgression was characterised by a relatively steep shoreline trajectory and the infilling by TST deposits of a large amount of accommodation space landward of the initial coastline. When regression began, due to a decrease in the rate of sea-level rise or the initiation of a minor sea-level fall, the little remaining accommodation space on top of the TST deposits was rapidly filled. Thick successions of shoreface deposits referred to the HST/FRST developed further seaward where a large much accommodation space remain, in particular seaward of the initial coastline.

Two or possibly three successions characterised by reciprocal architecture were deposited. Each of these represent a phase of half-graben subsidence, that took place during an overall rise in sea-level.

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## Figure captions

**Fig. 1:** Map of North Sea area. Mesozoic graben system shown in orange, study area in blue.

**Fig. 2:** Map of Søgne Basin with most important Middle Jurassic structural features and studied wells.

**Fig. 3:** Important lithostratigraphic units of the Jurassic in the Danish Central Graben.

**Fig. 4:** E - W log panel of the Bryne Formation in the Søgne Basin. In yellow are valley-fill deposits of major incised valley system and equivalent deposits. Well logs on panel are gamma-ray (left) and sonic velocity logs (right).

**Fig. 5:** N - S log panel of the Bryne Formation in the Søgne Basin. In yellow are valley-fill deposits of major incised valley system and equivalent deposits. Well logs on panel are gamma-ray (left) and sonic velocity logs (right).

**Fig. 6:** Regional N - S log panel from the southernmost well in the Søgne Basin (Amalie-1) to O-1 southernmost in the Danish Central Graben. Well logs are gamma-ray (left) and sonic velocity (right). With yellow and blue are deposits equivalent to the succession treated in this paper.

**Fig. 7:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from Amalie-1 well.

**Fig. 8:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from West Lulu-3 well.

**Fig. 9:** Core photos, examples of tidally influenced fluvial and estuary channel deposits. a: erosive contact between two channel units, lower unit cross-bedded with abundant mud-drapes, Amalie-1 (5118.5 m). b: lenticular bedded siltstone of tidal flat or passive channel environment erosively overlain by cross-bedded channel sandstone, Amalie-1 (5110.7 m). c: ripple cross-laminated sandstone with mud flasers, Amalie-1 (5084.7 m). d: bioturbated, heterolithic sandstone with mud laminae, Amalie-1 (5082.6).

**Fig. 10:** Core photos, examples of bay-head delta and tidally influenced fluvial and estuary channel deposits. a: base of large channel sandstone with basal conglomerate of mudstone clasts overlain by cross-bedded sandstone, Cal-1A sequence boundary and base of major incised valley is picked at channel base, West Lulu-3 (3711 m). b: cross-bedded sandstone with double? mud-drapes, tidally influenced fluvial channel, base of subunit 4A in incised valley, West Lulu-3 (3685.6 m). c: current ripple cross-laminated sandstone with abundant mud flasers, subunit 4B in incised valley, West Lulu-2 (3842.6 m). d: climbing ripple cross-laminated sandstone with mud flasers, mud drapes including double drapes at top and bottom, bay-head delta, upper TST of Cal-1A, West Lulu-3 (3654.5 m).

**Fig. 11:** Core photos, examples from mainly distal or marginal estuary environments. a: heterolithic sandstone and siltstone with lenticular and inclined parallel bedding, change in dip between lowermost and upper part, tidal flat or upper point bar of tidal channel showing "inclined heterolithic stratification", upper TST of Cal-1A, Amalie-1 (5064.2 m). b: parallel laminated and lenticular bedded heterolithic siltstone, tidal flat, subunit 5 in incised valley, Amalie-1 (5075.5 m). c: parallel laminated silty mudstone, lagoon or tidal flat, upper TST of Cal-1A, Amalie-1 (5062.7 m). d: organic rich mudstone and coal cut erosively by base of channel sandstone, passive channel fill and marsh or swamp deposits cut by estuary channel base, split seam of large coal unit and lithic interbeds, upper TST of Cal-1A, Amalie-1 (5067.9 m).

**Fig. 12:** Core photos, examples from paralic and shallow marine deposits from succession overlying the incised valley fill. a: thoroughly bioturbated estuary channel sandstone with dominance of *Teichichnus* trace fossils, uppermost Cal-1A TST, West Lulu-3 (3647.5 m), b: Clast- and matrix-supported pebble conglomerate, sharp bases, fining up dominating trend, coarsening upward occurs, transgressive conglomerate, uppermost TST of Cal-1C, West Lulu-2 (3782.2 m). c: SCS/HCS - bedded sandstone of prograding shoreface, FRST of Cal-1B, Lulu-1 (3575.6 m). d: HCS and wave ripple cross-lamination in muddy sandstone, *Teichichnus* burrows, lower shoreface to offshore transition zone, FRST of Cal-1A, Lulu-1 (3593.6 m).

**Fig. 13:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from West Lulu-1 well.

**Fig. 14:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from West Lulu-2 well.

**Fig. 15:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from 3/7-4 well.

**Fig. 16:** Examples of sedimentary environments and facies associations. Core and gamma-ray log from West Lulu-3 well.

**Fig. 17:** Core photos, examples from shoreface and shelf deposits. a: sandstone showing SCS/HCS and low-angle trough cross-bedding, lower shoreface of prograding shoreface unit, FRST of Cal-1A, Amalie-1 (5049.25 m). b: erosion surface (regressive surface of erosion) separating heterolithic offshore siltstone below from silty sandstone of the offshore transition zone above that shows HCS, wave ripple lamination and trough cross-bedding, prograding shoreface succession , FRST of Cal-1A, Amalie-1 (5051.75 m). c: regressive surface of erosion, erosive base of shoreface sandstone cutting into offshore mudstone, HST/FRST Cal-1A, Amalie-1 (5055.25 m). d: thoroughly bioturbated silty sandstone - sandy siltstone, transgressive shoreface and shelf, upper TST of Cal-1A, Amalie-1 (5061.2 m).

**Fig. 18**: Examples of sedimentary environments and facies associations. Core and gamma-ray log from Lulu-1 well.

**Fig. 19**: Examples of sedimentary environments and facies associations. Core and gamma-ray log from Amalie-1 well.

**Fig. 20a**: Correlation panel of incised valley deposits in western part of study area, gamma-ray and sedimentological core logs.

**Fig. 20b**: Correlation panel of incised valley deposits in eastern part of study area, gamma-ray and sedimentological core logs.

**Fig. 20c**: Symbols of sedimentary structures and lithologies used on correlation panels figs 20a, b, 26a, b, and core logs showing sedimentary environments and facies (figs 7, 8, 13, 14, 15, 16, 18, and 19).

**Fig. 21**: Palaeogeographic map, early transgression in incised valley system, valley dominated by tidally influenced, laterally migrating fluvial channels, estuaries present downstream.

**Fig. 22**: Palaeogeographic map, continuing transgression in incised valley system, estuaries established in valleys.

**Fig. 23**: Block diagrams of central and western part of southern Søgne Basin. a: pre-incision, lacustrine deltas prograde into lakes established in the deep part of basin near main boundary fault. b: valley is cut by fluvial erosion at low relative sea-level.

**Fig. 24**: Block diagrams of central and western part of southern Søgne Basin. a: early valley fill deposited during transgression of incised valley, estuary is established in lower estuary, marine bay or lagoon in deep part of basin. b: late valley fill deposited during continued transgression, lower valley drowned, estuary present in upper valley.

**Fig. 25**: Palaeogeographic map, after completion of valley infill are swamps and mires established in most of the study area, minor basin-axial rivers may still deliver clastic sediments to deep part of basin.

**Fig. 26a**: Correlation panel of deposits overlying the incised valley-fill in the western part of the study area, gamma-ray and sedimentological core logs. Legend: see Fig. 20c.

**Fig. 26b**: Correlation panel of deposits overlying the incised valley-fill in the western part of the study area, gamma-ray and sedimentological core logs. Legend: see Fig. 20c.

**Fig. 27:** Palaeogeographic map, upper TST of Cal-1A, lagoon with bay-head deltas, deposits of protective barrier probably removed by surf-zone erosion during transgression.

**Fig. 28:** Palaeogeographic map, FRST of Cal-1A (or Cal-1B), fast regression as a result of a falling relative sea-level leaves a chenier plain or strand plain behind the prograding coast line.

**Fig. 29:** Sequence architecture of Cal-1A, -1B, and -1C, thin coal beds separate incised valley-fill lowermost in Cal-1A and -1B from upper TST (green and red) and HST/FRST (yellow and grey) showing reciprocal distribution of systems tracts. Inset below is schematic diagram of subsiding half-graben with Lulu Salt Structure.

**Fig. 30:** Block diagrams of central and western part of southern Søgne Basin. a: after completion of valley infill are swamps and mires established in most of the study area, minor basin-axial rivers may still deliver clastic sediments to deep part of basin, main boundary fault is inactive and valley floor is low-gradient. b: deeper parts of basin is transgressed after faulting event, large lagoons or estuaries are established during early flooding, bay-head deltas from the west and flood tidal deltas from the east prograde into the lagoon.

**Fig. 31:** Block diagrams of central and western part of southern Søgne Basin. a: coast line reaches briefly the West Lulu area during maximum transgression, only a thin veneer (max. 2 - 3 m) of transgressive shelf and shoreface deposits is deposited east of the MFS-shoreline. b: falling relative sea-level causes regression and progradation of shoreface into empty accommodation space in the central and eastern part of the basin, a chenier or strand plain is formed behind the prograding coast-line.

**Fig. 32:** Development of reciprocal architecture in subsiding half-graben. 1: sea-level 1 (SL 1), valley fill completed, sea-level slowly rising but coastline stabilised by barrier and growing raised mires on low-gradient coastal plain, no fault activity. 2: sea level 1 after faulting event at main boundary fault, lower hanging-wall slope submerged due to rotation, most sediment input from the hanging-wall slope trapped in coastal barrier/back-barrier system. 3: rapidly rising sea-level to sea-level 2 (SL 2), transgression slow due to steep gradient, thick TST deposits accumulate in narrow zone. 4: falling sea-level to sea-level 3 (SL 3), forced regression causes erosion into TST deposits and deposition of sharp based shoreface deposits in FRST, maximum flooding surface separates TST deposits that occupy all updip accommodation from HST/FRST deposits occupying most downdip accommodation.

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 1 | massive and laminated silt- and claystone | massive or mm to cm-scale interlaminated silt- and claystone | less than 50cm thick beds | | offshore, fairweather deposition and suspension fall-out after storms |
| 2 | interbedded siltstone and sandstone | cm-scale interbedded silt- and sandstone; sharp based, normal graded sand laminae show parallel lamination and wave ripples | beds max. 10cm | weak to moderate bioturbation; Anconichnus., Planolites., Palaeophycus. and Teichichnus. | offshore, near storm wave base |
| 3 | bioturbated siltstone and sandstone | bioturbated siltstone, vf. sandstone beds with sharp bases may show wave or combined flow ripples, parallel lamination and HCS | siltbeds less than 3m, sand-beds up to 10cm, rarely 50cm | moderate to intense bioturbation; Teichichnus., Thallas., Skolithos., Planolites. | offshore and offshore transition, storm activity alternating with long periods dominated by fair-weather conditions |
| 4 | HCS dominated sandstone | vf. and f.grained sandst. with siltstone laminae; sharp based sandstone beds with HCS and subordinate wave ripple lamination | beds from 10 to 30cm | weak bioturbation | offshore transition, storm- and waning storm deposition |
| 5 | SCS dominated sandstone | f.grained sandstone, SCS, low-angle planar x-bedding and scour structures | beds from 20 to 50cm | trace fossils are rare | lower and middle shoreface, above fair-weather wave base |
| 6 | trough and planar x-bedded sandstone | f. to c.grained sandstone, occasionally pebbly; trough x-bedding, planar x-bedding and subordinate current- and wave ripples | 20 to 50cm beds in units up to 3m thick | bioturbation in the most fine grained intervals as Diplocraterion and Skolithos | upper shoreface; rip channels, nearshore bars and troughs |
| 7 | horizontally laminated and planar x-bedded sandstone | f. to m.grained sandstone, and more coarse grained laminae; horizontal lamination with low-angle erosion surfaces and low-angle planar x-bedding | 5 to 15cm thick beds in units up to 50cm thick | trace fossils are rare; roots and Skolithos? may occur | foreshore |
| 8 | conglomerate and pebbly sandstone | clast-supported pebble and granule conglomerate, less common matrix supported conglomerate and pebbly sandstone; clast-supported conglomerate may show bedding or x-bedding; conglomerate veneers on erosion surfaces | conglomerate beds max. 10cm; pebbly sandstone beds up to 30cm thick | | beach and breaker zone deposits; may represent a transgressive lag |
| 9 | poorly sorted, bioturbated muddy sandstone and heterolith | poorly sorted sandstone with subordinate siltstone; soft-sediment deformation structures and bioturbation dominate, some wave and current ripples may occur | 5 to 10cm beds in up to 1m thick units | often thoroughly bioturbated; Teichichnus and Diplocraterion. may occur | transgressive marine sandstone deposited below fair-weather wave base during a rising sea-level |

Table 1a

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 10 | horizontally laminated and current rippled sandstone | erosively based fu. units of vf. to m.grained sandstone; horizontal or gently inclined lamination and current ripples, locally soft-sediment deformation structures or high-angle x-bedding may occur | 5 to 20cm thick beds | moderate bioturbation, roots may occur | wash-over sediments |
| 11 | structureless rooted sandstone | various sandstones and heteroliths fully or partly homogenized by root burrowing | 50cm to 3m | thoroughly bioturbated by roots | beach ridge plain |
| 12 | fu. x-bedded sandstone with muddrapes | fu. units of c.-f. grained sand; planar and trough x-bedding with ripple x-lamin., flaser and wavy bedding in upper parts of units, abundant clay laminae, clay clasts and coal debris, interbedded sandstone and mudstone may occur | fu. units from 4 to 10m | moderate, rarely intense bioturbation; Teich. | major tidal channel or active tidal inlet |
| 13 | fu. interbedded mudstone and sandstone | f. and vf.grained sandstone and heteroliths with mud clasts; ripple x-lamin., horiz. lamin., flaser, lentic. and wavy bedding, x-bedding | fu. units typically from 50cm to 2.5m | moderate to intense bioturbation | tidal creek or inactive major tidal channel |
| 14 | cu. sandstone with abundant mud laminae | vf. to f.grained sand; bioturbated with mud laminae mud flasers and ripple x-lam. | cu. units up to 2m thick | moderate to intense bioturbation, Teich. | tidal sand bar/flat |
| 15 | cu. x-bedded sandstone with mud laminae | vf. to m.grained sand and heteroliths; x-bed., x-lam., flaser bed. and mud laminae | cu. units up to 4m thick | generally moderate bioturbation, Teich. and Diplo. | proximal flood tidal delta or estuary sand bar |
| 16 | fu. heterolithic sandstone and mudstone | thinly interbedded sandstone, mudstone and heteroliths; ripple x-lam., horiz.lam., flaser bed. | units less than 1m thick | moderate to intense bioturbation, Diplocraterion and Planolites are common | tidal flat and distal flood tidal delta |
| 17 | cu./fu sandstone and heterolith | vf. to m.grained cu. sandstone units with planar x-bedding, horiz. x-lam. current and wave ripple x-lam. and small scale HCS/SCS; commonly assoc. with fu. channel units | up to 5m thick units | moderately bioturbated; Teich., Diplo. | bay head delta/bay shoreface |
| 18 | massive or laminated mudstone and bioturbated sandstone | horizontally laminated or massive mudstone with interbeds and laminae of sandstone; horizontal lamination, wave ripples, flaser and lenticular bedding. | units less than 2m thick | moderate to intense bioturbation | low energy outer estuary, estuary central basin or lagoon |
| 19 | organic rich rooted mudstone | organic rich mudstones with plant fragments, thin coals and with abundant rootlets | less than 50cm | moderate to intense bioturbation by roots | marsh or vegetated coastal swamp |
| 20 | coal | | max. 5m | | mire |

Table 1b

| no. | facies name | description | dimensions | biogenic structures | interpretation |
|---|---|---|---|---|---|
| 21 | fu. interbed. sandstone and fines | sharp based fu. and ungraded x-bed. and x-lam. sandstone with abund. heterolithic beds and mud lam., beds with abund. coal or mud clasts occur | max. 12m thick units | upper part of channel units may be bioturbated with Diplo. and Teich. | tidally influenced fluvial channel |
| 22 | fu. and ungraded sandstone | sharp based fu. x-bed. and x-lam. sandstone, heterolithic sandst. may dominate upper part of units, some beds may have abund. coal and mud clasts; large amalgam. units may be ungraded | max. 8m thick units | | major fluvial channel |
| 23 | intraformational conglomerate | pebble- to cobble sized, matrix- or clast-supported conglomerate in sand matrix. Clasts are angular mud- or siltstone. Conglomerate beds at base of fu. sandstone units are parallel- or x-bedded. | beds are up to 75cm thick | | channel lag deposits |
| 24 | fu. thin- bedded or x-bedded sandstone | sharp based fu. sandstones; thin-bedded with current ripple x-lam., horiz. lam., or x-bedded. Intraform. clasts and coal fragm, soft sedim. def. | units less than 2m | | crevasse channel or minor fluvial channel |
| 25 | chaotic bedded sandstone | poorly sorted sandstone wtih mud laminae; laminae deformed and overturned, coal and mud clasts scattered throughout | beds typically 20 to 50cm thick | | channel margin deposits of fluvial channels |
| 26 | sideritic siltstone and mudstone | siltstone and mudstone with siderite bands and nodules, and abundant plant remains and roots, indistinct patches of sandst. may occur | typically from 0.5 to 2m | | abandoned channel fill |
| 27 | cu-units of deformed siltstone sandstone | stacked cu-units of siltstone and sandstone dominated by soft-sediment deformation structures with current-, wave-, and climb. ripple lam. in sandst. units, and parall. and climb.ripple lam. and wavy and lent. bedding in siltst. units. Mudstone clasts and coal fragments may locally be abundant. Thinner, sharp based fu-sandstones with deformed x-bedding may occur at top of cu-intervals. | 2 - 5 m thick units may be stacked in 10 - m thick cu-successions | | lacustrine delta; stacked minor cu-units topped by channel sandstones may represent delta lobes in a larger lacustrine delta |
| 28 | cu. units of sharpbased sandstones and siltstone | cu. units of vf. to m.grained sandstone with silt- and mudstone; horizontal or current-ripple lam., root traces and soft-sediment deformations are common, base gradational to floodplain mudstones | units up to 2m thick, single beds 10 to 50cm | | levee and crevasse splay |
| 29 | disturbed silty mudstone | mud- and siltstone, subord. sandstone, coal debris; horiz. lam., sediments disturbed by roots, soft-sediment def. and pedogenesis | generally less than 1m thick | thoroughly bioturbated, mainly by roots | floodplain fines |
| 30 | organic rich, laminated mudstone | organic rich mudstone with sand and silt laminations | up to 8m thick | | lake and pond |

Table 1c

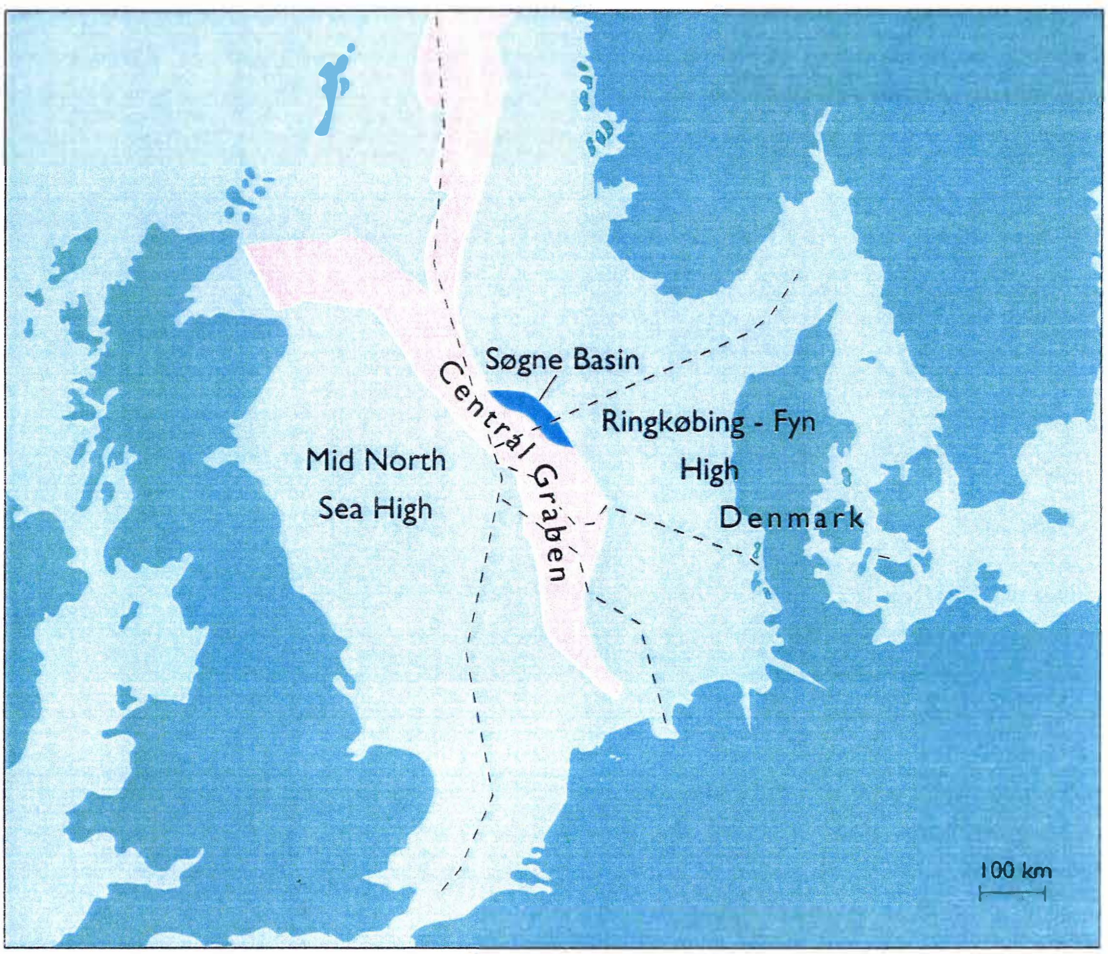

Søgne Basin
Central Graben
Ringkøbing - Fyn
High
Mid North
Sea High
Denmark
100 km

Fig. 1

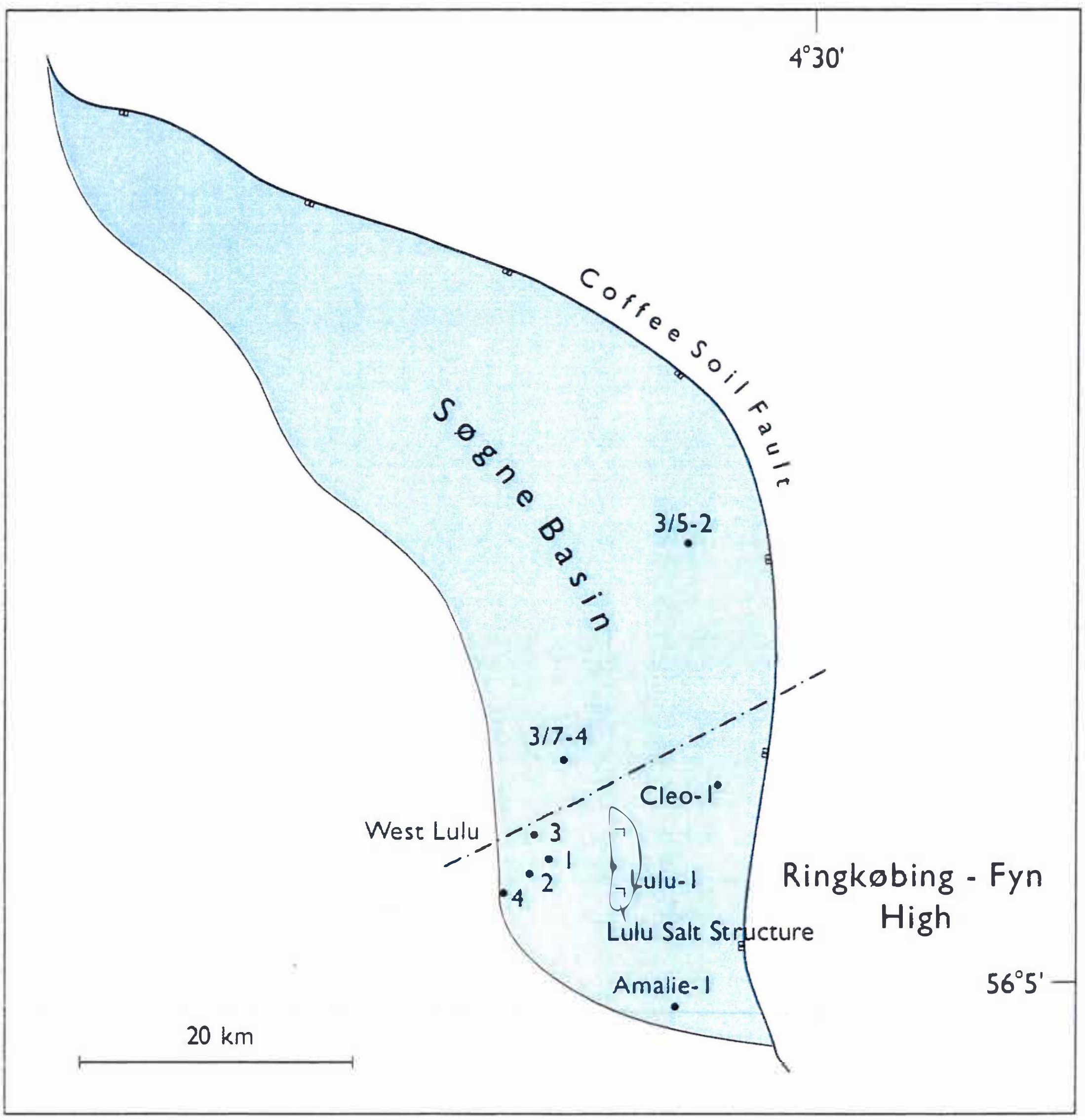
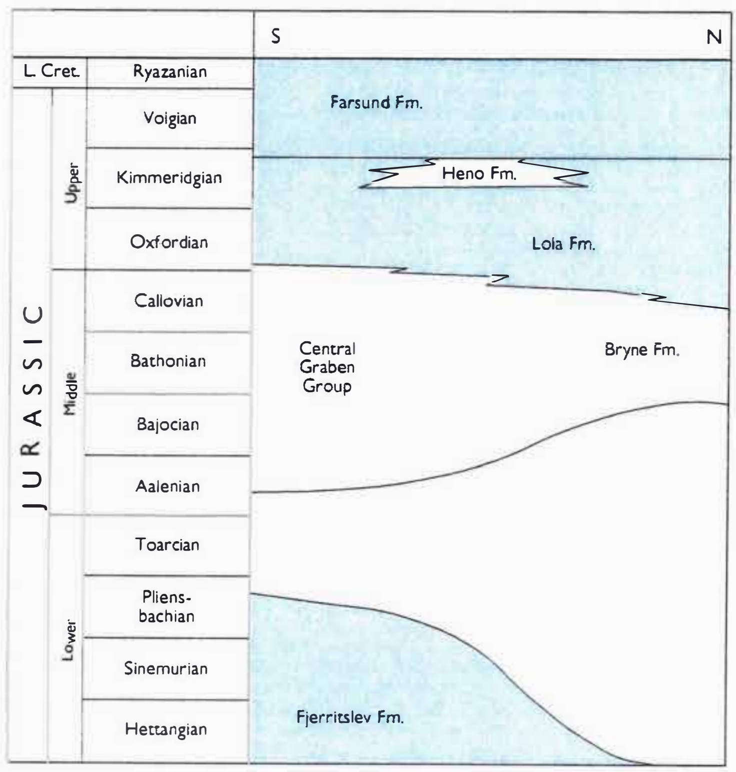

4°30'
Coffee Soil Fault
Søgne Basin
3/5-2
3/7-4
Cleo-1
West Lulu
3
1
2
4
Lulu-1
Lulu Salt Structure
Ringkøbing - Fyn
High
56°5'
Amalie-1
20 km

Fig.2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JURASSIC
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Voigian
Kimmeridgian
Oxfordian
Middle
Callovian
Bathonian
Bajocian
Aalenian
Lower
Toarcian
Pliens-
bachian
Sinemurian
Hettangian
Farsund Fm.
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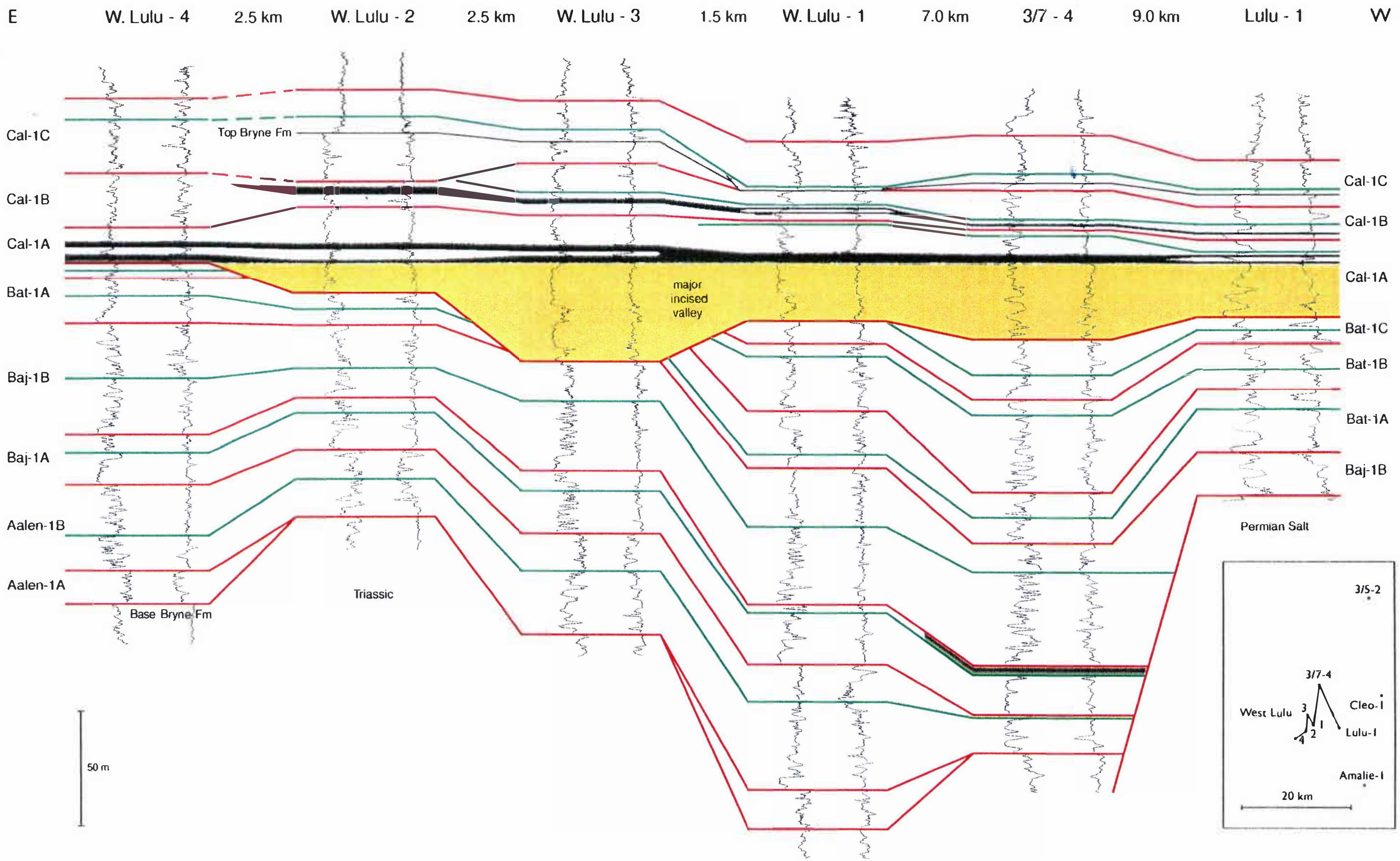
Lola Fm.
Central
Graben
Group
Bryne Fm.
Fjerritslev Fm.

Fig.3



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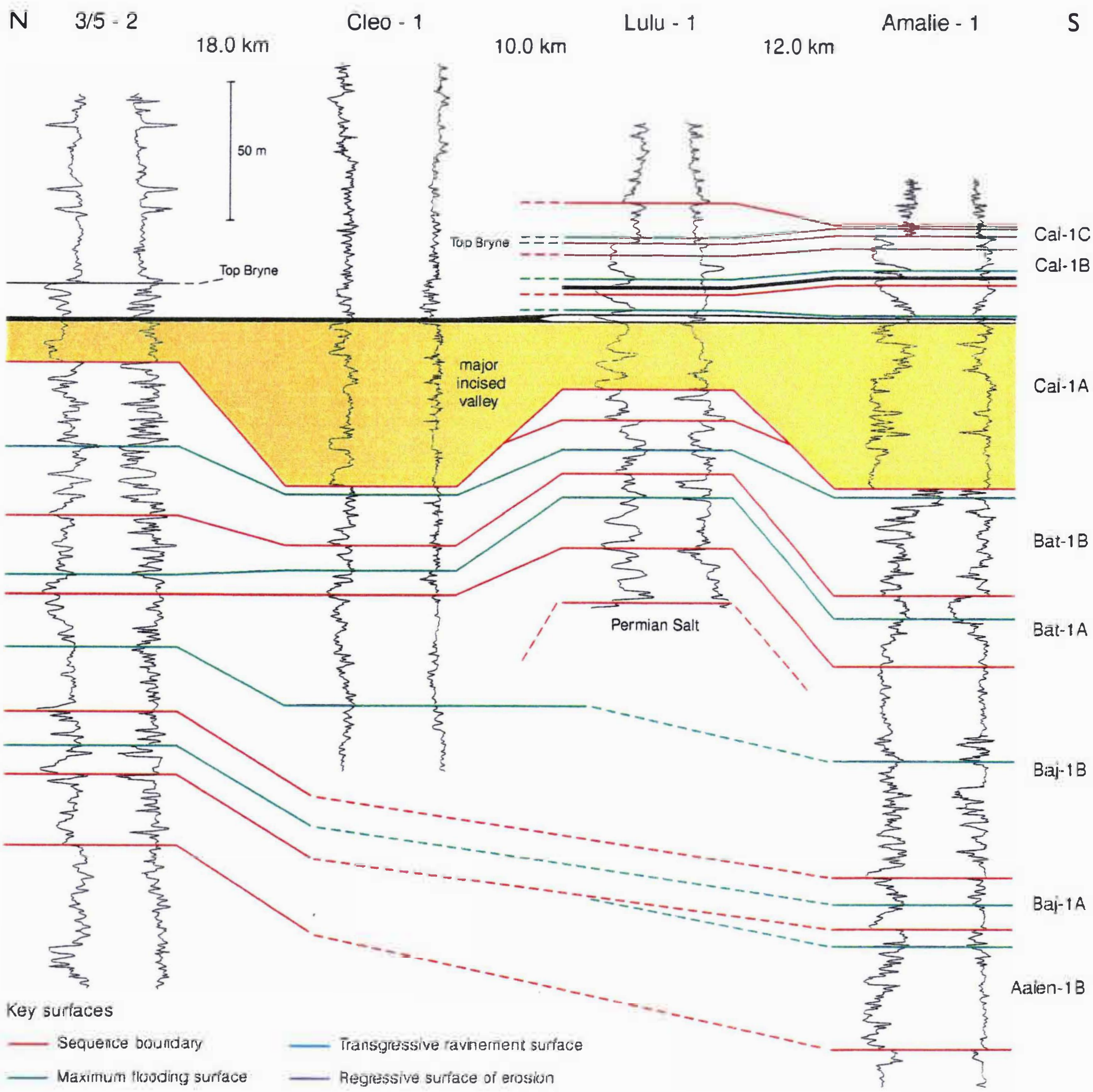
3/7 - 4
9.0 km
Lulu - 1
W
Cal-1C
Cal-1B
Cal-1A
Bat-1A
Baj-1B
Baj-1A
Aalen-1B
Aalen-1A
Top Bryne Fm
major incised valley
Base Bryne Fm
Triassic
Cal-1C
Cal-1B
Cal-1A
Bat-1C
Bat-1B
Bat-1A
Baj-1B
Permian Salt
50 m
3/5-2
3/7-4
West Lulu
Cleo-1
Lulu-1
Amalie-1
20 km


Fig.4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Lulu - 1
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Amalie - 1
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Top Bryne
major incised valley
Permian Salt
Cal-1C
Cal-1B
Cal-1A
Bat-1B
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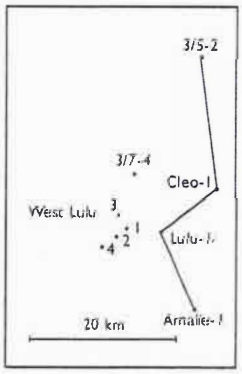
Aalen-1B
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion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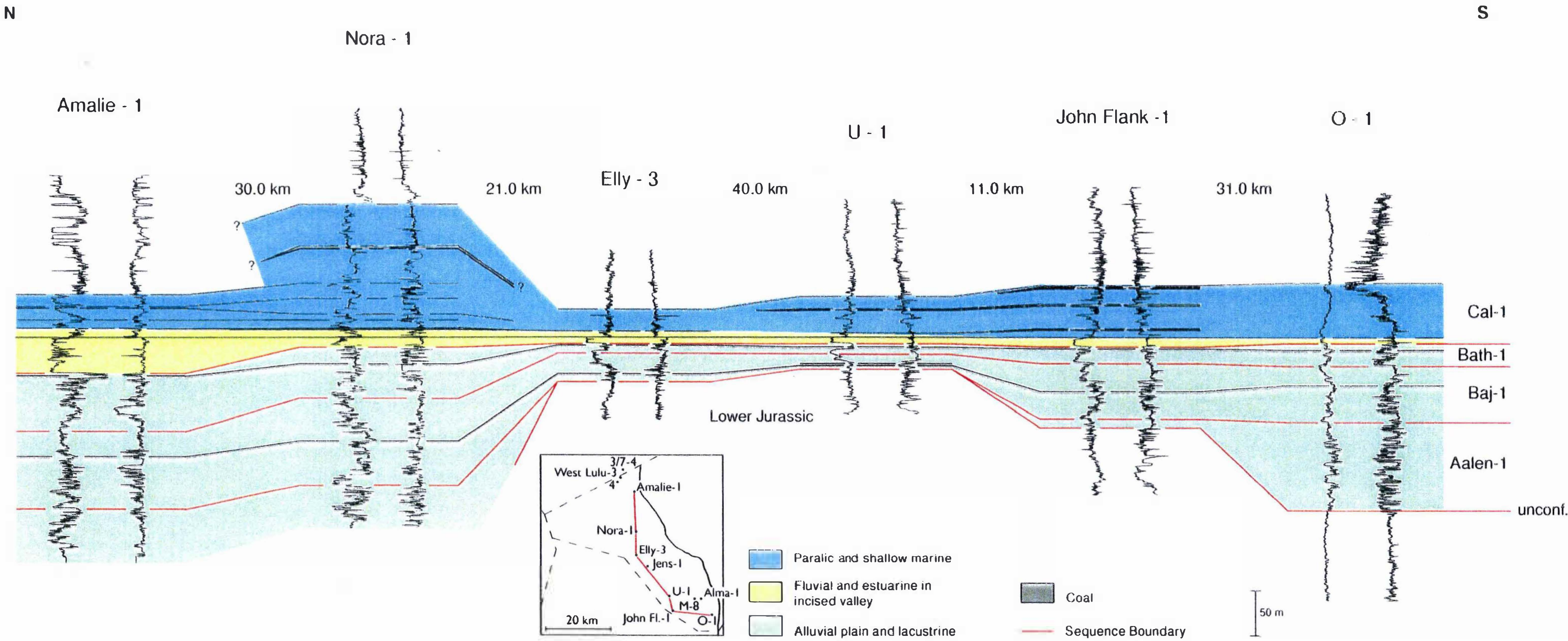
Amalie-1
20 km

Fig.5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31.0 km
O - 1
Cal-1
Bath-1
Baj-1
Lower Jurassic
Aalen-1
unconf.
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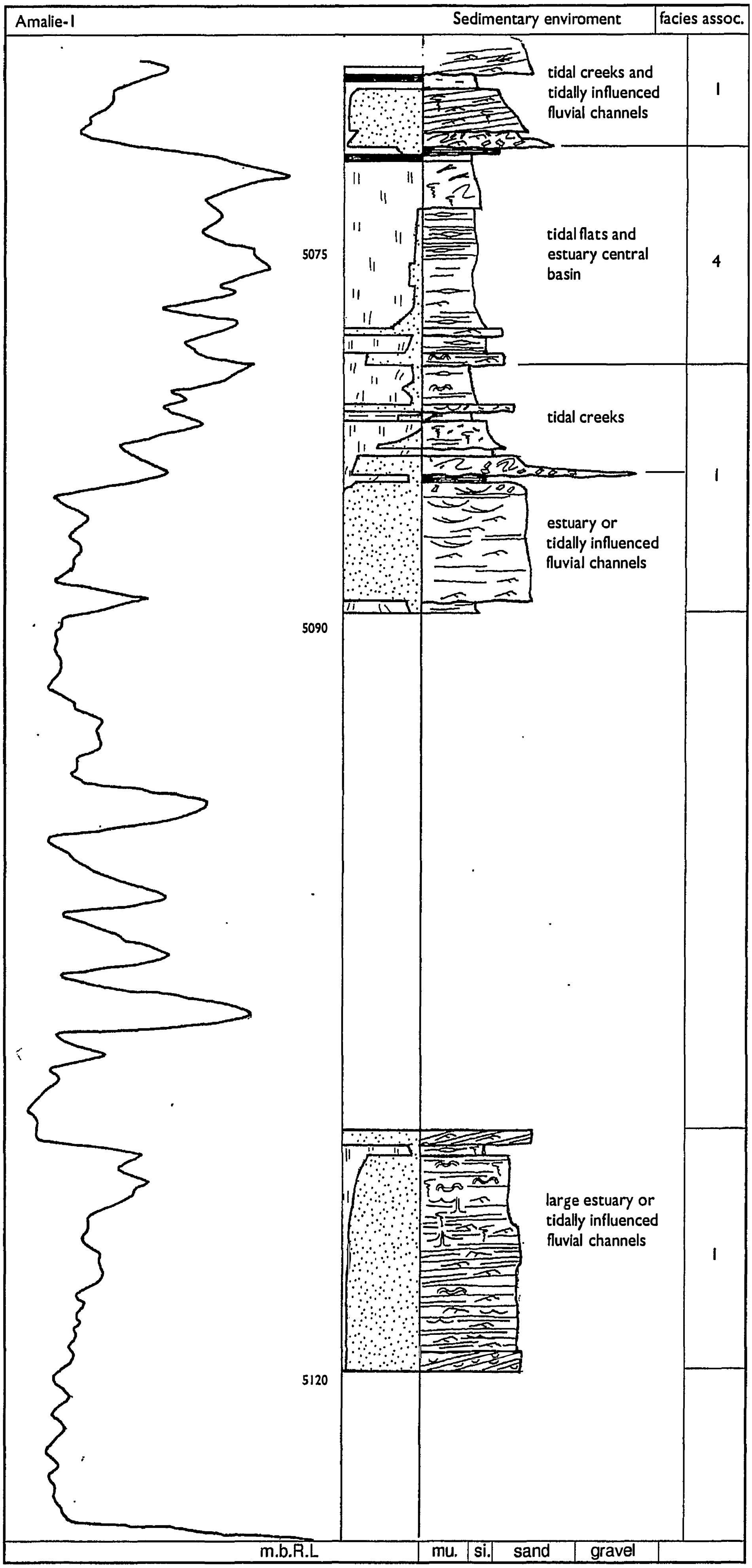
West Lulu-3
4
Amalie-1
Nora-1
Elly-3
Jens-1
U-1
Alma-1
M-8
20 km
John Fl.-1
O-1
Paralic and shallow marine
Fluvial and estuarine in incised valley
Alluvial plain and lacustrine
Coal
Sequence Boundary
50 m

Fig.6



Amalie-1
Sedimentary enviroment
facies assoc.
tidal creeks and tidally influenced fluvial channels
1
5075
tidal flats and estuary central basin
4
tidal creeks
1
estuary or tidally influenced fluvial channels
5090
large estuary or tidally influenced fluvial channels
1
5120
m.b.R.L
mu.
si.
sand
gravel


Fig.7

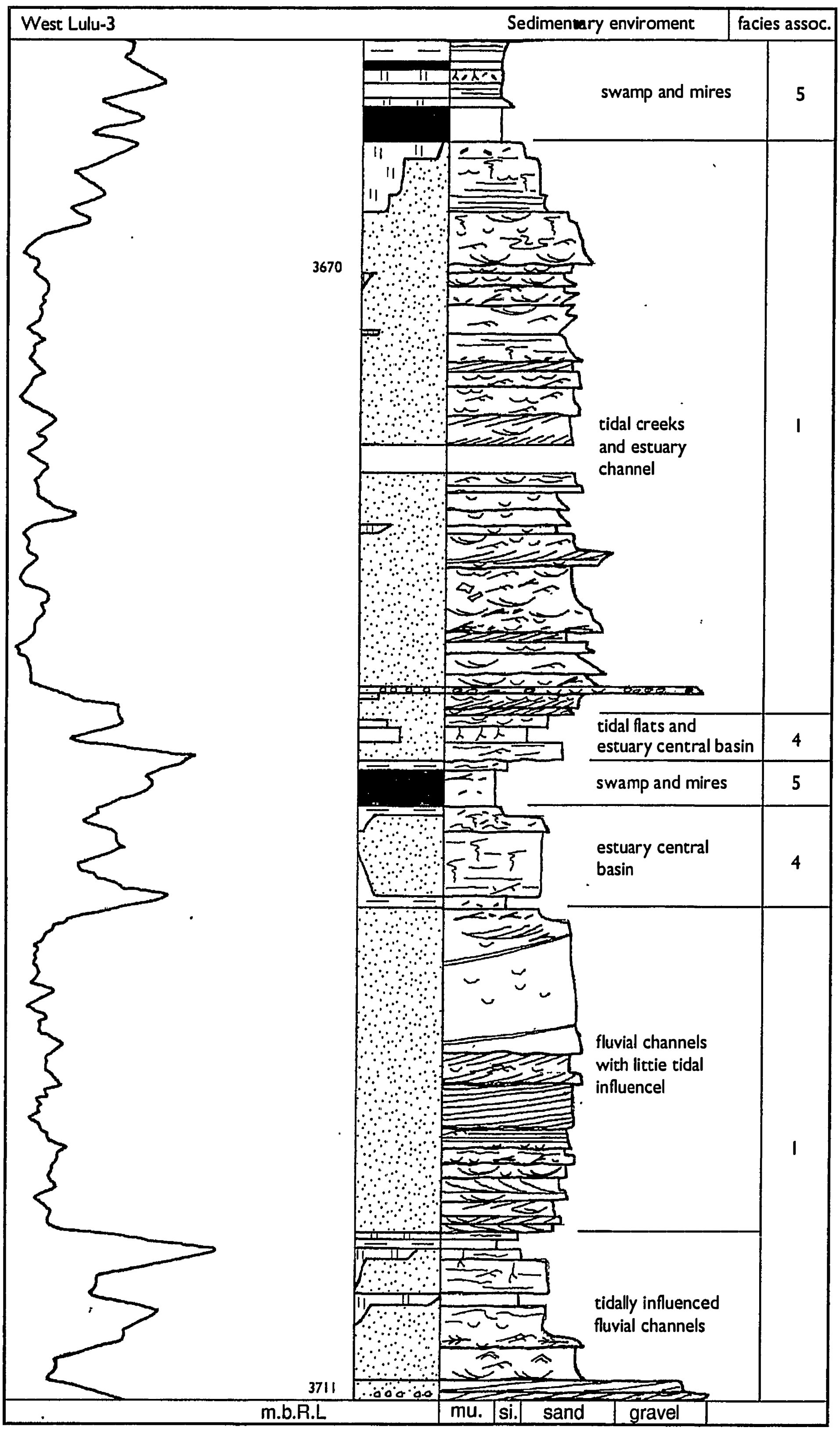

West Lulu-3
Sedimentary enviroment
facies assoc.
swamp and mires
5
3670
tidal creeks
and estuary
channel
1
tidal flats and
estuary central basin
4
swamp and mires
5
estuary central
basin
4
fluvial channels
with littie tidal
influencel
1
tidally influenced
fluvial channels
3711
m.b.R.L
mu.
si.
sand
gravel

Fig.8

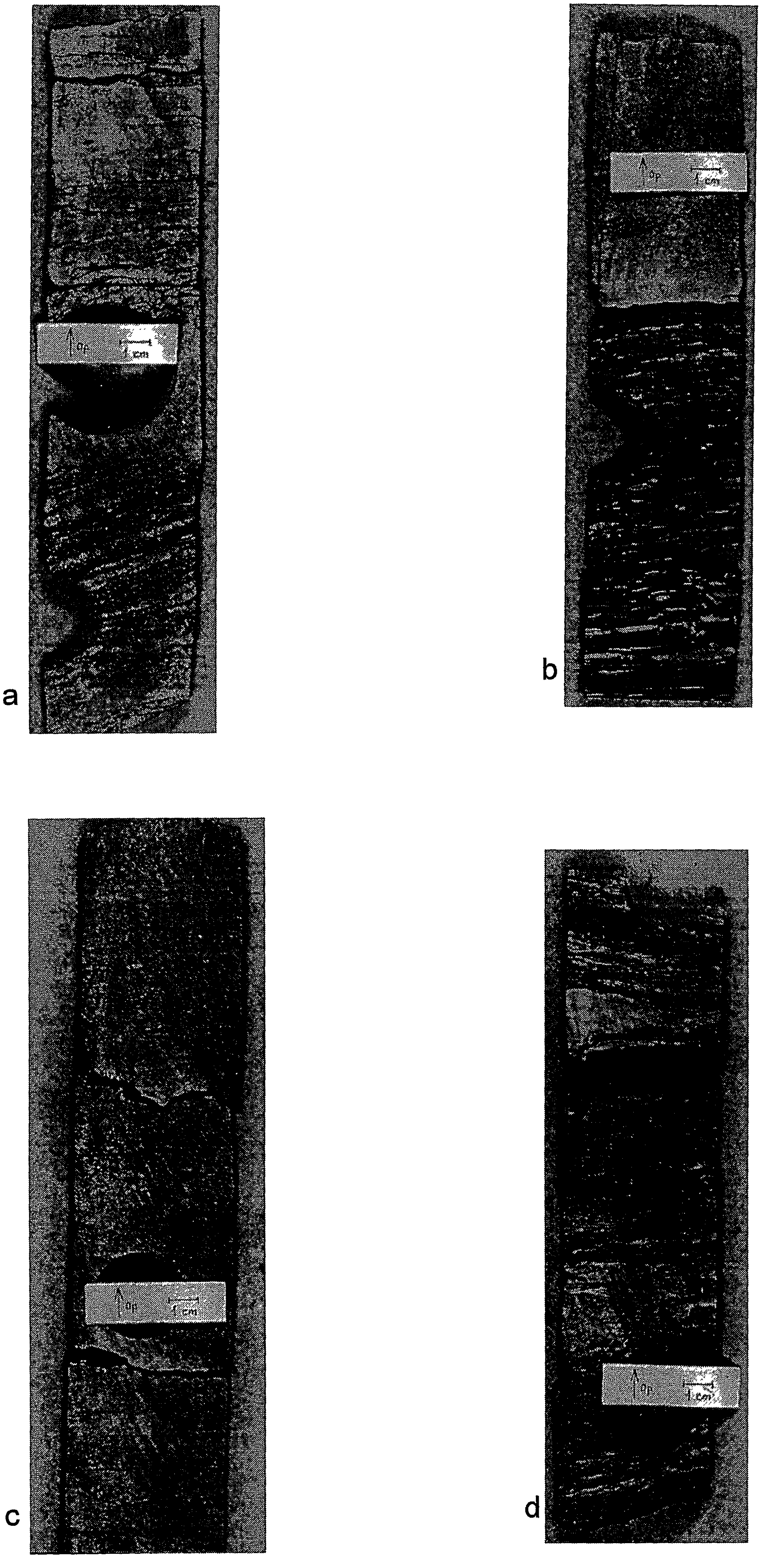



Fig.9

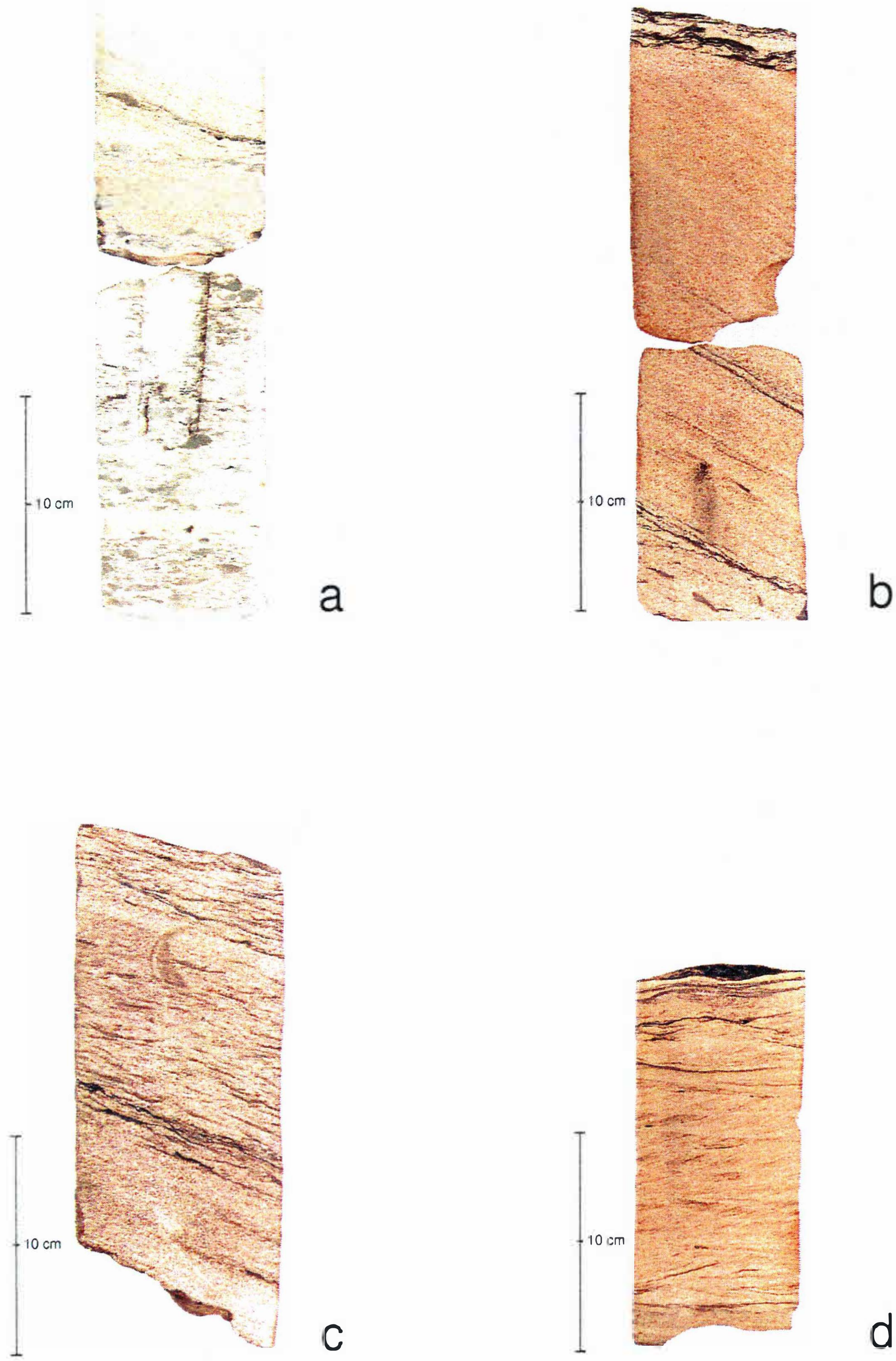



Fig. 10

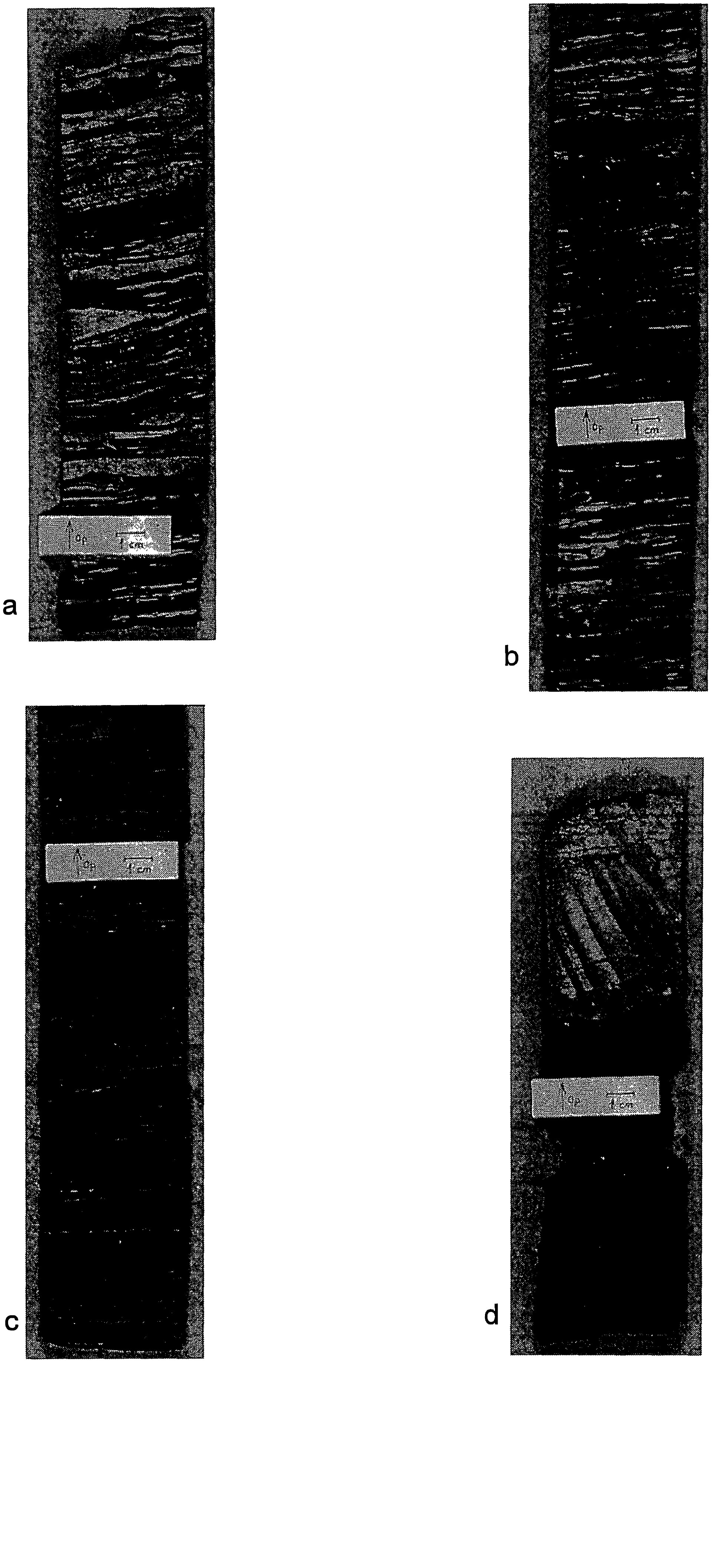



Fig.11

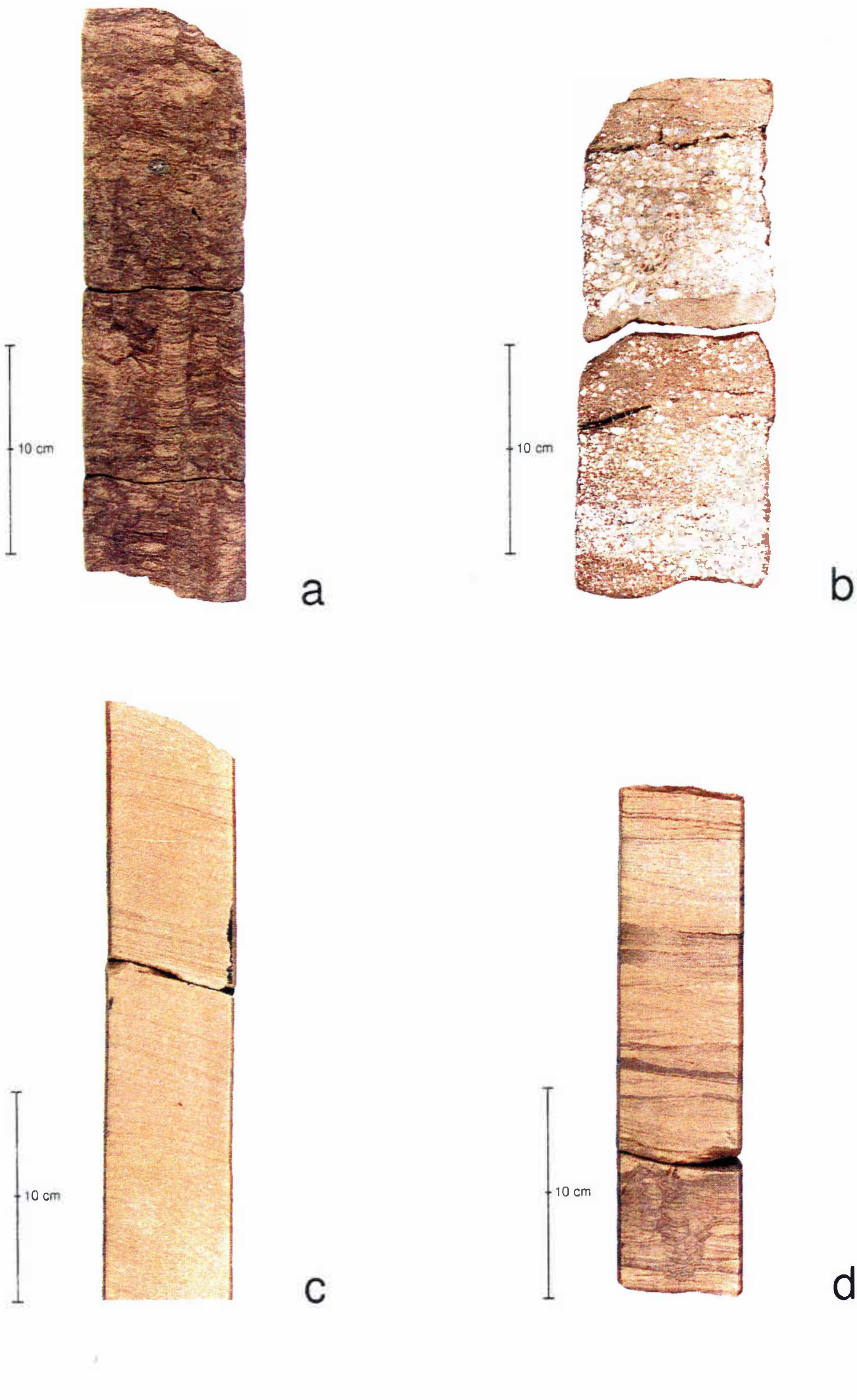



Fig. 12

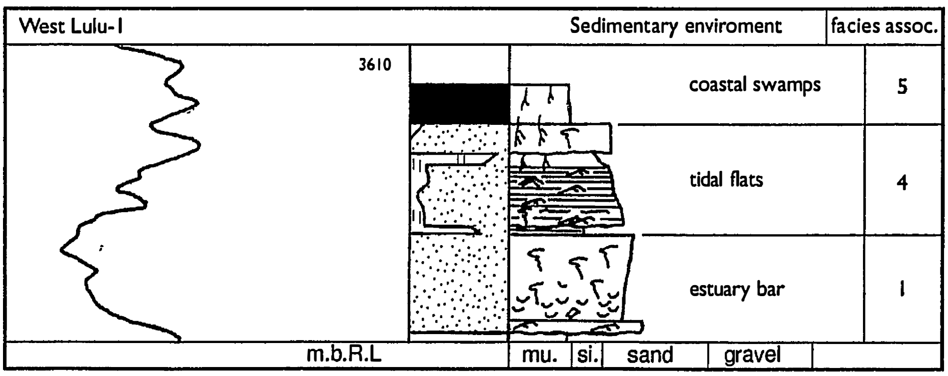

West Lulu-1
Sedimentary enviroment
facies assoc.
3610
coastal swamps
5
tidal flats
4
estuary bar
1
m.b.R.L
mu.
si.
sand
gravel

Fig.13

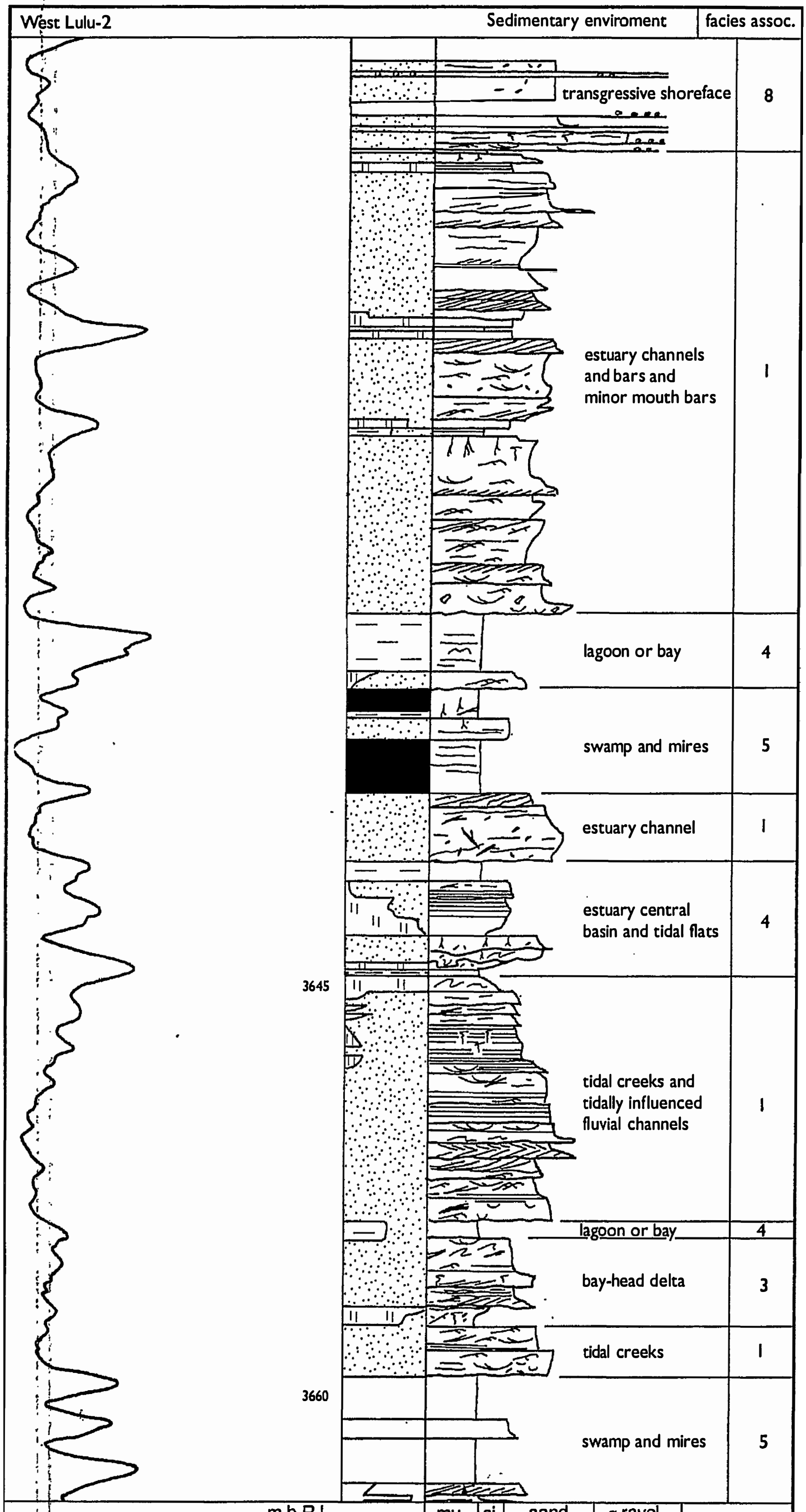
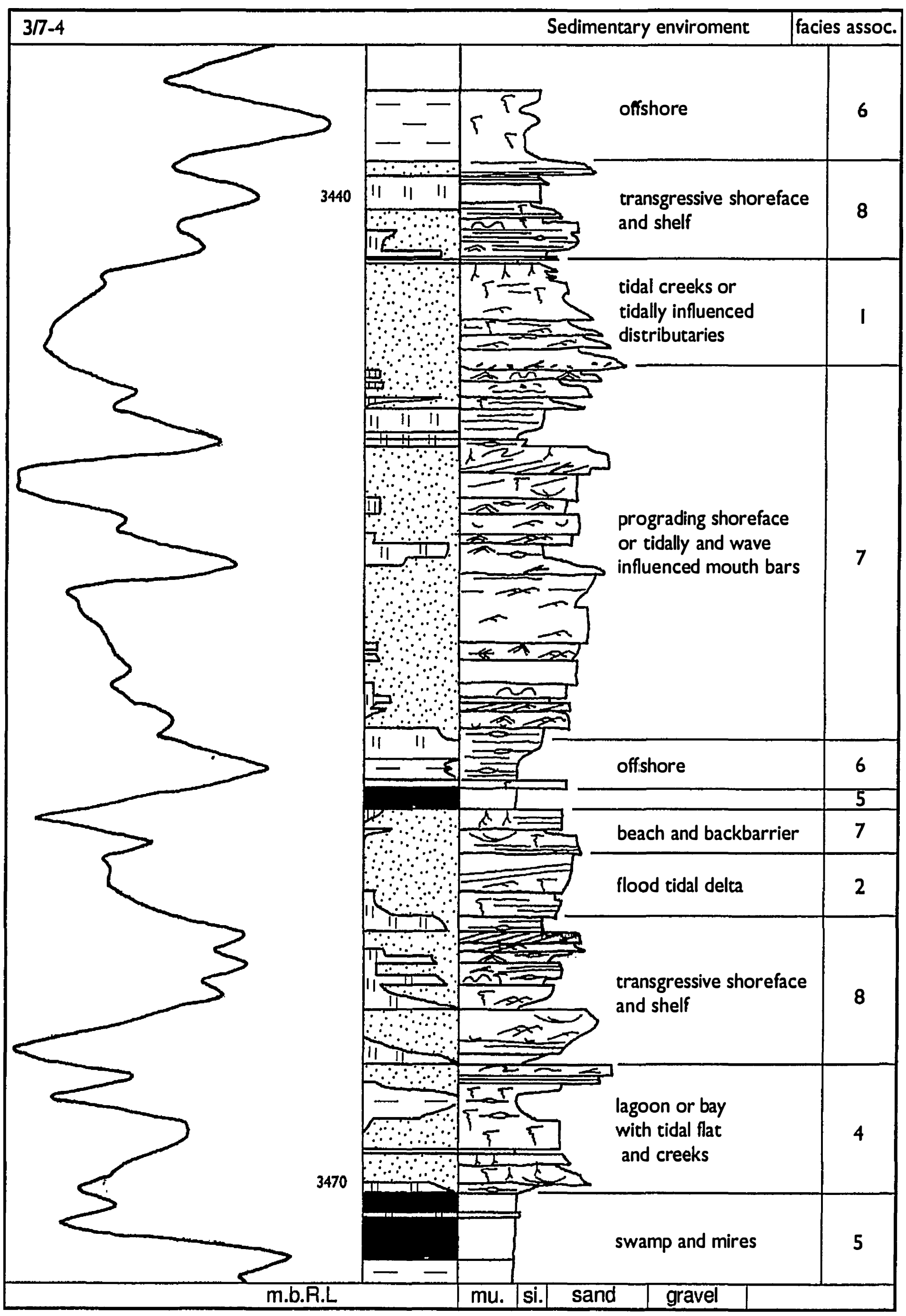

West Lulu-2
Sedimentary enviroment
facies assoc.
transgressive shoreface
8
estuary channels and bars and minor mouth bars
1
lagoon or bay
4
swamp and mires
5
estuary channel
1
estuary central basin and tidal flats
4
3645
tidal creeks and tidally influenced fluvial channels
1
lagoon or bay
4
bay-head delta
3
tidal creeks
1
3660
swamp and mires
5
m.b.R.L
mu.
si.
sand
gravel

Fig.14



3/7-4
Sedimentary enviroment
facies assoc.
offshore
6
3440
transgressive shoreface and shelf
8
tidal creeks or tidally influenced distributaries
1
prograding shoreface or tidally and wave influenced mouth bars
7
offshore
6
5
beach and backbarrier
7
flood tidal delta
2
transgressive shoreface and shelf
8
lagoon or bay with tidal flat and creeks
4
3470
swamp and mires
5
m.b.R.L
mu.
si.
sand
gravel


Fig.15

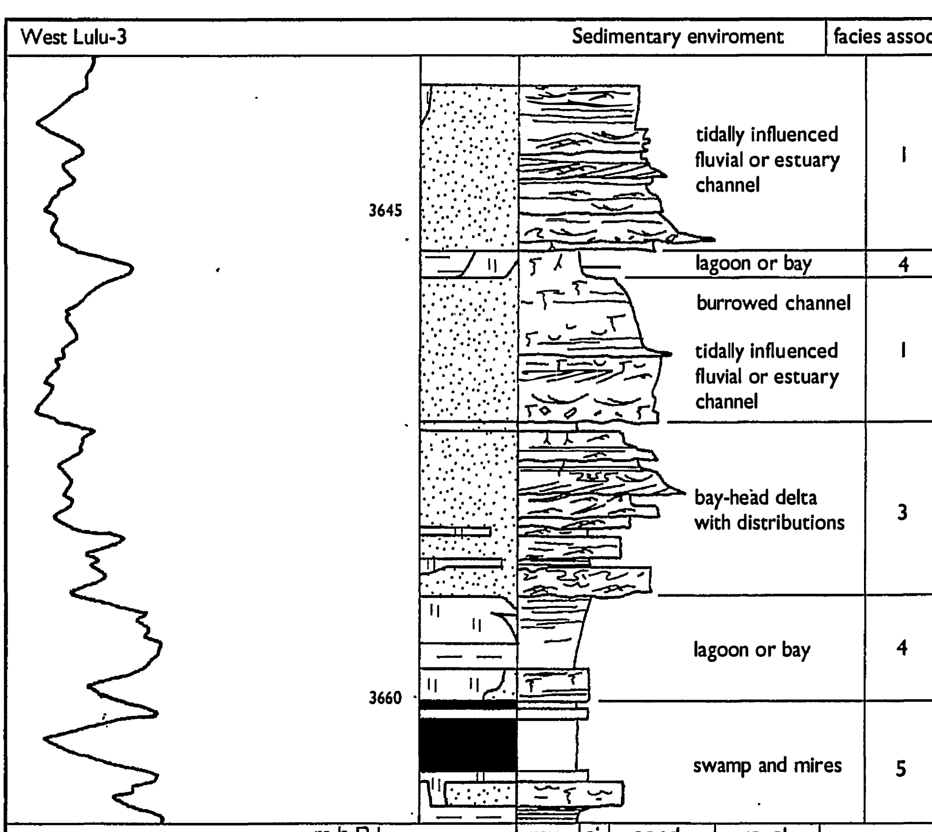

West Lulu-3
Sedimentary enviroment
facies assoc.
3645
3660
tidally influenced fluvial or estuary channel
1
lagoon or bay
4
burrowed channel
tidally influenced fluvial or estuary channel
1
bay-head delta with distributions
3
lagoon or bay
4
swamp and mires
5
m.b.R.L
mu.
si.
sand
gravel

Fig. 16

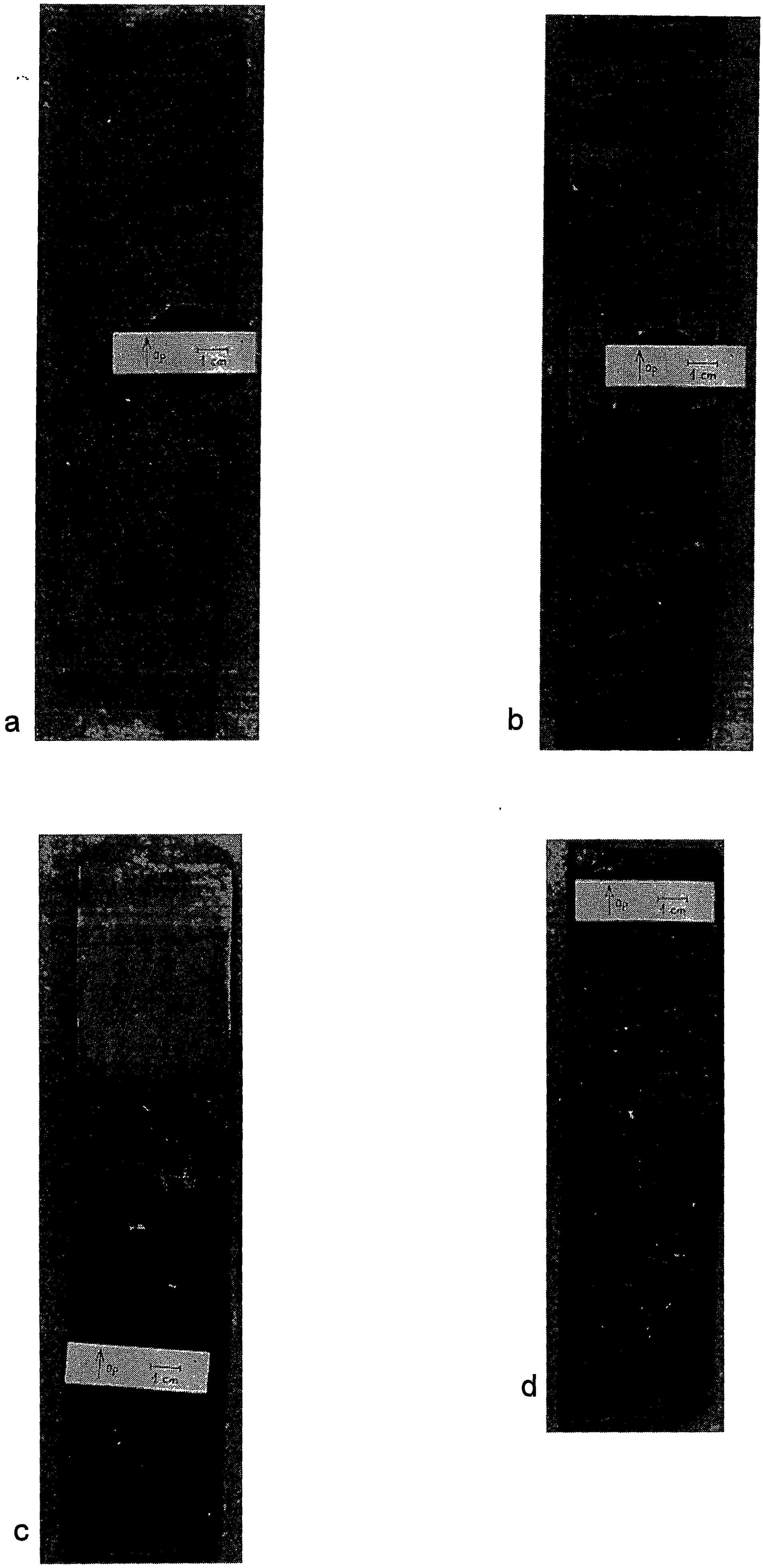
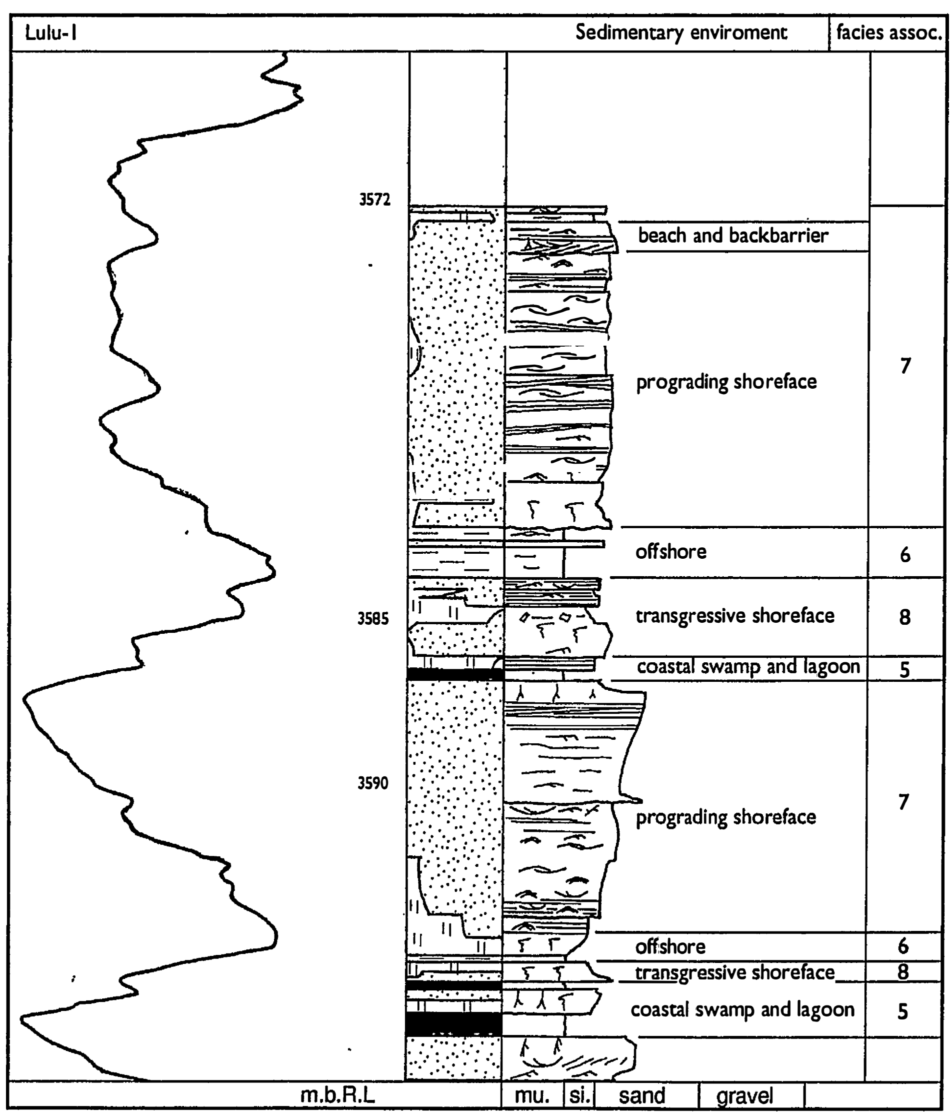



Fig.17



Lulu-1
Sedimentary enviroment
facies assoc.
3572
3585
3590
beach and backbarrier
prograding shoreface
7
offshore
6
transgressive shoreface
8
coastal swamp and lagoon
5
prograding shoreface
7
offshore
6
transgressive shoreface
8
coastal swamp and lagoon
5
m.b.R.L
mu.
si.
sand
gravel


Fig.18

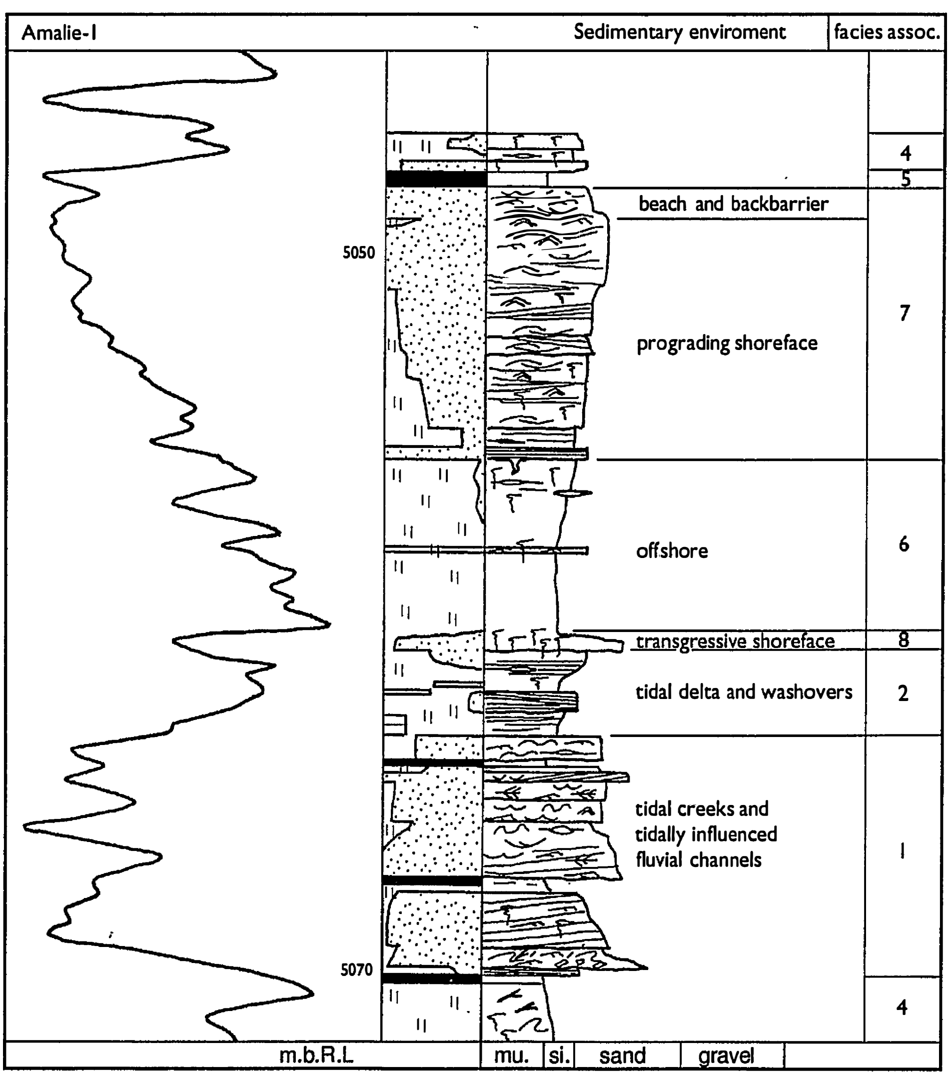
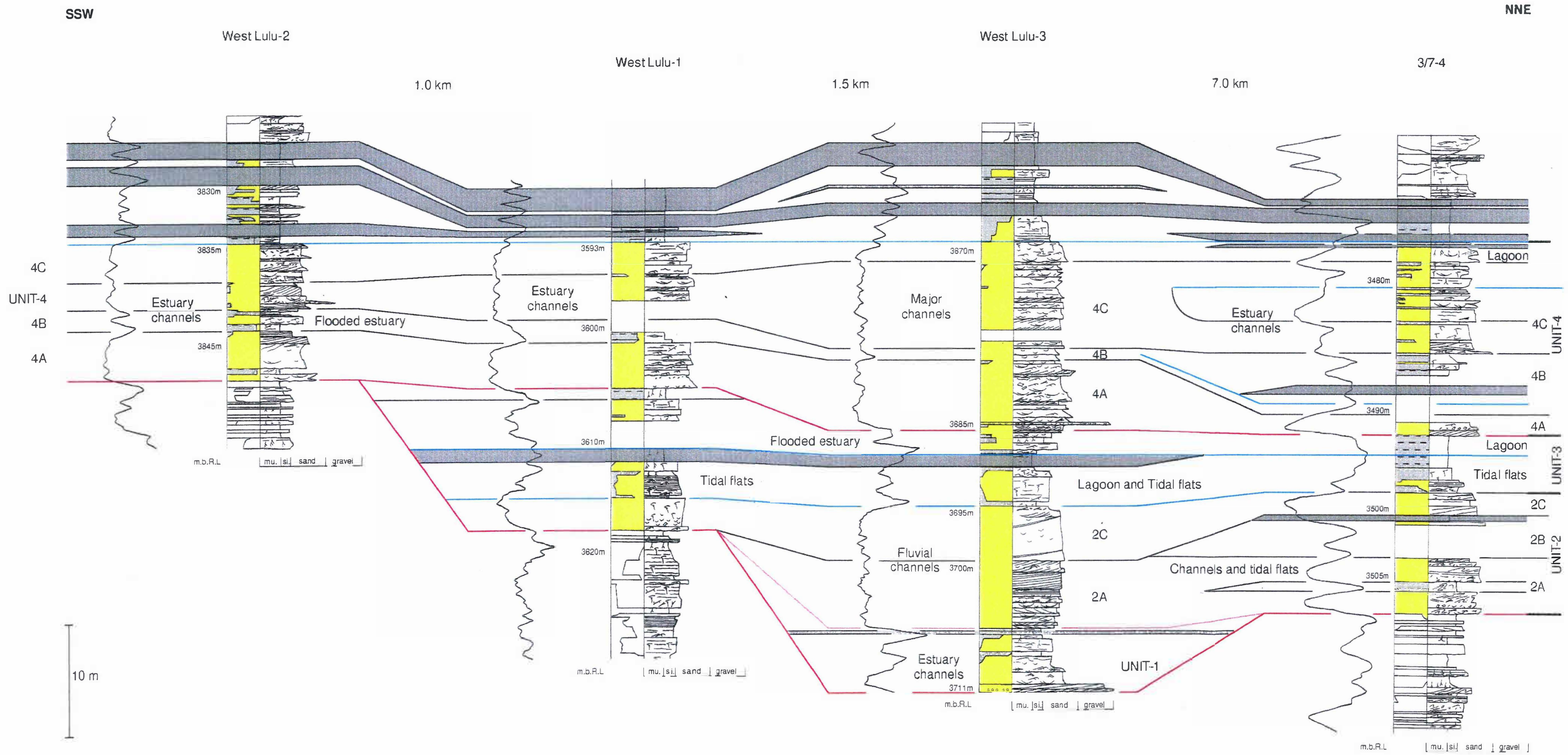
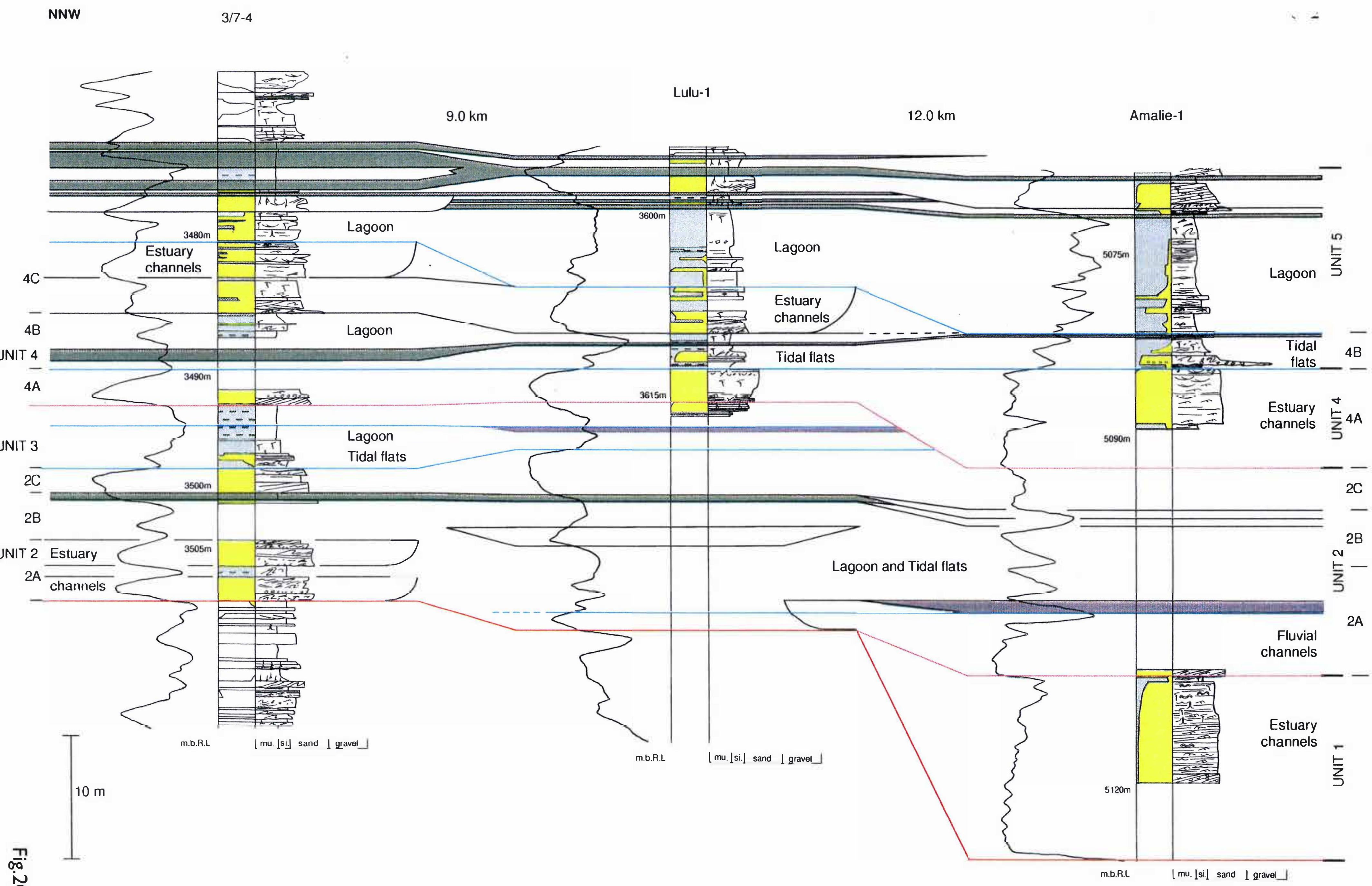

Amalie-1
Sedimentary enviroment
facies assoc.
5050
5070
beach and backbarrier
prograding shoreface
offshore
transgressive shoreface
tidal delta and washovers
tidal creeks and tidally influenced fluvial channels
4
5
7
6
8
2
1
4
m.b.R.L
mu.
si.
sand
gravel

Fig.19


SSW
NNE
West Lulu-2
West Lulu-1
West Lulu-3
3/7-4
1.0 km
1.5 km
7.0 km
4C
UNIT-4
4B
4A
Estuary channels
Flooded estuary
Estuary channels
Major channels
4C
4B
4A
Estuary channels
Lagoon
4C
4B
4A
UNIT-4
Flooded estuary
Tidal flats
Lagoon and Tidal flats
Lagoon
Tidal flats
UNIT-3
2C
2B
2A
UNIT-2
2C
2A
Fluvial channels
Channels and tidal flats
Estuary channels
UNIT-1
10 m
3830m
3835m
3845m
3593m
3600m
3610m
3620m
3670m
3685m
3695m
3700m
3711m
3480m
3490m
3500m
3505m
m.b.R.L
mu. si. sand gravel
Fig.20A



NNW
3/7-4
Lulu-1
9.0 km
12.0 km
Amalie-1
3480m
3490m
3500m
3505m
3600m
3615m
5075m
5090m
5120m
Lagoon
Estuary channels
Lagoon
Lagoon
Tidal flats
Estuary
channels
Lagoon
Estuary channels
Tidal flats
Lagoon and Tidal flats
Lagoon
Tidal flats
Estuary channels
Fluvial channels
Estuary channels
4C
4B
UNIT 4
4A
UNIT 3
2C
2B
UNIT 2
2A
UNIT 5
4B
UNIT 4
4A
2C
2B
UNIT 2
2A
UNIT 1
m.b.R.L
mu. si. sand gravel
10 m


Fig.20B

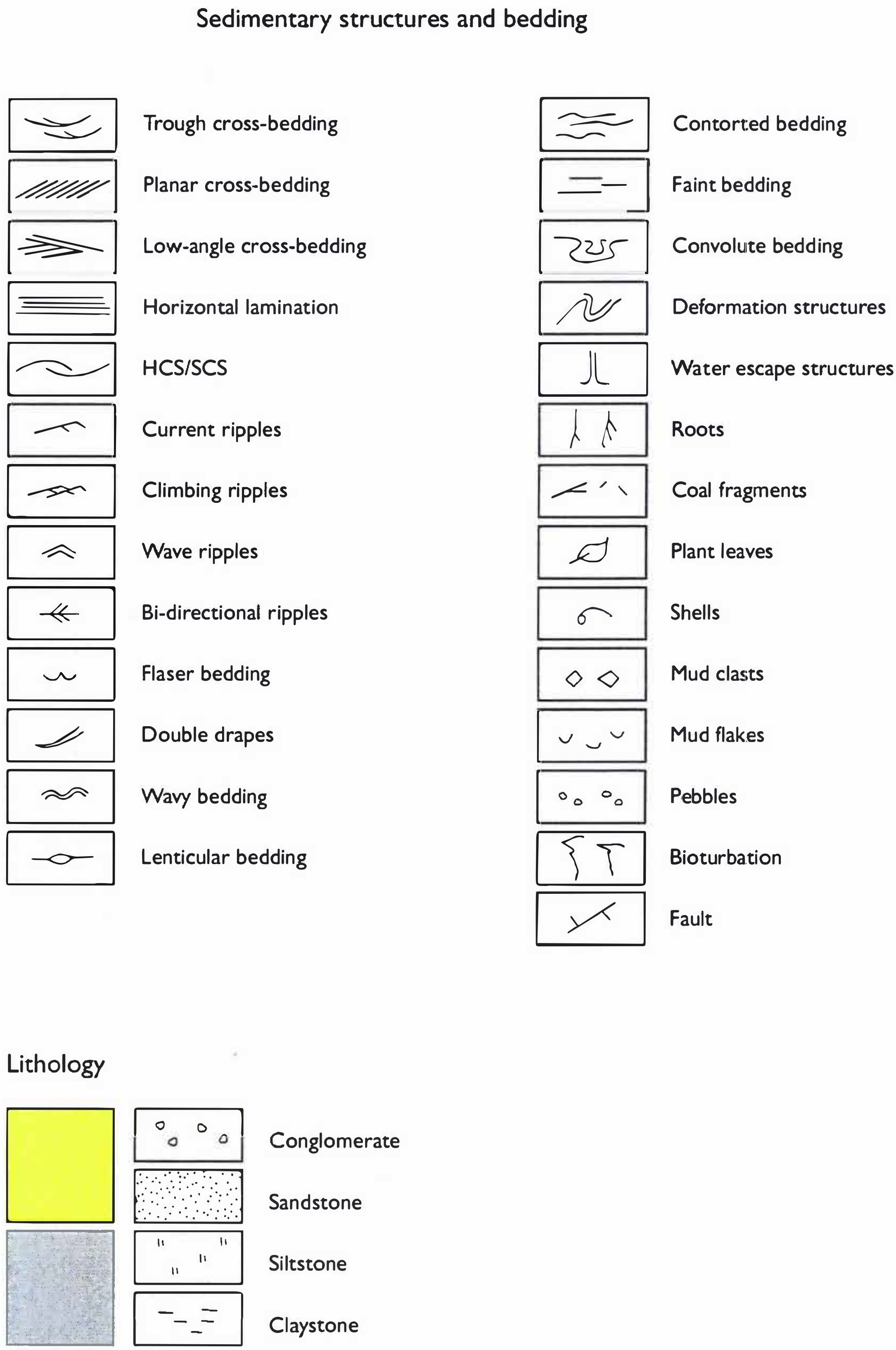

Sedimentary structures and bedding
Trough cross-bedding
Planar cross-bedding
Low-angle cross-bedding
Horizontal lamination
HCS/SCS
Current ripples
Climbing ripples
Wave ripples
Bi-directional ripples
Flaser bedding
Double drapes
Wavy bedding
Lenticular bedding
Contorted bedding
Faint bedding
Convolute bedding
Deformation structures
Water escape structures
Roots
Coal fragments
Plant leaves
Shells
Mud clasts
Mud flakes
Pebbles
Bioturbation
Fault
Lithology
Conglomerate
Sandstone
Siltstone
Claystone

Fig.20C

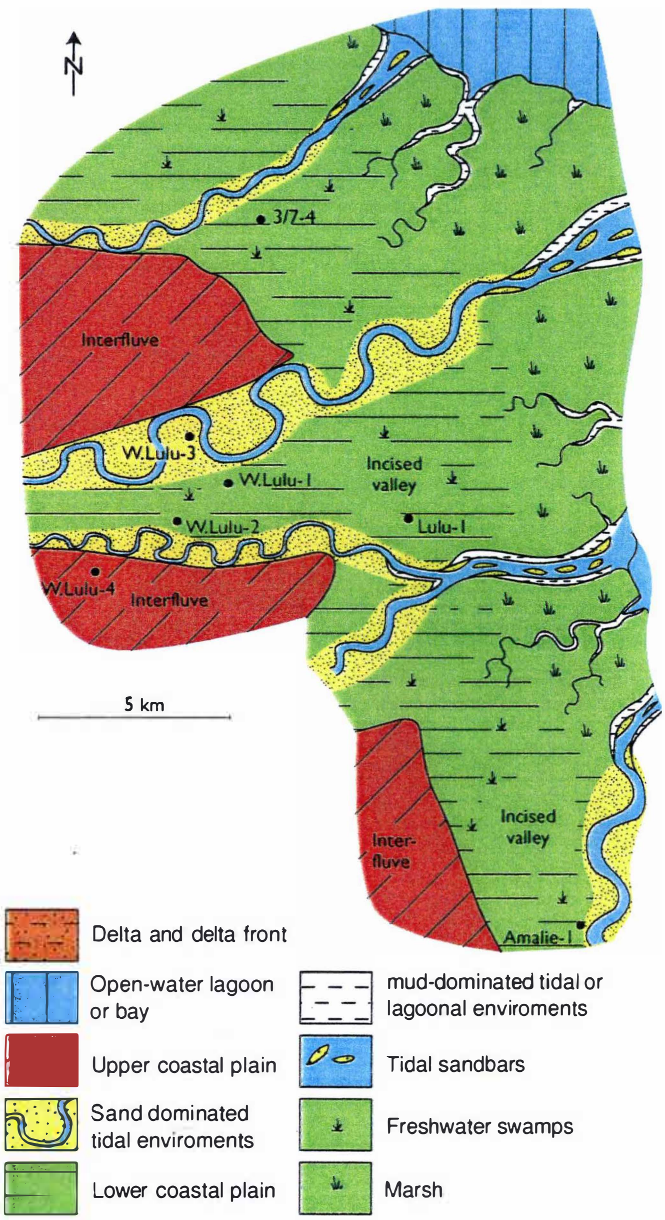
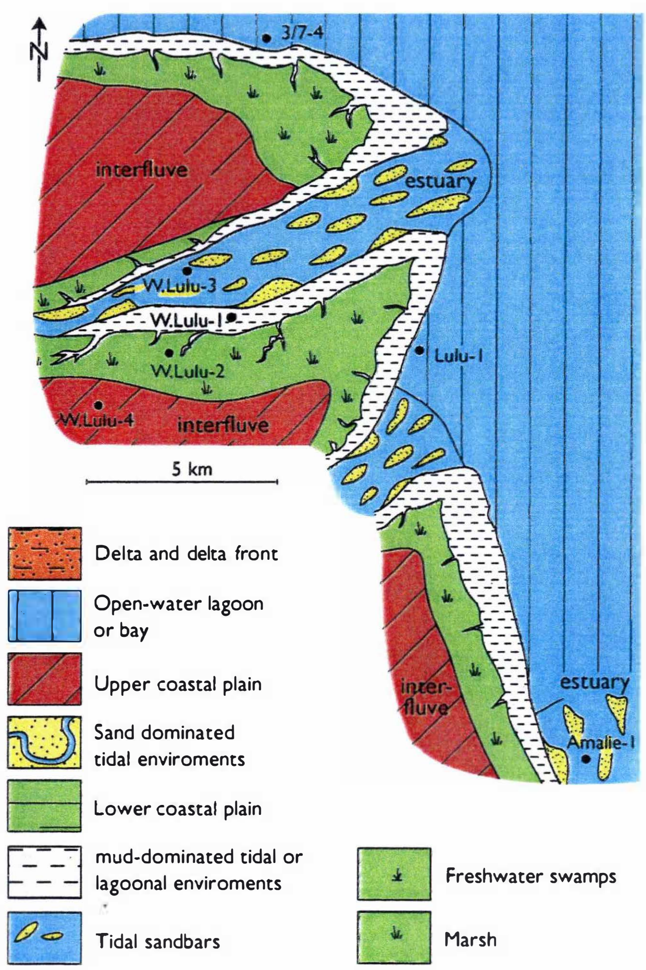

N
3/7-4
Interfluve
W.Lulu-3
W.Lulu-1
Incised valley
W.Lulu-2
Lulu-1
W.Lulu-4
Interfluve
5 km
Inter-fluve
Incised valley
Amalie-1
Delta and delta front
Open-water lagoon or bay
Upper coastal plain
Sand dominated tidal enviroments
Lower coastal plain
mud-dominated tidal or lagoonal enviroments
Tidal sandbars
Freshwater swamps
Marsh

Fig.21

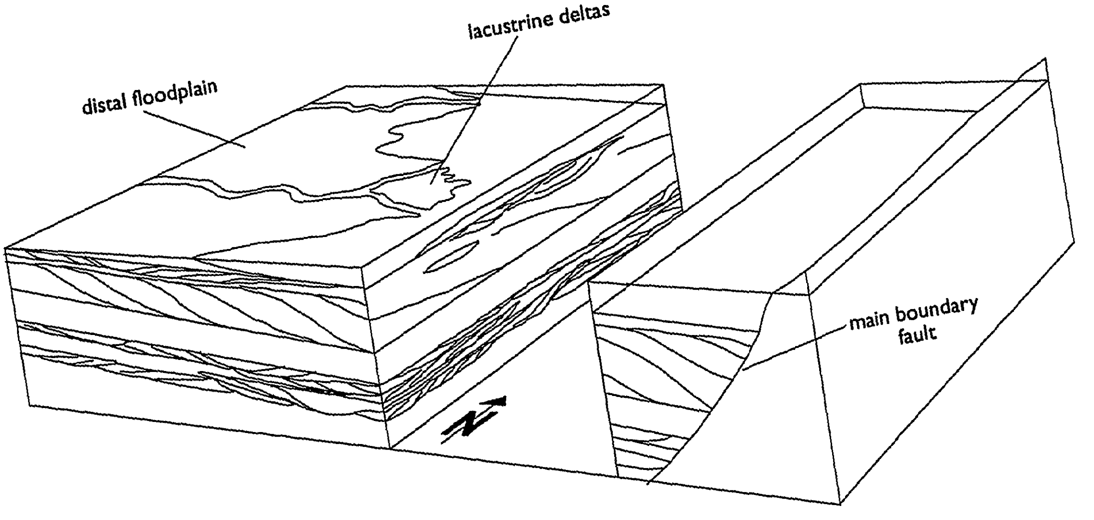


N
3/7-4
interfluve
estuary
W.Lulu-3
W.Lulu-1
W.Lulu-2
Lulu-1
W.Lulu-4
interfluve
5 km
inter-
fluve
estuary
Amalie-1
Delta and delta front
Open-water lagoon
or bay
Upper coastal plain
Sand dominated
tidal enviroments
Lower coastal plain
mud-dominated tidal or
lagoonal enviroments
Tidal sandbars
Freshwater swamps
Marsh


Fig.22

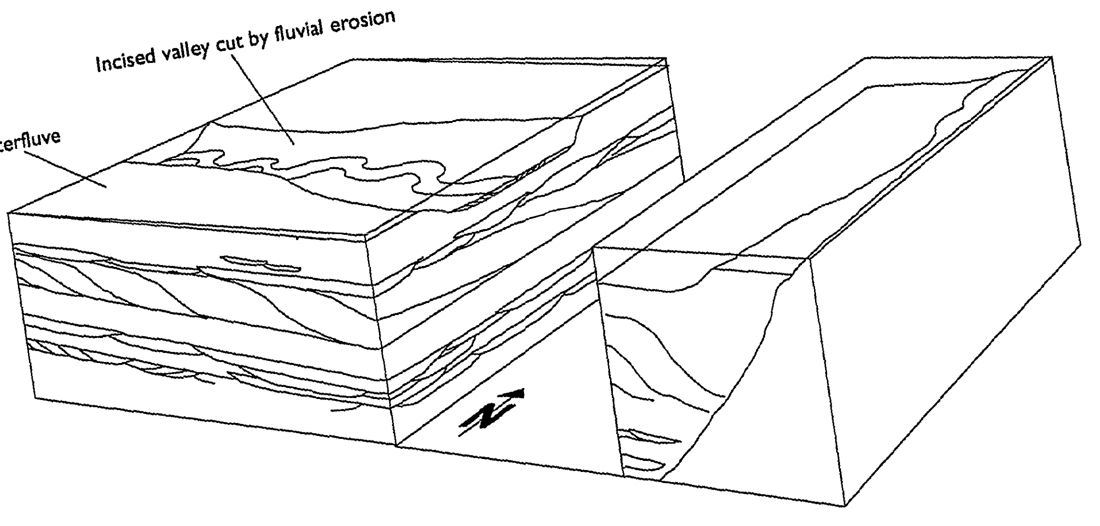
Lacustrine delta progradation - HST

A



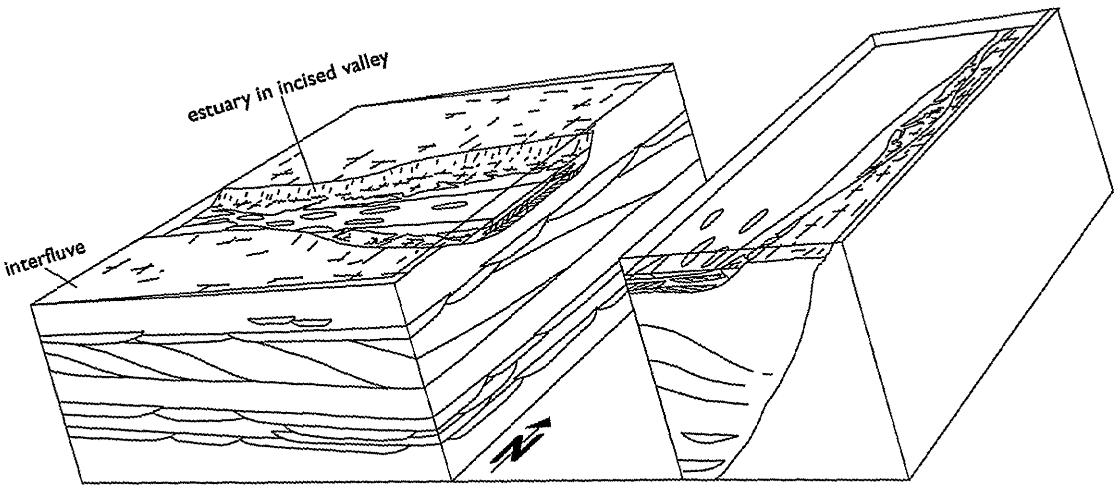

Valley incision - LST

B



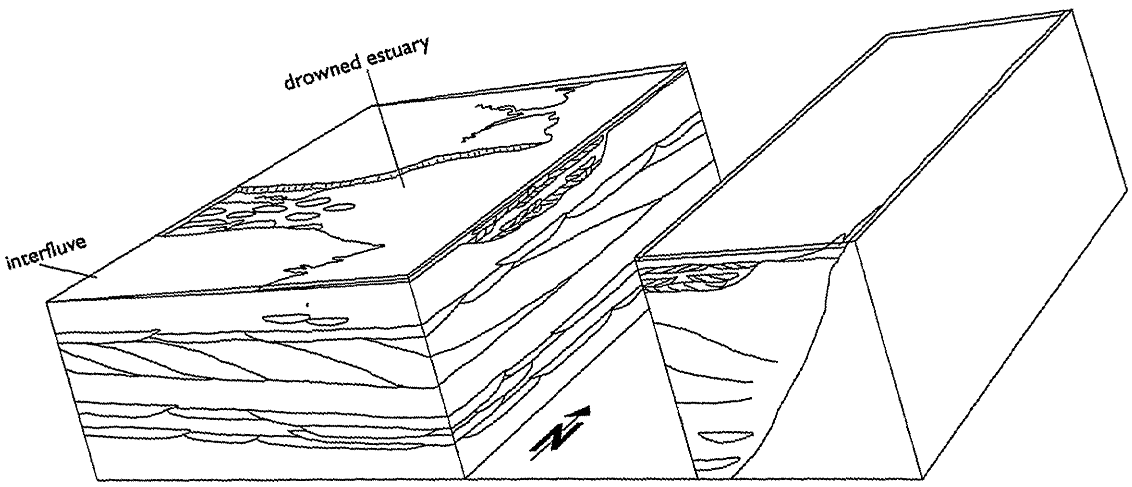
Early valley fill - LST / lower TST

A




Late valley fill - lower TST

B



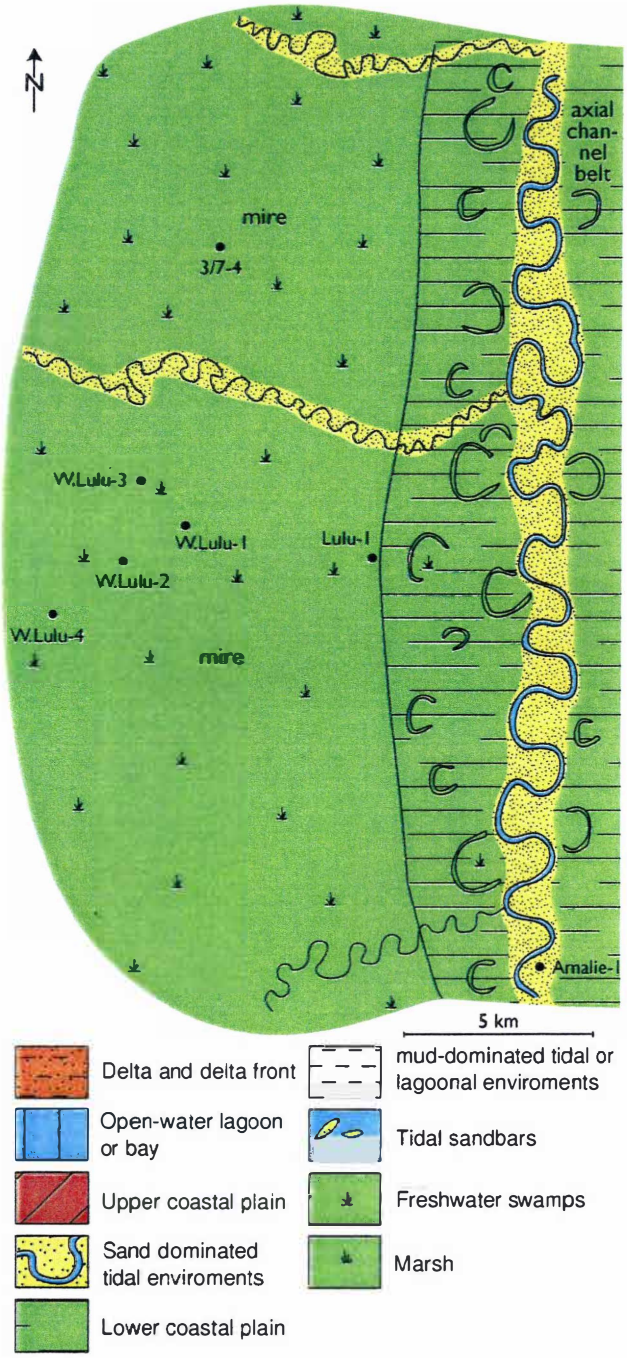
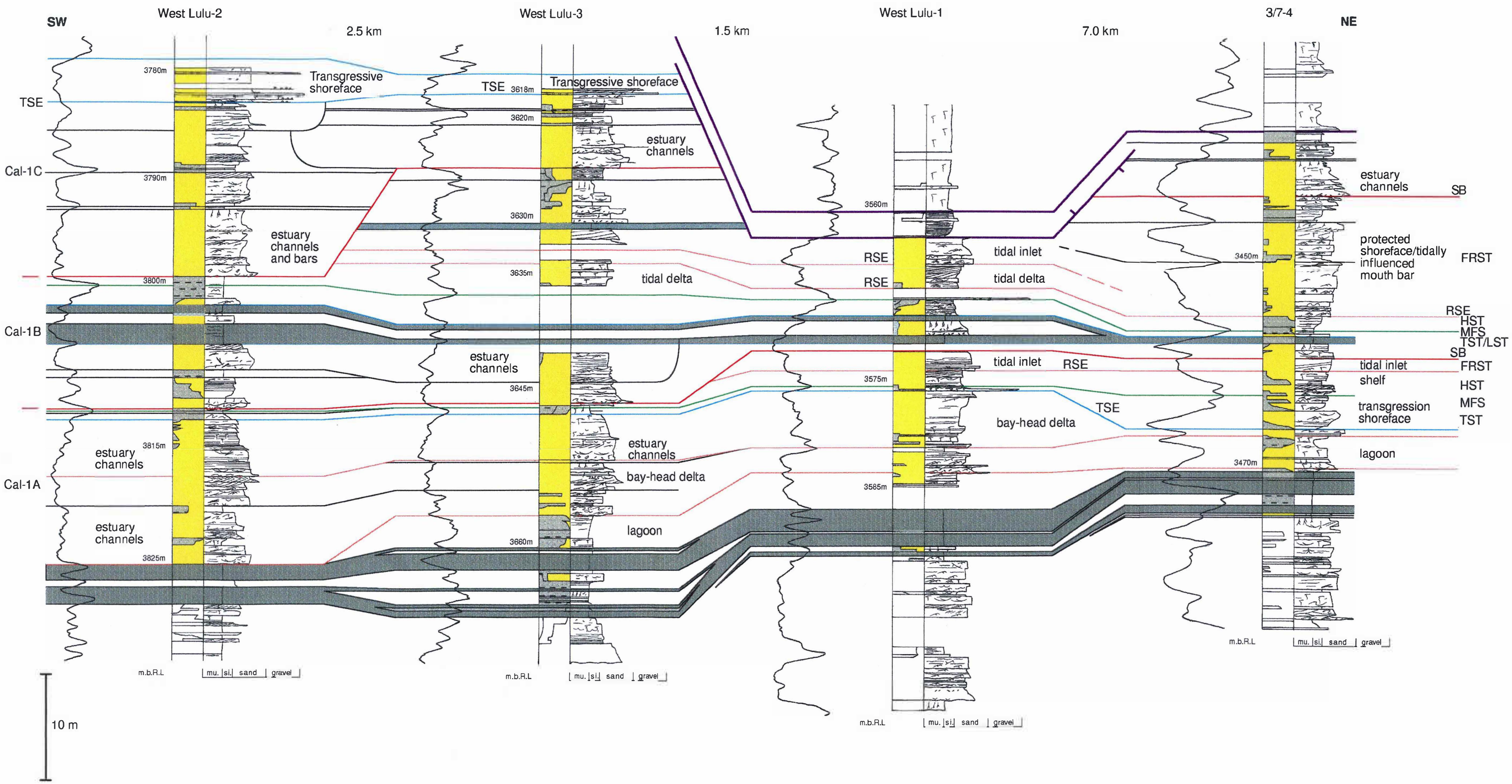

N
mire
3/7-4
axial chan-nel belt
W.Lulu-3
W.Lulu-1
W.Lulu-2
W.Lulu-4
Lulu-1
mire
Amalie-1
5 km
Delta and delta front
Open-water lagoon or bay
Upper coastal plain
Sand dominated tidal enviroments
Lower coastal plain
mud-dominated tidal or lagoonal enviroments
Tidal sandbars
Freshwater swamps
Marsh

Fig.25



SW
West Lulu-2
2.5 km
West Lulu-3
1.5 km
West Lulu-1
7.0 km
3/7-4
NE
TSE
Cal-1C
Cal-1B
Cal-1A
3780m
3790m
3800m
3815m
3825m
Transgressive shoreface
estuary channels and bars
estuary channels
estuary channels
TSE
3618m
3620m
3630m
3635m
3645m
3660m
Transgressive shoreface
estuary channels
tidal delta
estuary channels
estuary channels
bay-head delta
lagoon
3560m
3575m
3585m
RSE
RSE
tidal inlet
tidal delta
tidal inlet
RSE
TSE
bay-head delta
3450m
3470m
estuary channels
SB
protected shoreface/tidally influenced mouth bar
FRST
RSE
HST
MFS
TST/LST
SB
tidal inlet
FRST
shelf
HST
transgression shoreface
MFS
TST
lagoon
m.b.R.L
mu. si. sand gravel
10 m

Fig.26A

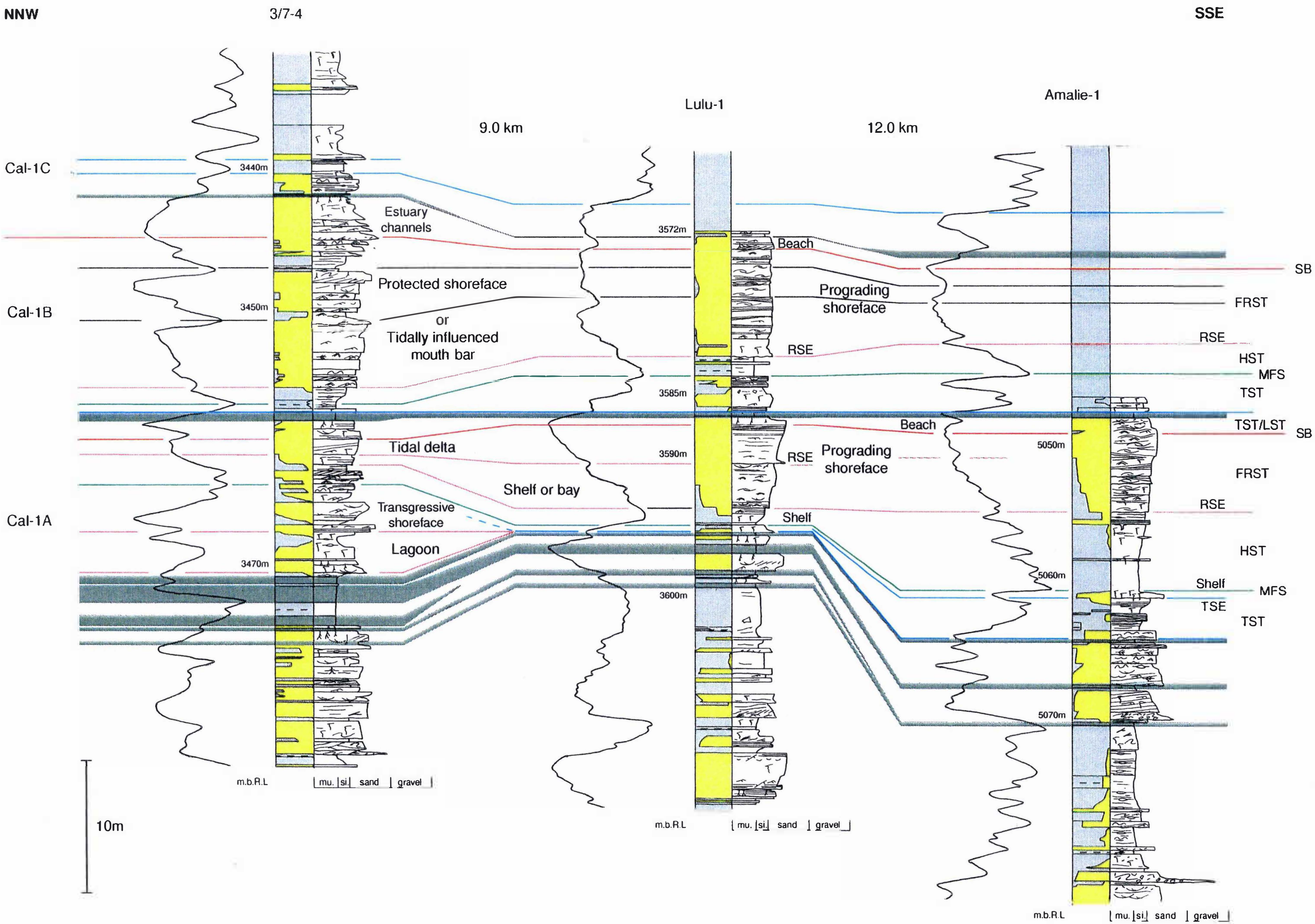

NNW
3/7-4
SSE
Lulu-1
Amalie-1
9.0 km
12.0 km
Cal-1C
Cal-1B
Cal-1A
3440m
3450m
3470m
3572m
3585m
3590m
3600m
5050m
5060m
5070m
Estuary channels
Protected shoreface
or
Tidally influenced mouth bar
Tidal delta
Shelf or bay
Transgressive shoreface
Lagoon
Beach
Prograding shoreface
RSE
Beach
RSE
Prograding shoreface
Shelf
SB
FRST
RSE
HST
MFS
TST
TST/LST
SB
FRST
RSE
HST
Shelf
MFS
TSE
TST
10m
m.b.R.L
mu. si. sand gravel
m.b.R.L
mu. si. sand gravel
m.b.R.L
mu. si. sand gravel

Fig.26B

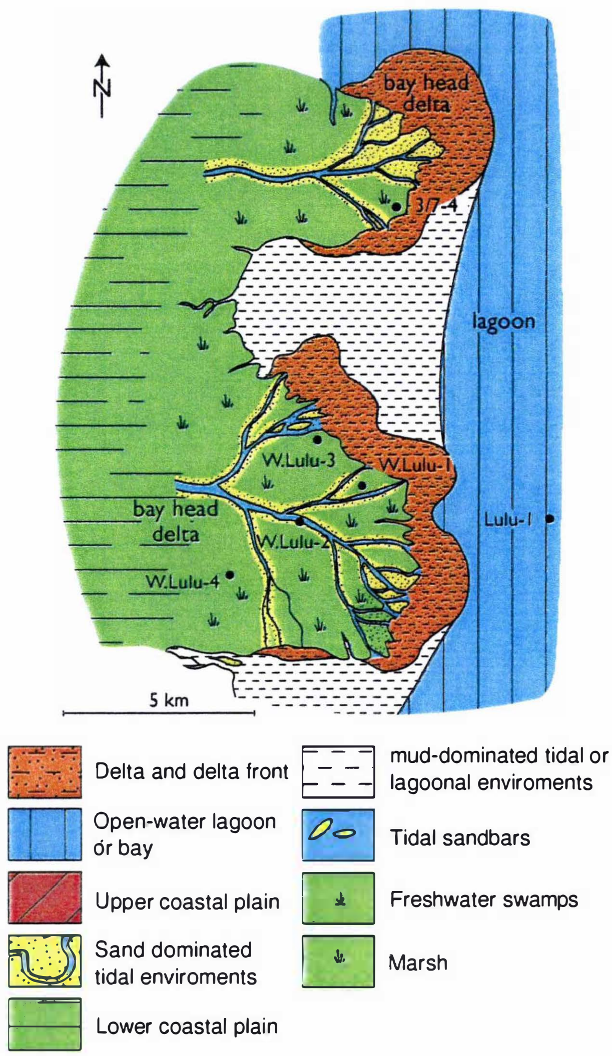

N
bay head delta
3/7-4
lagoon
W.Lulu-3
W.Lulu-1
bay head delta
Lulu-1
W.Lulu-2
W.Lulu-4
5 km
Delta and delta front
mud-dominated tidal or lagoonal enviroments
Open-water lagoon or bay
Tidal sandbars
Upper coastal plain
Freshwater swamps
Sand dominated tidal enviroments
Marsh
Lower coastal plain

Fig.27

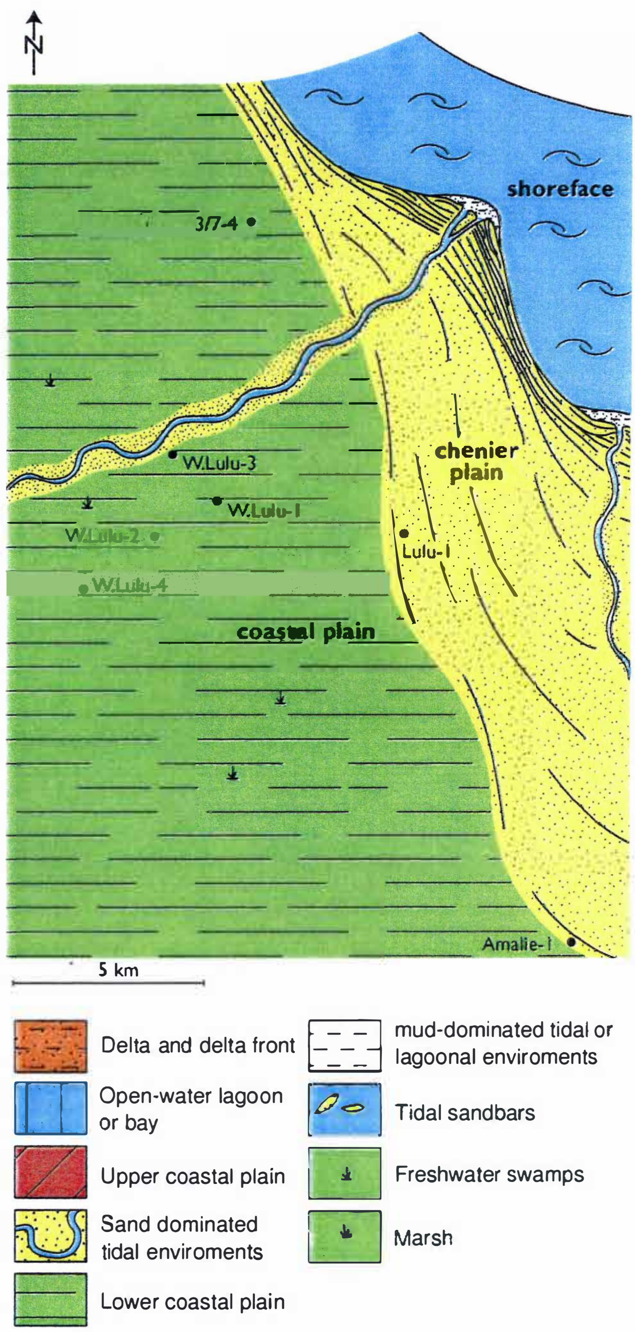

N
shoreface
3/7-4
chenier plain
W.Lulu-3
W.Lulu-1
W.Lulu-2
W.Lulu-4
Lulu-1
coastal plain
Amalie-1
5 km
Delta and delta front
Open-water lagoon or bay
Upper coastal plain
Sand dominated tidal enviroments
Lower coastal plain
mud-dominated tidal or lagoonal enviroments
Tidal sandbars
Freshwater swamps
Marsh

Fig.28

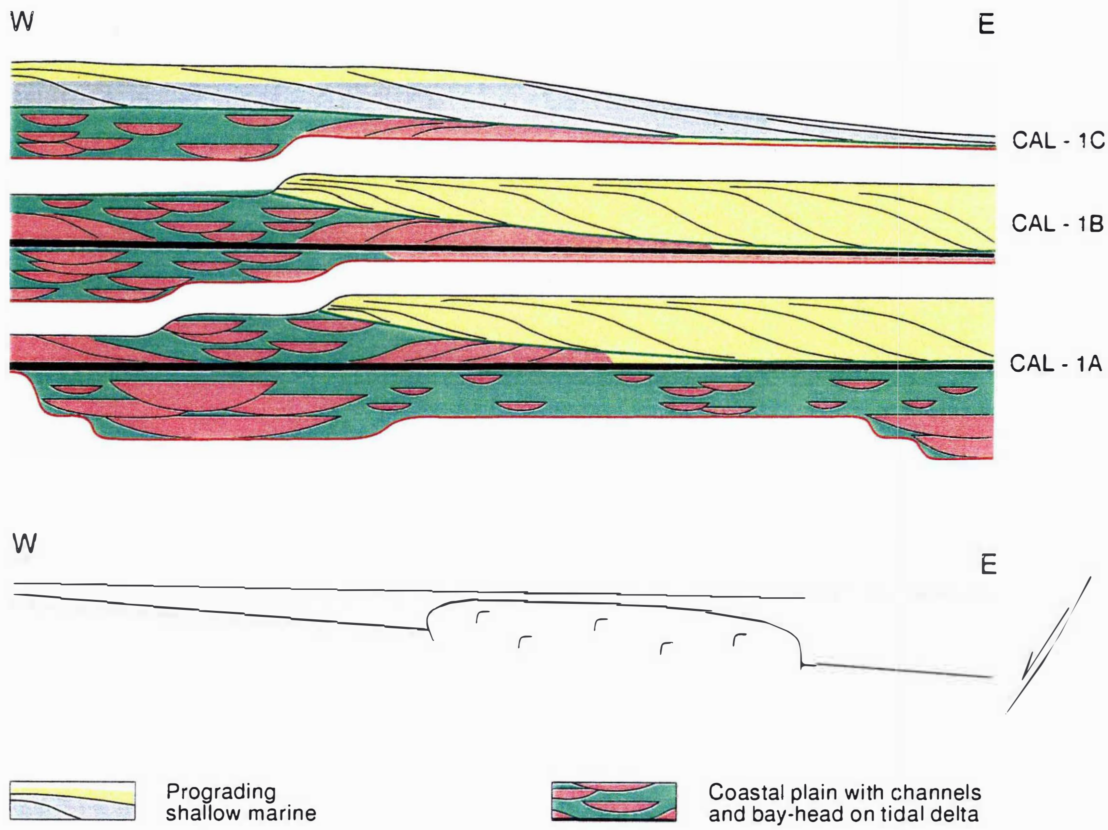
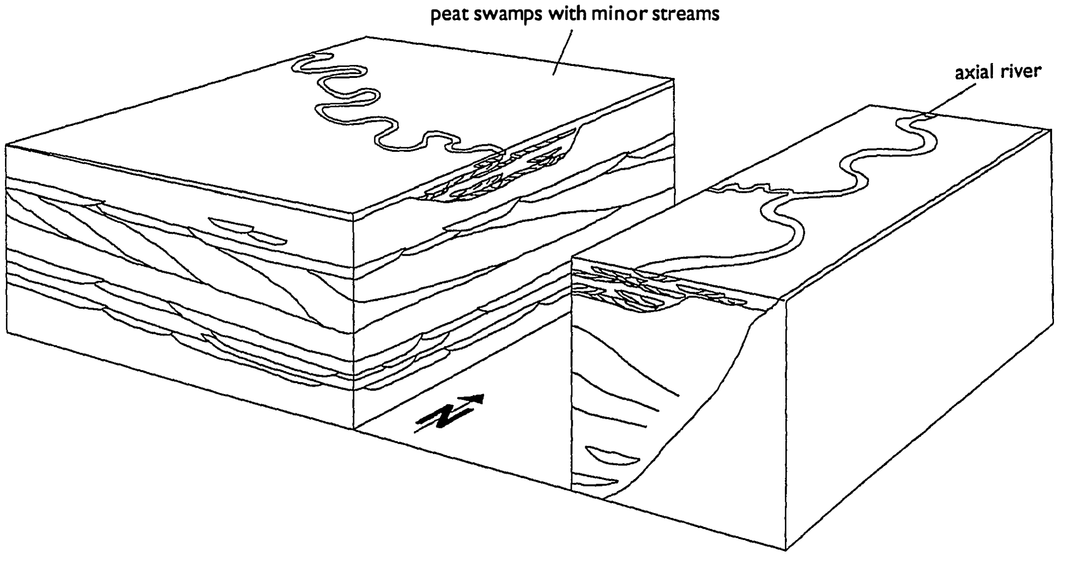

W
E
CAL - 1C
CAL - 1B
CAL - 1A
W
E
Prograding shallow marine
Coastal plain with channels and bay-head on tidal delta

Fig.29

A

## Peat cap formation




B

## Transgression - upper TST / early flooding

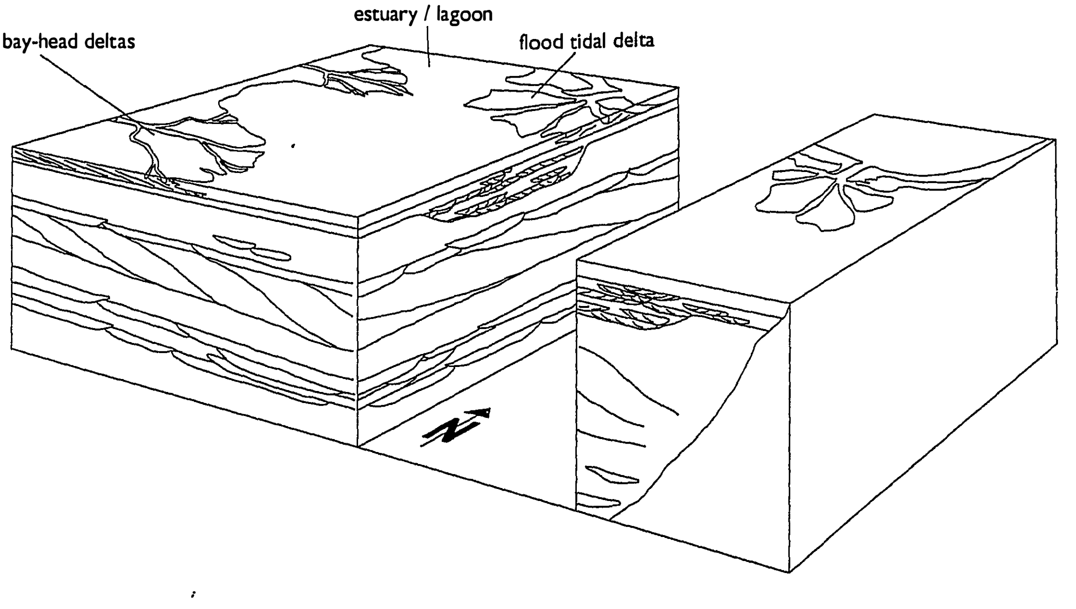
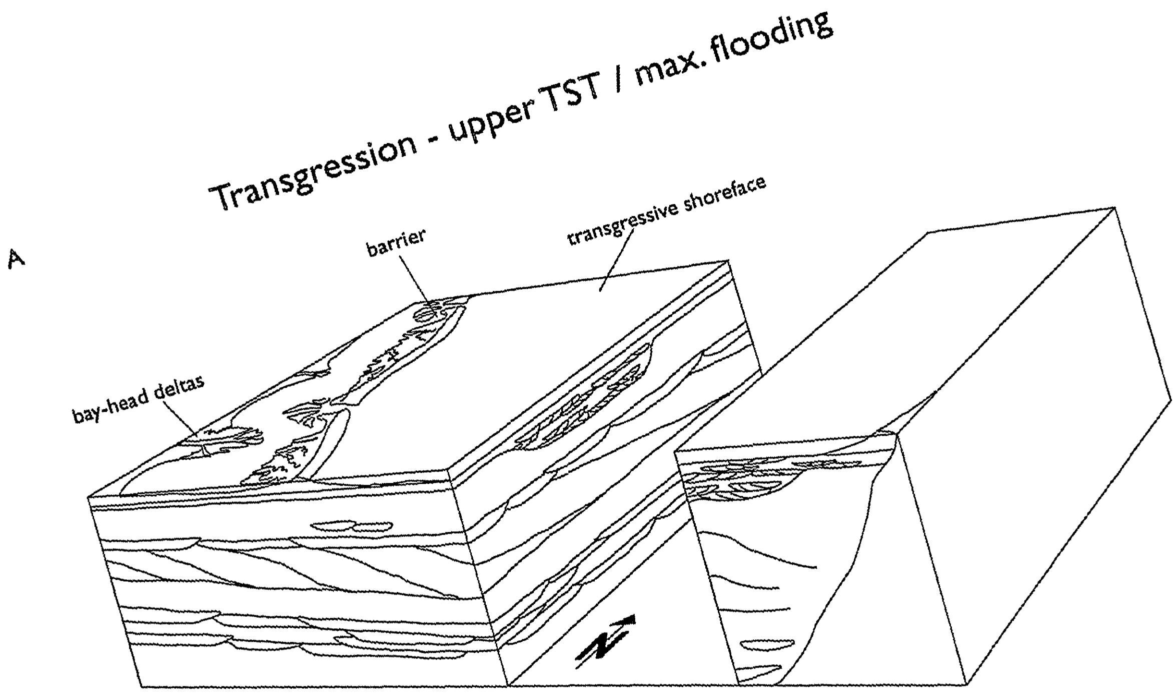
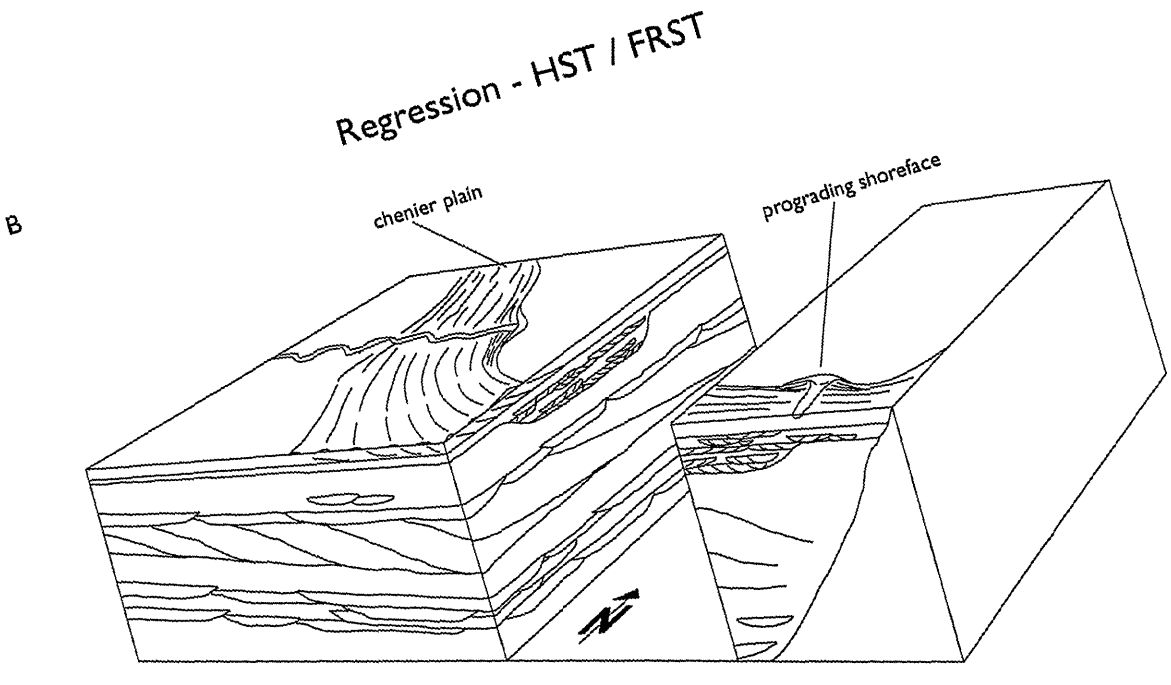



Fig.30


Transgression - upper TST / max. flooding
A
barrier
transgressive shoreface
bay-head deltas


Regression - HST / FRST
B
chenier plain
prograding shoreface

Fig

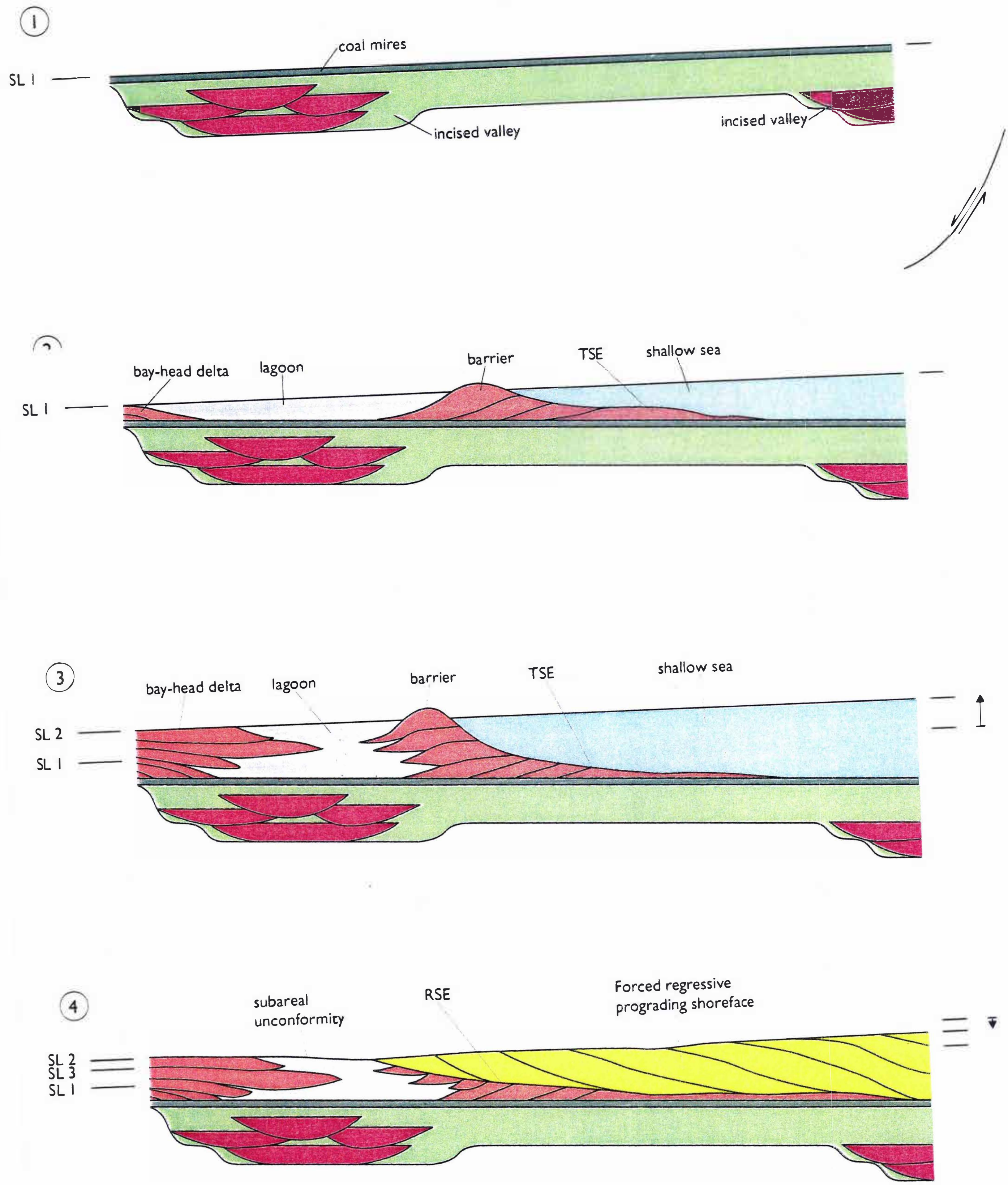

1
coal mires
SL 1
incised valley
incised valley
bay-head delta
lagoon
barrier
TSE
shallow sea
SL 1
3
bay-head delta
lagoon
barrier
TSE
shallow sea
SL 2
SL 1
4
subareal
unconformity
RSE
Forced regressive
prograding shoreface
SL 2
SL 3
SL 1

Fig.32

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/68

# Sedimentology and sequence stratigraphy of Middle Jurassic deposits

## Danish and Norwegian Central Graben
## Part 4

Jan Andsbjerg

Ph.D. Thesis, University of Copenhagen,
Geological Institute

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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# Middle Jurassic palaeogeography of the Danish Central Graben, southern North Sea

Jan Andsbjerg

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

# Middle Jurassic palaeogeography of the Danish Central Graben; southern North Sea

Jan Andsbjerg

# Contents

## Abstract

A sequence stratigraphic framework for the Middle Jurassic succession in the Danish Central Graben was used as basis for the subdivision of the succession into six correlatable map units, and a palaeogeographic map was constructed for each unit. Each map was constructed using the available core and log data for environmental interpretations and the sparse biostratigraphy and sequence stratigraphic key-horizons picked on logs and in cores for correlations. Units 1 through 3 show an expanding alluvial plain dominated basin with variable fluvial and lacustrine influence. Unit 4 is dominated by braided rivers upstream and large meandering rivers and estuaries downstream reflecting a major sea-level fall and renewed rise. Units 5 and 6 represents a gradual north to south marine transgression across a coastal plain dominated by lagoonal, lacustrine, low-energy fluvial and mire environments. A comparison with the Middle Jurassic succession elsewhere in the southern and central North Sea region suggests that the final Callovian transgression of the Central Graben may have started in the Søgne Basin area coming either through the deepest trough of the Danish Subbasin or through the northern subbasins of the Norwegian - Danish Basin.

## Introduction

Middle Jurassic deposits are abundant throughout the North Sea Rift System from East Greenland and the Mid Norwegian shelf in the north to the Central Graben in the south (fig.1). In the Viking Graben, where Middle Jurassic sandstones constitute the largest oil and gas reservoirs of the North Sea region, Middle Jurassic stratigraphy, depositional history and palaeogeography have been comprehensively described. However, the somewhat smaller sandstone reservoirs of the Middle Jurassic in the southern North Sea have generated much less interest. In the Danish Central Graben a palaeogeography based on the few wells available then was published by Koch (1983). Michelsen et al. (1987) produced an overview of the depositional history. The present work is partly based on the sequence stratigraphic framework and palaeogeography of the Danish Central Graben presented by Andsbjerg and Dybkjær (in prep.), and on the detailed palaeogeography and high resolution sequence stratigraphy of the Middle Jurassic in the Søgne Basin published by Andsbjerg (in prep.).

## Structural setting

The Danish Central Graben is part of the Central Graben (fig. 1), a complex N - S trending Mesozoic intra-cratonic rift basin. It was initiated in the Triassic and was most active during the Middle and Late Jurassic (Møller, 1986). The Central Graben separates the Mid North Sea High to the west from the East North Sea Block of the Ringkøbing -Fyn High to the east. The development of the Danish Central Graben was determined by differential subsidence of grabens and basins along N - S and NW - SE trending faults.

Subsidence of the Danish Central Graben started in the north-eastern part of the area, where the Søgne Basin and Tail End Graben began to subside as separate half-grabens during the Middle Jurassic (Gowers and Sæbøe, 1985; Møller, 1986). Initiation of rift-associated subsidence was probably related to domal uplift and subsequent dome collapse in the North Sea area (Ziegler, 1982,1990; Underhill and Partington, 1993a, 1993b). Most authors agree that asymmetric subsidence was initiated in the Søgne Basin in connection with boundary fault activity during the Middle Jurassic (e.g. Gowers and Sæbøe, 1985, Møller, 1986; Cartwright, 1991; Michelsen et al., 1992, Korstgaard et al., 1993). Middle Jurassic subsidence happened mainly along N - S trending faults inherited from the pre-Jurassic, especially along segments of the Coffee Soil Fault (fig. 2). In accordance with the model for rift basin subsidence presented by Prosser (1993) and adapted by Nøttvedt et al. (1995) early subsidence may have taken place during a rift initiation sub-stage at a number of more widely spaced faults with a smaller amount of throw each. However, evidence for Middle Jurassic deposition beyond the boundaries of the rift climax basin will largely have been obliterated by erosion of uplifted rift shoulders.

Salt structures were generated in the Søgne Basin in the Triassic (Mogensen et al., 1992). Subsidence and faulting in Middle Jurassic times initiated the development of boundary fault salt pillows and updip salt structures in the southern Søgne Basin.

## Lithostratigraphic units

A formal lithostratigraphy for the Middle Jurassic was published by Jensen et al. (1986). All Middle Jurassic deposits of the Søgne Basin in the north-eastern part of the Danish Central Graben were referred to the Bryne Formation (fig. 3), which had previously been established in the Norwegian Central Graben by Vollset and Dorè (1984). In the southern part of the Danish Central Graben the Middle Jurassic deposits were referred to the Central Graben Group (fig. 3), defined in the Dutch Central Graben by NAM and RGD (1980).

### The Bryne Formation

Middle Jurassic sandstones with interbedded mudstones and coals were encountered by the first exploration well in the Danish part of the Søgne Basin, Lulu-1 (fig. 2). Similar deposits encountered in the Norwegian part of the Central Graben were included in the Bryne Formation.

In the Søgne Basin the Bryne Formation is separated from Triassic and Permian deposits by a major unconformity. The Bryne Formation is conformably overlain by marine mudstones of the Upper Jurassic Lola Formation and unconformably by Cretaceous deposits on structural highs (Jensen et al., 1986). The Bryne Formation shows thicknesses from 130 to 300 metres in wells in the Danish part of the Søgne Basin. Seismic data suggest that the Bryne Formation may attain larger thicknesses in the deepest parts of the basin.

A detailed sedimentological analysis of cores from the Lulu-1 well was published by Frandsen (1986), who interpreted the sediments as deposits of a deltaic interdistributary bay overlain by coastal sediments. Middle Jurassic deposits further south in the Danish Central Graben had previously been interpreted as alluvial plain and delta plain deposits by Koch (1983). Damtoft et al. (1992) suggested a fluvial channel and floodplain environment for the Bryne Formation, whereas Johannessen and Andsbjerg (1993) interpreted alluvial plain deposits overlain by tidal and shallow marine deposits. Andsbjerg (in prep.) who presents a high resolution sequence stratigraphy for the Bryne Formation has interpreted it as alluvial or fluvially dominated coastal plain deposits in the lower part of the formation separated from mainly estuarine and shallow marine deposits at the top by fluvial and estuarine incised valley deposits.

### Central Graben Group

The deposits of the Central Graben Group in the southern part of the Danish Central Graben were interpreted as alluvial plain and delta plain deposits by Koch (1983). In the paper by Andsbjerg and Dybkjær (in prep.) the Central Graben Group is interpreted as alluvial plain deposits overlain by low-energy coastal plain deposits being gradually transgressed.

The Central Graben Group in the Danish Central Graben is subdivided into the Lower Graben Sand Formation and the Middle Graben Shale Formation (Jensen et al., 1986). The Lower Graben Sand Formation is dominated by sandstones interbedded with siltstone, mudstone and minor beds of conglomerate and coal. The Lower Graben Sand Formation may attain thicknesses of at least 170 m. The Middle Graben Shale Formation consists of siltstone interbedded with mudstone, coal and thin sandstone beds, and it may be up to 50 m thick.

Whereas the Bryne Formation in the Danish Central Graben is defined in the Søgne Basin, and the Central Graben Group is defined for deposits in the Salt Dome Province and the southern Tail End Graben, the Nora-1 well in the northern Tail End Graben shows similarities with both lithostratigraphic units. The Middle Jurassic succession of that well can, with exception for the lowermost and uppermost units, be correlated in detail to the Bryne Formation in the Søgne Basin, and the overall log patterns can be correlated to the Central Graben Group. However, the only good correlative to the uppermost part of the succession in Nora-1 is found in the Middle Graben Shale Formation in the southern part of the Danish Central Graben.

## Correlations and sequence stratigraphic framework

### Biostratigraphic datings

The Middle Jurassic of the central and southern North Sea generally has a poor biostratigraphic resolution. This is due both to the predominance of non-marine facies, and to degrading of palynomorphs at the large depths where Middle Jurassic deposits are encountered. In the Danish Central Graben correlations cannot be based on biostratigraphic markers; but the few datings available put some constraints on the log correlations.

In the northern part of the Danish Central Graben the upper part of the Bryne Formation is reasonably well dated in a few wells by dinoflagellate cysts found in marine and estuarine deposits (Andsbjerg and Dybkjær, in prep.). Above the major sequence boundary, which separates the fluvial dominated succession of the lower Bryne Formation from the predominantly paralic and marginal marine deposits of the upper Bryne Formation in this area (Andsbjerg, in prep.), the Bryne Formation shows Late Bathonian - Late Callovian ages. The occurrence of the dinoflagellate cysts *Cleistosphaeridium varispinosum* and *Nannoceratopsis gracilis* in incised valley fills right above the sequence boundary suggests that the valley fill was deposited in the Late Bathonian - earliest Callovian. The presence of *Dissilodinium willei* in the section above the incised valley fill deposits suggests a Middle Callovian age for that interval, and the occurrence of *Ctenidodinium continuum*, *Liesbergia scarburghensis* and *Meiourogonyaulax* cf. *caytonensis* near the top of the Bryne Formation indicates a latest Callovian - earliest Oxfordian age (Andsbjerg and Dybkjær, in prep.). In the uppermost part of the succession below the major sequence boundary does the presence of the dinocyst *Adnatosphaeridium caulleryi* suggest an age not older than the Bathonian (Andsbjerg and Dybkjær, in prep.). This evidence in combination with the Late Bathonian ages above the sequence boundary indicates, that sequence boundary incision took place during the Bathonian; probably during the later part of the Bathonian. The occurrence of *Scriniocassis* sp. in the lowermost Bryne Formation indicates an age not younger than the Late Bajocian for that interval (Andsbjerg and Dybkjær, in prep.).

In the southern part of the Danish Central Graben where wells with successions of the Central Graben Group are not as closely spaced as the wells with Bryne Formation sediments in the northern part of the study area, are good biostratigraphic datings are even more sparse. A few good datings are supplied by age diagnostic spores. *Krauselisporites hyalina* in the upper part of the Lower Graben Sand Formation suggests a Bathonian age, and *Kekryphalospora distincta* lower in that formation indicates an age not younger than Early Bajocian. A few dinoflagellate cysts have been found in the Lower Graben Sand Formation. In the upper part of the formation the Late Bajocian - basal Callovian *Pareodynia evitii* has been found below an erosive channel base, which is supposed to correlate to the major sequence boundary separating the upper and lower Bryne Formation (Andsbjerg and Dybkjær, in prep.).

In the uppermost part of the succession, the coal-bearing Middle Graben Shale Formation *Chytroeisphaeridia hyalina* and *Ctenidodinium sellwoodii* are found in beds not younger than Mid or Late Callovian respectively; whereas *Energlynia acollaris* and *Wanaea thyssanota* may range into the Early Oxfordian (Andsbjerg and Dybkjær, in prep.). Also found within this section are *Pareodinia prolongata* and *Rigaudella aemula* which may range up to the Middle Oxfordian (Andsbjerg and Dybkjær, in prep.).

## Sequence stratigraphy

The sequence stratigraphic terminology applied is that introduced by the EXXON group (e.g. Posamentier et al. 1988; Posamentier and Vail 1988; Van Wagoner et al. 1988, 1990). In the sequence stratigraphic on which this paper is based (Andsbjerg, in prep.) sequences are subdivided into the lowstand, transgressive, highstand and forced regressive systems tract following the modifications to the EXXON-model suggested by Hunt and Tucker (1992). Key surfaces are sequence boundary (SB), flooding surface (FS), maximum flooding surface (MFS), transgressive surface of erosion (TSE) and regressive surface of erosion (RSE).

## Log based sequence stratigraphic framework

Although biostratigraphic datings alone do not allow basin-wide correlations, log-based correlations supported by biostratigraphic data are possible in most of the study area. With the exception of wells where the Middle Jurassic succession is strongly condensed due to the structural position of the wells, well-log patterns in all of the study area show similarities that are the basis for basin-wide correlations (figs 4, 5, 6). A number of stratal units and their bounding surfaces can be discerned and traced across the study area. These units and surfaces are defined and named in the sequence stratigraphic models for the Jurassic of the Danish Central Graben by Andsbjerg and Dybkjær (in prep.) and for the Søgne Basin by Andsbjerg (in prep.) (fig. 5). Although not all units and key surfaces from the high resolution sequence stratigraphic study of Andsbjerg (in prep.) can be traced into the southern part of the Danish Central Graben, overall log patterns and most important key surfaces can be traced to most wells in that area (figs 4, 6). In the upper part of the succession above the base Callovian unconformity the sequence stratigraphic subdivision and nomenclature of Andsbjerg (in prep.) has been preferred due to its higher resolution instead of the less detailed subdivision of Andsbjerg and Dybkjær (in prep.), which has been used in the lower part of the succession.

Among the features correlatable across most of the Danish Central Graben (see figs 4, 5 and 6) the single most important is the presence of one or a few thick coal beds lowermost in the coalbearing part of the succession sitting close above a major erosional channel base. The channel base may occur as the base of the incised valley-system in the Søgne Basin (Andsbjerg, in prep.), as the base of fluvial conglomerates in the southwestern part of the area and as the base of large channel sandstones. This unit, which is referred to the lower part of sequence Cal-1A (Andsbjerg, in prep.), has been dated to the latest Bathonian - Early Callovian. A basin-wide correlatable feature from the lower part of the succession is the coarsening upward, delta-like, progradational succession overlain by a mudstone unit, which frequently is cut by the above-mentioned erosion surface. This succession, which represents the HST of Baj-1 and the Bat-1 sequence of Andsbjerg and Dybkjær (in prep.), is dated as Early Bajocian - Bathonian. Above the coal succession marine influenced sandstones and shales belonging to the upper part of sequence Cal-1A and the sequences Cal-1B and Cal-1C (Andsbjerg, in prep.) are dated to the Middle Callovian to Early Oxfordian. The lowermost unit in the wells with a thick Middle Jurassic succession is difficult to correlate, probably due to varying onlap onto the pre-Middle Jurassic surface. It consists of interbedded channel sandstones and fine-grained floodplain deposits, that may be organised into several upward coarsening - upward fining units. These deposits, which are not younger than the Bajocian, represent the Aalen-1 and lower part of Baj-1 sequences (Andsbjerg and Dybkjær, in prep.) .

# Palaeogeography and depositional environments

## Map unit subdivision

The variations in stratigraphic resolution across the study area and the availability of core material for precise interpretations of sedimentary environment is reflected in the choice of map units. The relatively poor stratigraphic resolution in the lower part of the Middle Jurassic succession due to the structural position of some wells and the sparse core material from the lowermost part of the succession is the background for a lowermost map unit 1 that includes both the Aalen-1 and the lower part of the Baj-1 sequence. Map units 2 and 3 represent the HST of Baj-1 and the Bat-1 sequence respectively. The succession above the base Callovian unconformity, that shows an overall transgressive development has been subdivided into map units 4, 5 and 6.

### Map 1 (Aalen-1 and LST/TST of Baj-1)

A continuous sheet of Middle Jurassic sediments is present east of a line dividing the Danish Central Graben roughly north - south from the Mandal High area in the north to the area south-east of the Mads High in the south (probably none of these highs existed as structural features during the Middle Jurassic). Deposits of map unit 1 are less extensive. The western boundary of these deposits is east of the Elly wells, and deposits seem to be missing from the flanks of the Rosa Basin (fig. 7).

In the Søgne Basin the upper boundary of this map unit, the Baj-1 MFS is very distinct and easy to correlate (fig.5). This is also the case further south in the Danish Central Graben in wells with a thick Lower Graben Sand Formation (e.g. O-1, figs 4 and 6). However, in a number of wells with a more condensed Lower Graben Sand Formation the mudstone containing the MFS is much less distinct than another mudstone sitting higher in the Baj-1 sequence (e.g. Jens-1 and M-8, fig. 6). Another key horizon of map unit 1 which is easy to correlate in the Søgne Basin, is the base Baj-1 SB located at the base of a distinctive, correlatable channel sandstone (fig. 5). Further south in the Danish Central Graben this surface has been picked at the base of a distinctive channel sandstone unit located within this lower part of the succession (figs 5 and 6).

The unit has been cored in Alma-1, Elly-3, Nora-1 and West Lulu-3, where it is represented by distal floodplain or lacustrine mudstones in Alma-1 and Elly-3, and by channel and crevasse splay sandstones interbedded with distal floodplain mudstones in West Lulu-3 and Nora-1 (figs 8, 9). Well logs suggest that the unit, also in wells where it is not cored, commonly consists of channel sandstones interbedded with fine-grained floodplain deposits. The size, and the lateral consistency of typical fining upward log patterns seen in the channel units in the Søgne Basin suggests that large river channels of a laterally migrating, sinuous type in periods dominated the northern part of the study area (Andsbjerg, in prep.) (fig. 5). The uppermost part of the unit in the Søgne Basin is characterised by a fining upward suite of floodplain deposits, that suggests a gradual flooding of the area. Most wells in the southern part of the study area are dominated by floodplain deposits with lacustrine deposits and relatively thin units of fluvial channels. Many wells in that part of the basin show a very condensed unit 1 (figs 4 and 6).

A few of the rare marine dinoflagellate cysts from the lower part of the Middle Jurassic succession have been found uppermost in the Baj-1 TST in the Elly-3 well, suggesting marine incursions up to the time of maximum flooding. Positive evidence for marine conditions have not been found in other wells, and marine influence was probably restricted to the southern and south-western part of the study area. Marine incursions in that area may have turned shallow lakes into brackish and salt water lagoons in a low-energy coastal plain (fig. 7).

With the northern part of the study area in periods dominated by large river channels, and occasional marine or brackish floodings occurred in the southern part of the study area, paleoflow was probably from the north, through the Søgne Basin, the axial parts of the Tail End Graben and the Salt Dome Province, towards a marine basin in the Dutch Central Graben (Van Adrichem Boogaert and Kouwe, 1993). In periods with a high relative sea-level drainage would probably pass through large shallow lakes before reaching coastal areas further south (fig. 7). The presence of large river channels of a sinuous, laterally migrating type in the northern part, that drain into a marine basin to the south in the Dutch Central Graben, may indicate that the relatively small channel units in the southern part of the Danish Central Graben represent distributaries on a delta plain.

**Map unit 2 (Baj-1 HST)**

Compared to map unit 1 deposits of this unit are found in a slightly larger area, that includes the flanking areas of the Rosa Basin and the eastern part of the Elly area (fig. 10). This map unit is in most of the area represented by fine-grained deposits of a distal floodplain or shallow lacustrine environment overlain by a coarsening upward succession of increasingly proximal floodplain sediments (figs 11, 12). The depositional environment was a low-energy floodplain with abandoned fluvial channels forming oxbow lakes, probably small, active, distributary channels and in the deeper part of the basin large and small lakes. Lacustrine deltas prograded into lakes and large floodplain areas saw incremental growth of levees and crevasse splay complexes (fig. 10). The initial lacustrine flooding is not observed in the two wells, Jens-1 and M-8 in the axial part of the study area (fig. 6). This may indicate that the initial flooding did not reach structurally high areas in the central part of the southern Danish Central Graben. When lacustrine infill and delta progradation was completed the distributary channels were substituted by an axial system of laterally migrating rivers, similar to the system that dominated unit 1. Paleoflow may have varied considerably as streams and minor rivers flowed towards lakes and lagoons; but with the presence of a contemporary marine basin in the Dutch Central Graben regional flow probably was towards the south (fig. 10).

**Map unit 3 (Bat-1)**

Laterally extensive, fining upward, channel sandstones are found above the Bat-1 SB in the Søgne Basin (figs 5), thus indicating that a laterally migrating river system was established in the northern part of the Danish Central Graben after progradational filling of lakes and distal floodplain areas had been completed during the highstand of the previous sequence (fig. 13). A low-energy coastal plain with minor distributary channels existed in the Salt Dome Province.

After a meandering river system had been established in the Søgne Basin, flooding of the area was resumed causing the receiving basin to expand slightly towards the west. A succession dominated by fine-grained sediments was deposited in most of the basin as a result of this flooding. Fine-grained distal floodplain deposits and lacustrine mudstones dominated in the southern part of the Danish Central Graben and in the deeper parts of the basin in the northern part of the area (figs 14, 15c). In wells where this unit is represented by a relatively thick succession it typically shows an overall fining upward trend indicating a gradual drowning of a distal floodplain by lake waters (fig. 14: West Lulu-1). In wells where it is represented by a more condensed succession lacustrine mudstones lie abruptly on a flooding surface (fig. 14: Elly-3). In some wells the upper part of the unit shows a coarsening upward pattern, which may indicate infilling of the lake by a prograding lacustrine delta (e.g. Nora-1, fig. 4). In the western part of the Søgne Basin map unit 3 consists of interbedded floodplain and channel deposits overlain by interbedded lacustrine mudstones and thin coal beds. Some channel sandstones show evidence for tidal influence such as abundant double mud drapes, mud flasers, and bi-directional ripple cross-lamination (e.g. West Lulu-1, 3/7-4) suggesting that deposition took place on a coastal plain not far from a marine bay. Also in the Salt Dome Province does a single well show evidence for tidal influence (Skjold Flank-1). In light of the evidence for tidal influence in some channel sandstones it may be expected that lakes changed into brackish water lagoons during small scale sea-level rises; however, no palynological evidence for that have been found.

In the southern part of the Danish Central Graben lakes seem to have developed in all available accommodation space. In the Søgne Basin lakes only occurred in deep parts of the basin, whereas a floodplain with tidally influenced fluvial channels dominated in the western part of that basin. At this time (Bathonian) the Dutch Central Graben had become non-depositional (Van Adrichem Boogaert and Kouwe, 1993) and regional drainage patterns thus may have changed. Marine conditions have not been reported from within the Central Graben during the Bathonian, and the location of the receiving basin thus has not been identified. One possibility is the Danish Subbasin to the east but a connection between that basin and the Central Graben is so far unproved.

**Map unit 4 (LST and lower TST of Cal-1A)**

In most wells the floodplain and lacustrine deposits of map unit 3 are abruptly cut by the erosional base of coarse grained fluvial channels (figs 15c, 16). This erosional channel base is the base Cal-1A sequence boundary, which in the Søgne Basin bounds a major system of incised valleys (Andsbjerg, in prep.) (fig. 16).

In the Søgne basin the channel deposits are mainly sandy, and probably represent the deposits of sinuous rivers. Sedimentary structures such as flaser bedding and double mud drapes commonly associated with tidal influence, that are abundant in many of these channel sandstones (fig. 15a) suggests that deposition took place in a tidally influenced river some distance upstream from an estuary, and occasionally in large estuary channels. In the south-western part of the Danish Central Graben core evidence from Elly-3 (fig. 15b, c) show that deposition took place in a gravelly braided river (fig. 17). The striking similarity between the GR-logs from this interval in Elly-3 and in U-1 about 40 kilometres further to the south-east may suggest that the braided river system extended widely along the south-western margin of the study area (fig. 4). The gravelly braided river sediments of this area are the most proximal looking Middle Jurassic deposits found in the Danish Central Graben, and there is a clear proximal - distal relationship between this area and the tidally influenced fluvial sandstones of the Søgne Basin (fig. 17). This relationship indicates a change in regional slope and with that a change from a southerly regional paleoflow to a northerly paleoflow. There may also be an easterly component to the paleoflow from relatively high-lying areas in the west dominated by gravelly braided rivers to lowland areas with slow-moving sinuous rivers near the Coffee Soil Fault in the east (fig. 17).

**Map unit 5 (upper TST, HST/FRST of Cal-1A and Cal-1B)**
After infill of the incised valleys was completed, early transgression in the Søgne Basin area began with the growth of extensive mires behind protecting coastal barriers (fig. 18). The resulting coal unit probably correlates with the lowermost coals of the Middle Graben Shale in the southern part of the study area, that in several wells are superimposed on channel deposits of map unit 4 (figs 4, 6). Thick coals at this level are found in the wells of the western part of the Søgne Basin and in the Jens-1 well at the western margin of the Rosa Basin (figs 5., 6). Thin coals developed in the central and eastern parts of the Søgne Basin, in the Tail End Graben, and in most of the Salt Dome Province (fig. 4). The depositional environment in the areas with development of thick coals was one of extensive peat-forming mires on a coastal plain protected against severe marine incursions, and with almost no input of sediment from terrestrial sources (Petersen and Andsbjerg, 1996). The areas to the east and south-east of the basin with development of thin coals was dominated by more coast-near mires on a coastal plain, where growth of thick coal-forming peat was impeded by a faster rising watertable outpacing the rate of peat accumulation (fig. 18). A continued rise in sea-level caused the deeper parts of the Søgne Basin and northern Tail End Graben to be transgressed during this period. A veneer of bioturbated, transgressive shelf and shoreface sand covered the transgressed areas (figs 19a, 20). The extensive coastal plain mires in the Søgne Basin were replaced by lagoons and estuaries behind a barred coastline. Bay-head deltas and proximal estuary channels dominated the western part of the Søgne Basin, whereas the central and eastern parts of the basin were dominated by lagoons, tidal flats and flood tidal deltas (fig. 21). A minor sea level fall during the overall sea level rise caused regression of the coastline and the development of a vegetation-covered chenier plain behind a prograding beach and shoreface (Andsbjerg, in prep.) (figs 19b, 20). The mire dominated coastal plain may have continued to exist throughout this period in the southern part of the Danish Central Graben, which was still very little influenced by the marine embayment that evolved in the deepest part of the Søgne Basin (fig. 18). In the southern part of the Danish Central Graben estuaries, lagoons and shallow lakes may have developed in deeper parts of the basin during sea level rise, and filled in during sea level fall and changed into extensive vegetated swamps during the initial stages of renewed sea level rise (fig. 21).

**Map unit 6 (Cal-1C)**
During the final stages of transgression the Søgne Basin and Tail End Graben changed into a narrow marine bay, that gradually expanded towards the south along the basin axis, and with a further increase in sea level up the hanging-wall slope to the west (fig. 22). Initially the Søgne Basin was as in the previous phase dominated by extensive estuaries and lagoons, that were replaced by a prograding beach and chenier plain during a short-lived

sea-level fall. When sea-level rise was resumed, the tidally influenced coastal plain retreated towards the south until all of the Danish Central Graben was inundated (fig. 22). Coastal plain sediments of this unit can be traced as far north as Nora-1 in the Tail End Graben. Whereas the Søgne Basin was probably completely transgressed by the end of the Callovian (Andsbjerg and Dybkjær, in prep.) the coastal plain environment probably remained in the southern part of the study area until some time in the Early Oxfordian. Further south in the Dutch Central Graben the coastal plain was not completely transgressed until the Late Oxfordian (Van Adrichem Boogaert and Kouwe, 1993). The lithostratigraphic units of the different parts of the region are presented in fig. 23.

## Review of palaeogeography in the southern and central North Sea

In order to see the results of this study in a wider regional context the palaeogeographic model for the Danish Central Graben is compared with published studies of the Middle Jurassic in other parts of the southern and central North Sea area. This include the Dutch Central Graben to the south, the UK and Norwegian Central Graben and the Moray Firth area to the north, the Cleveland Basin of Yorkshire and the Sole Pit Basin to the west, and the Norwegian-Danish Basin to the east.

### Southern Central Graben

Palaeogeographic data for the Dutch Central Graben are provided by lithostratigraphic studies by Herngreen and Wong (1989) and Van Adrichem Boogaert and Kouwe (1993).

In the Dutch Central Graben the Aalenian - Callovian period was characterised by significant tectonic activity. Deposition of the Werkendam Formation marine claystone stopped in the Late Bajocian. The Dutch Central Graben remained non-depositional during the Bathonian - Early Callovian. Deposition of fluvial dominated sediments of the Lower Graben Formation was resumed in the Middle to Late Callovian (Herngreen and Wong, 1989; Van Adrichem Boogaert and Kouwe, 1993). The Lower Graben Formation, which is separated from the Werkendam Formation by a significant unconformity, varies in thickness from 40 to 562 m. The latest Callovian - Early Oxfordian Middle Graben Formation represents a shift to lacustrine and coastal swamp conditions. The formation is dominated by lacustrine mudstones with laterally extensive coal beds interbedded with thin marine claystones in the basal part ( Herngreen and Wong, 1989; Van Adrichem Boogaert and Kouwe, 1993).

### Cleveland Basin and Sole Pit Trough

An extensive literature has been published on the onshore sections of the Cleveland Basin in Yorkshire, whereas little is available on the offshore Sole Pit Basin. Overviews of the Middle Jurassic of Yorkshire has been presented by Hancock and Fisher (1981) and Rawson and Wright (1992). Also Alexander (1989) covered all of the Middle Jurassic in Yorkshire. Gowland and Riding (1991) presents the Scarborough Formation and the Scalby

Formation is treated by Leeder and Nami (1979), Fisher and Hancock (1985), and by Eschard et al. (1991).

During the Aalenian to Bathonian up to 200 m of delta plain or coastal plain sediments alternating with shallow marine deposits were deposited in the Cleveland Basin. Due to Toarcian - Aalenian uplift in the North Sea region are the lowermost Middle Jurassic sediments of the Dogger Formation unconformably separated from the Lower Jurassic succession. The Early Aalenian Dogger Formation sandstones were deposited in a shallow marine environment. A coastline probably lay to the north and west. To the south was a warm, shallow shelf sea (Rawson and Wright, 1992). Locally the Dogger Formation may be overlain by a thin coal bed (Alexander, 1989). The remainder of the Middle Jurassic succession is referred to the Ravenscar Group, which consists of coastal plain deposits interbedded with marine deposits. The base of the Saltwick Formation (Aalenian), which unconformably overlies the Dogger Formation, includes channels, that are incised into the Dogger Formation, indicating a sea-level fall and not only a simple progradation (Alexander, 1989). Like the other non-marine formations of the Ravenscar Group, the Saltwick Formation was deposited on a tidally influenced coastal plain, never far from the coastline (Alexander; 1989, 1992). The Eller Beck and Scarborough Formations represent transgressions from the east in the Late Aalenian and in the Middle Bajocian respectively. In between a minor transgression from the south, represented by the Lebberston Member, temporarily interrupted deposition of the coastal plain deposits of the Early Bajocian Cloughton Formation (Rawson and Wright, 1992). The Bathonian Scalby Formation rests erosionally on the Scarborough Formation. The lower part of the Scalby Formation consists of a fluvial to estuarine valley-fill complex (Nami and Leeder, 1978; Alexander, 1986; Eschard et al., 1991). The channel deposits are dominated by stacked, laterally extensive channel sandstones, that show a varying degree of tidal influence. The valley fill deposits are overlain by a continuous, black shale deposited in a marsh environment (Eschard et al., 1991). The upper part of the Scalby Formation was deposited on a low-energy delta or coastal plain with only minor channels (Eschard et al., 1991). The Cleveland Basin was finally transgressed during the Early Callovian resulting in a condensed succession of the marine limestones of the Combrash Formation resting on top of the Scalby Formation.

The West Sole Group of the Sole Pit Trough offshore Yorkshire comprises sediments of Aalenian to Early Callovian in age (Cameron et al., 1992).

## UK Central Graben

Donovan et al. (1993) gave a sequence stratigraphic description of the Jurassic deposits at the western margin of the UK Central Graben and Cameron et al. (1992) covering the southern North sea and Gatliff et al. (1994) covering the Central North Sea gave a treatment of the UK Central Graben.

The Middle Jurassic deposits of the UK central North sea were assigned to the Fladen Group by Deegan and Scull (1977). The main elements of the Fladen Group are the predominantly volcanic Rattray Formation and the non-marine Pentland Formation. Three volcanic centres of Jurassic age have been proven in the UK sector; the Forties volcanic province at the triple junction between the Moray Firth and the Viking and Central Grabens saw onset of volcanic activity in the Early Jurassic, the Puffin Centre in the southern West Central Graben was mainly active during the Middle Jurassic, and the Glenn volcanic centre also at the triple junction was mainly active during the Callovian (Smith and Ritchie, 1993).

The Pentland Formation is laterally equivalent to parts of the Rattray Formation, but also oversteps the volcanic succession (Gatliff et al., 1994). Thick successions of the Pentland Formation are preserved in the East Central Graben, where up to 595 m of non-marine sediments have been drilled (Gatliff et al., 1994). In the West Central Graben coal bearing coastal plain deposits of the Pentland Formation are unconformably overlain by a Callovian - Oxfordian progradational wedge of offshore to shoreface and paralic deposits referred to the lowermost member of the Fulmar Formation (Donovan et al., 1993) or the Sgiath Formation (Gatliff et al., 1994). The shallow marine units have also been defined as the Frigate formation in the Fisher Bank Basin by Clark et al. (1993). Generally the paralic deposits are limited to the Callovian part of the succession but locally paralic conditions may have persisted until Oxfordian times, as the occurrence of the coal-rich lower part of the Sgiath Formation (Gatliff et al., 1994) and lowermost member of the Fulmar Formation (Donovan et al., 1993) suggests.

## Moray Firth

A review of the Middle Jurassic of the onshore sections of Moray Firth is presented by Trewin and Hurst (1993). The Middle Jurassic offshore succession of the Inner Moray Firth has been treated by Andrews et al. (1990) and Stephen et al. (1993).

Middle Jurassic deposits in the Moray Firth area are separated from the Lower Jurassic succession by a major unconformity where at least Late Toarcian, Aalenian and Bajocian deposits are absent (Stephen et al., 1993). Onshore the Middle Jurassic succession is represented by the mainly Bathonian Brora Coal Formation, the Callovian Brora Argillaceous Formation, and the Callovian to Oxfordian Brora Arenaceous Formation (Trewin and Hurst, 1993). The Brora Coal Formation is mainly fluvial and low-energy alluvial plain in origin. However, in its upper part are lagoonal deposits showing extensive marine influence (MacLennan and Trewin, 1989). An extensive coal overlies the lagoonal deposits. The Bathonian - Callovian boundary probably lies within the lagoonal deposits below the coal (MacLennan and Trewin, 1989). Above the coal is a transgressive marine sandstone overlain by a marine shale of the Brora Argillaceous Formation. The transgressive sandstone marks the main Callovian marine transgression in the area (Trewin and Hurst, 1993). Above the marine shale is a coarsening upward succession of marine sandstone including the Brora Arenaceous Formation with its uppermost part dated to the Oxfordian (Trewin and Hurst, 1993). Offshore in the Inner Moray Firth is a Bathonian to Lower Callovian succession very much similar to the onshore succession. Thick alluvial plain mudstones with fluvial channel sandstones are overlain by lagoonal mudstones and the Brora Coal bed (Stephen et al., 1993). Above the coal bed Early Callovian transgression is recorded by marine mudstones that grade upwards to marine sandstone. A condensed argillaceous unit record maximum flooding on top of the Early Callovian succession. The Middle to Late Callovian succession consists of coarsening upward marine mudstone to sandstone units separated by flooding surfaces (Stephen et al., 1993; their fig. 11). A Callovian to Oxfordian transgression is tentatively suggested to have come from the Hebridean Basin in the south and south-west across the Scottish Highlands or along the trace of the Great Glen Fault (Stephen et al., 1993).

## Norwegian Central Graben and adjacent areas

Very little has been published on the Middle Jurassic in the Norwegian Central Graben and on the northern subbasins of the Norwegian - Danish Basin. A palaeogeography of the south-eastern Norwegian offshore was published by Hamar et al. (1983) and a regional geological study of the Norwegian offshore by Færseth and Pederstad (1988).

The Central Graben and the Norwegian-Danish Basin formed an unified plain with fluvial sedimentation in a marshland environment during the Aalenian-Bathonian (Hamar et al., 1983). The Haldager and Bryne Formations of the area attain thicknesses of up to 200 m. Renewed Bathonian-Callovian fault activity subdivided the depositional area, when a ridge formed between the Central Graben and the Fiskebank Subbasin (Hamar et al. 1983). After flooding of the Fiskebank Subbasin the shallow marine sandstones of the Sandnes Formation with a maximum thickness of up to 100 m were deposited in that area (Hamar et al., 1983). A similar succession occurs in the Egersund Subbasin further to the north-east(Norwegian Petroleum Directorate, 1993, 1996). The shallow marine sandstones of the Sandnes Formation may be separated from the underlying coastal plain deposits of the Bryne or Haldager Formation by an unconformity (Færseth and Pederstad, 1988). Deposition of Haugesund Formation marine shales began in the Central Graben when Sandnes Formation sandstones were still being deposited to the north-east. In the north-eastern subbasins deposition of marine shales and siltstones began in Late Callovian - Oxfordian (Hamar et al., 1983).

## Norwegian-Danish Basin

The regional studies on the Norwegian-Danish Basin have their emphasis on the Danish subbasin, where many onshore wells have been drilled. An early palaeogeography of the Jurassic deposits was published by Larsen (1966). Later works are those of Michelsen (1978), Koch (1983) and Nielsen (1995).

The up to 200 m thick Middle Jurassic succession in the Norwegian-Danish Basin is separated from the marine mudstones of the Lower Jurassic Fjerritslev Formation by a regional unconformity (Michelsen, 1978). The hiatus associated with the unconformity is insignificant in the Sorgenfrei-Tornquist Zone at the north-eastern margin of the basin, where it occurs within sediments of Aalenian age (Michelsen, 1975; Michelsen and Nielsen, 1991; Nielsen 1995), but it increases strongly towards the south-west due to erosional truncation of the Lower Jurassic and a progressively younger onlap onto the unconformity. Close to the Ringkøbing-Fyn High the hiatus corresponds to most of the Jurassic (Nielsen, 1995).

The Middle Jurassic deposits of the Norwegian-Danish Basin are referred to the Haldager Formation and the lower part of the Flyvbjerg Formation (Michelsen, 1978, 1989). The lowermost part of the Middle Jurassic succession is dominated by marine shoreface sandstones and interbedded marine mudstones and sandstones. Above the marine deposits is a succession of estuarine channel deposits overlain by interbedded estuarine, lagoonal and barrier deposits with marine sandstones and mudstones on the top (Nielsen, 1995). An Aalenian to Early Bajocian age is assigned to this lower part of the Middle Jurassic succession (Nielsen, 1995). The upper part of the Middle Jurassic succession is dominated by fluvial and fluvial-estuarine channel deposits of Early Bajocian-Callovian age. Estuarine channel deposits are mainly concentrated in the Sorgenfrei-Tomquist Zone, whereas fluvial deposits dominate the margins of the Sorgenfrei-Tomquist Zone and on the platforms outside the zone. Uppermost in the Middle Jurassic succession are fluvial deposits common in the more marginal parts of the expanding basin, while lagoonal and shallow marine deposits dominate deeper parts of the basin including the Sorgenfrei-Tomquist Zone (Nielsen, 1995). A transgressive surface, on top of which the succession consists of marine deposits of the Flyvbjerg Formation, occurs close to the Callovian - Oxfordian boundary (Nielsen, 1995).

## Regional palaeogeography

Palaeogeographic studies that cover all or a large part of the North Sea region are available. Among these are several publications by Ziegler (e.g. Ziegler, 1982, 1990). Another palaeogeographic study covering most of the North Sea area was published by Cope et al. (eds.), (1992).

A basal Middle Jurassic unconformity of variable magnitude is present in most parts of the region. The smallest hiatus seems to be represented by the unconformity in the Cleveland Basin - Sole Pit Trough and at the southern margin of the Norwegian Danish Basin, where only a small time interval is missing from the deposits at the Toarcian - Aalenian boundary. The large unconformity that separates the fully marine shales of the Werkendam Formation from the coastal plain deposits of the Lower Graben Formation in the Dutch central graben is much younger with a Late Bajocian - Middle Callovian hiatus.

Sediments deposited in a relatively uniform fluvially dominated coastal plain depositional environment characterise the Aalenian - Bathonian succession in most of the region, although the oldest deposits sitting on top of the basal unconformity in the Cleveland Basin and the Norwegian - Danish Basin are marine (Rawson and Wright, 1992; Nielsen, 1995). As suggested by Hamar et al. (1983) the Aalenian - Bathonian coastal plain deposits may have overstepped the basinal boundary. The active depositional area thus may have covered a much larger part of the region than the strongly fault-bounded Late Jurassic basins, but it had a much more subdued topographic relief. Conditions however, were not uniform through all that period. As evidence from the Cleveland Basin (Rawson and Wright, 1992), the Danish Central Graben (this study) and the Danish Subbasin (Nielsen, 1995) shows, marine transgressions did occur, indicating that relative sea-level changes influenced deposition. Whereas the major part of the region was dominated by terrestrial deposition throughout this period, the southernmost part of the Central Graben in the Dutch sector was characterised by fully marine conditions until the Middle or Late Bajocian, and then by non-deposition until the Middle or Late Callovian (Van Adrichem Boogaert and Kouwe, 1993). This may indicate that the Dutch Central Graben was not to the same degree influenced by the rise and collapse of the North Sea Dome (Ziegler, 1982, 1990; Underhill and Partington, 1993a). The presence of a fully marine basin southernmost in the North Sea during the Aalenian to Middle Bajocian may have had a profound influence on fluvial drainage patterns in much of the region.

Major changes in depositional environment are first reported from the Cleveland Basin. Here estuarine conditions occur in incised valley-fill deposits of the Scalby Formation dated to the Early Bathonian (Eschard et al., 1991). A change to fully marine conditions took place in the Cleveland Basin in the Early Callovian. In the Søgne Basin of the Danish

Central Graben estuarine conditions are recorded from incised valley-fill deposits of latest Bathonian - Early Callovian (Petersen and Andsbjerg, 1996; this study), and further north a similar age is assigned to lagoonal deposits in the onshore Moray Firth (MacLennan and Trewin, 1989). In the Danish Central Graben the basal erosion surface of the incised valley system (Cal-1A SB) is a sequence boundary with an age close to the Bathonian - Callovian boundary. In the Inner Moray Firth and in the Danish Central Graben the change from fluvially dominated coastal plain to paralic deposits is associated with the formation of extensive coals. The incised valley estuaries in the Søgne Basin are capped by thick, coals, dated to the Early Callovian, which can be traced further south in the Danish Central Graben where they outline the shift from fluvial dominated to marine influenced coastal plain (figs 4, 5, 6). In the Inner Moray Firth an extensive coal, dated to the earliest Callovian, separates the lagoonal deposits uppermost in the Brora Coal Formation from overlying marine sandstones (MacLellan and Trewin, 1989).

In the Norwegian and UK Central Graben a major unconformity is reported to straddle the Bathonian - Callovian boundary (e.g. Færseth and Pederstad, 1988; Donovan et al., 1993). The unconformity shown by Donovan et al. (1993) as lavender SB in well 22/16-2 (their figs 18, 19) shows a pronounced likeness with the top Bryne Formation transgressive surface (figs 5, 20). As suggested by Donovan et al. (1993) it may be a composite surface, and it may represent an amalgamation of the Early Callovian transgressive surface and one or more underlying sequence boundaries, for example the Cal-1A sequence boundary which is strongly erosive in the Danish Central Graben (this study).

After deposition of the Early Callovian coal-forming peats in the Danish Central Graben a marine influenced coastal plain dominated by lagoons and coastal swamps developed in the southern part of the area, whereas alternating paralic and shallow marine conditions dominated the northern part of the area. The final marine transgression seems to have occurred near the Callovian - Oxfordian boundary. Due to uncertainties in the dating of the unconformity between the Pentland/Bryne Formations and the overlying Callovian - Oxfordian shallow marine deposits the change to marine conditions in the Norwegian and UK Central Graben cannot be dated with any certainty. However, the presence of coal-bearing coastal plain sediments within the otherwise shallow marine deposits of the lowermost Fulmar Formation or Sgiath Formation (Donovan et al., 1993; Gatliff et al., 1994; Underhill and Partington, 1993b) suggests that paralic and marginal marine conditions locally persisted until Oxfordian times. To the south the final transgression is late in the Dutch sector. In the Dutch Central Graben the change to marine-influenced coastal plain occurred in the latest Callovian - Early Oxfordian, whereas the final marine transgression moved southward through the Dutch Central Graben during the Late Oxfordian (Van Adrichem Boogaert and Kouwe, 1993). Alternations between marine and fluvial/estuarine conditions took place several times throughout the Late Bajocian - Callovian in the Danish Subbasin of the Norwegian - Danish Basin. Marginal platform areas of the Danish Subbasin with contain only the uppermost Haldager Formation and the Flyvbjerg Formation and a change to a marine Callovian - Oxfordian boundary (Nielsen, 1995). However, wells in the deepest trough of the Sorgenfrei - Tornquist Zone (e.g. Terne-1 and Haldager-1) show almost continuous estuarine or shallow marine conditions throughout the Middle Jurassic with only minor breaks of fluvially dominated deposition (Nielsen, 1995; his fig. 88). In the northern subbasins of the Norwegian - Danish Basin the ages and well logs presented for Norwegian wells 9/2-1, 9/2-2 and 9/2-3 (Norwegian Petroleum Directorate, 1993, 1996) suggest deposition of shallow and marginal marine deposits of the Sandnes

Formation in the Callovian -Oxfordian with a final transgression only late in the Oxfordian. A major part of the Callovian may be missing due to an erosive boundary separating the Sandnes and Bryne Formations at the Bathonian - Callovian boundary.

### Regional transgressions

Biostratigraphic data in particular are insufficient to map in detail the history of the late Middle Jurassic transgressions in the southern North Sea region. However, by combining the data presented in this paper and the published results from the reviewed papers some constraints can be given. Based on the available datings the Cleveland Basin seems to have changed to estuarine conditions earlier than other parts of the region except for the Sorgenfrei - Tornquist Zone, in the Late Bajocian - Early Bathonian. The change to fully marine conditions in the Early Callovian is contemporary with the change to shallow marine conditions in the Inner Moray Firth and the first marine incursions in the Søgne Basin. The transgression of the Moray Firth from the south-west took place almost simultaneously with the transgression of the Søgne Basin and adjacent parts of the Central Graben and the Norwegian - Danish Basin. The presence of Late Callovian - Oxfordian coastal plain deposits in the northern part of the Central Graben suggests that this area was not completely flooded until late in the Oxfordian, but deep grabens may have been inundated somewhat earlier (Underhill and Partington, 1993b). A general north to south transgression in the Central Graben has been suggested by Underhill and Partington (1993b). However, the published datings do not suggest a significant difference in time for the change from alluvial plain to paralic and shallow marine environments between the mid and northern Central Graben. Transgression may have taken place almost simultaneously in the deepest grabens along the eastern margin of the Central Graben such as the Søgne Basin and Tail End Graben in Danish Central Graben and in the East Central Graben to the north. Although the Cleveland Basin was transgressed even earlier, the transgression of the Central Graben is unlikely to have come from that direction without leaving traces in the Dutch Central Graben. A transgression towards the eastern margin of the Central Graben from the north-east through the Egersund and Fiske Bank Subbasins is possible although the presence of the shallow to marginal marine Sandnes Formation may speak against it. Another possible route is through the deep trough of the Sorgenfrei - Tornquist Zone which was dominated by alternating marine and estuarine conditions through most of the Middle Jurassic.

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## Figure captions

**Fig. 1:** Map of North Sea area. North Sea rift system shown in orange, Danish Central Graben in red.

**Fig. 2:** Map of Danish Central Graben with major structural features and well locations.

**Fig. 3:** Lithostratigraphic diagram of the Jurassic in the Danish Central Graben.

**Fig. 4:** Regional log correlation panel, N - S from Amalie-1 in southern part of Søgne Basin to O-1 southernmost in the Danish Central Graben with map units and sequences shown.

**Fig. 5:** Regional log correlation panel, W - E from West Lulu-4 to Amalie-1 in the Søgne Basin with map units and sequences shown.

**Fig. 6:** Regional log correlation panel, NW - SE from Jens-1 in the central part of the Danish Central Graben to O-1 southernmost in the Danish Central Graben with map units and sequences shown.

**Fig. 7:** Palaeogeographic map of map unit 1, Aalen-1 and LST/TST of Baj-1. Low-energy floodplain with shallow lakes. Alternating fluvial and lacustrine dominance throughout period represented by unit-1. A situation with a lacustrine dominated environment is shown.

**Fig. 8:** Gamma-ray and core logs of upper part of map unit 1 and lower part of unit 2 in wells West Lulu-3, Elly-3 and Alma-1. Fluvial channel sandstone's overlain by a succession that shows a gradual change to low-energy floodplain and lake.

**Fig. 9:** Core photos of map unit 1 sediments. a: Nora-1, 5281 m, trough cross-bedded sandstone, fluvial channel. b: Anne-3, 3524 m, oversteepened, disturbed cross-bedded sandstone with mud laminae and coal clasts, fluvial or crevasse channel.

**Fig. 10:** Palaeogeographic map of map unit 2, Baj-1 HST. Alluvial plain with mainly basin axial meandering rivers, deltas prograde into lakes.

**Fig. 11:** Gamma-ray and core logs of unit 2 in wells Nora-1 and Elly-3. Coarsening upward succession from lake and floodplain to fluvial channels.

**Fig. 12:** Core photos of map unit 2 sediments. a: Elly-3, 4064 m, Intraformational mudstone clasts in channel sandstone. b: Nora-1, 5172 m, intraformational mudstone clasts in disturbed, cross-bedded fluvial sandstone. c: Nora-1, 5183 m, cross-bedded channel sandstone with rip-off mud clasts. d: Nora-1, bioturbated and disturbed heterolithic mudstone, overbank or passive channel fill.

**Fig. 13:** Palaeogeographic map of map unit 3, Bat-1. Alluvial plain with major lakes occupying deep axial parts of subbasins.

**Fig. 14:** Gamma-ray and core logs of unit 3 in wells West Lulu-1 and Elly-3. In West Lulu-1 are fluvial channel sandstone's interbedded with and overlain by lacustrine and low-energy floodplain deposits. In Elly-3 is the unit dominated by rooted lacustrine mudstone and siltstone.

**Fig. 15:** Core photos of map unit 3 and 4 sediments. a: Amalie-1, 5118.5 m (unit 4), cross-bedded sandstone with abundant mud-drapes and flasers, estuary or tidally influenced fluvial channels, incised valley-fill. b: Elly-3, 4044.4 m (unit 4), cross-bedded, clast-supported pebble conglomerate, braided fluvial channel. c: Elly-3, 4045.6 m, lacustrine mudstone (unit 3) with sand and gravel filled crevasse erosively overlain by cross-bedded, clast-supported pebble conglomerate (unit 4) of braided fluvial channel. Erosion surface interpreted as Cal-1A sequence boundary.

**Fig. 16:** Gamma-ray and core logs of unit 4 in wells Elly-3, West Lulu-2, West Lulu-3 and Amalie-1. Braided fluvial conglomerate in Elly-3. Interbedded fluvial and estuarine channel sandstone's in West Lulu-2 and -3. Estuarine channel sandstone's and tidal flat and lagoonal heteroliths and mustiness in Amalie-1.

**Fig. 17:** Palaeogeographic map of map unit 4, LST and lower TST of Cal-1A. Major sea-level fall at Bathonian - Callovian boundary. Braided fluvial channels in the south-west change downstream to sinuous rivers and estuary channels in incised valley system. Meandering river occupies axial part of half-graben.

**Fig. 18:** Palaeogeographic map of map unit 5, upper TST, HST/FRST Cal-1A and Cal-1B. Callovian transgression. Low-gradient coastal plain with lagoons, shallow lakes and minor distributaries. Deeper parts of Søgne Basin and northern Tail End Graben transgressed with coastal barrier protecting lagoons. Søgne Basin was partly infilled by shoreface sediments during regressive regressions.

**Fig. 19:** Core photos of map unit 5 sediments. a: Amalie-1, 5046.5 m, bioturbated, muddy sandstone to siltstone, transgressive shoreface and shelf. b: Amalie-1, 5050 m, HCS/SCS sandstone of lower shoreface.

**Fig. 20:** Gamma-ray and core logs of units 5 and 6 in wells West Lulu-3 and Lulu-1. Shoreface and beach deposits dominate the succession in Lulu-1 situated closer to the basin axis, West Lulu-3 is dominated by estuarine and other backbarrier environments.

**Fig. 21:** Core photos of map unit 5 and 6 sediments. a: West Lulu-3, 3647.5 m, thoroughly bioturbated estuary channel sandstone with dominance of *Teichichnus* trace fossils. b: West Lulu-2, 3782.2 m, clast- and matrix-supported pebble conglomerate, sharp bases, fining up dominating trend, coarsening up occurs, transgressive

conglomerate. c: West Lulu-3, 3654.5 m, climbing ripple cross-laminated sandstone with mud flasers, mud drapes including double drapes at top and bottom, bay-head delta.

**Fig. 22**: Palaeogeographic map of map unit 6, Cal-1C. Continued Callovian transgression. Marine embayment expanding southward. Non-transgressed areas dominated by low-energy coastal plain. During regressive intervals are shoreface sediments deposited in deeper parts of basin.

**Fig. 23**: Stratigraphic diagram of the Middle Jurassic and lowermost Upper Jurassic in the southern and central North Sea region.

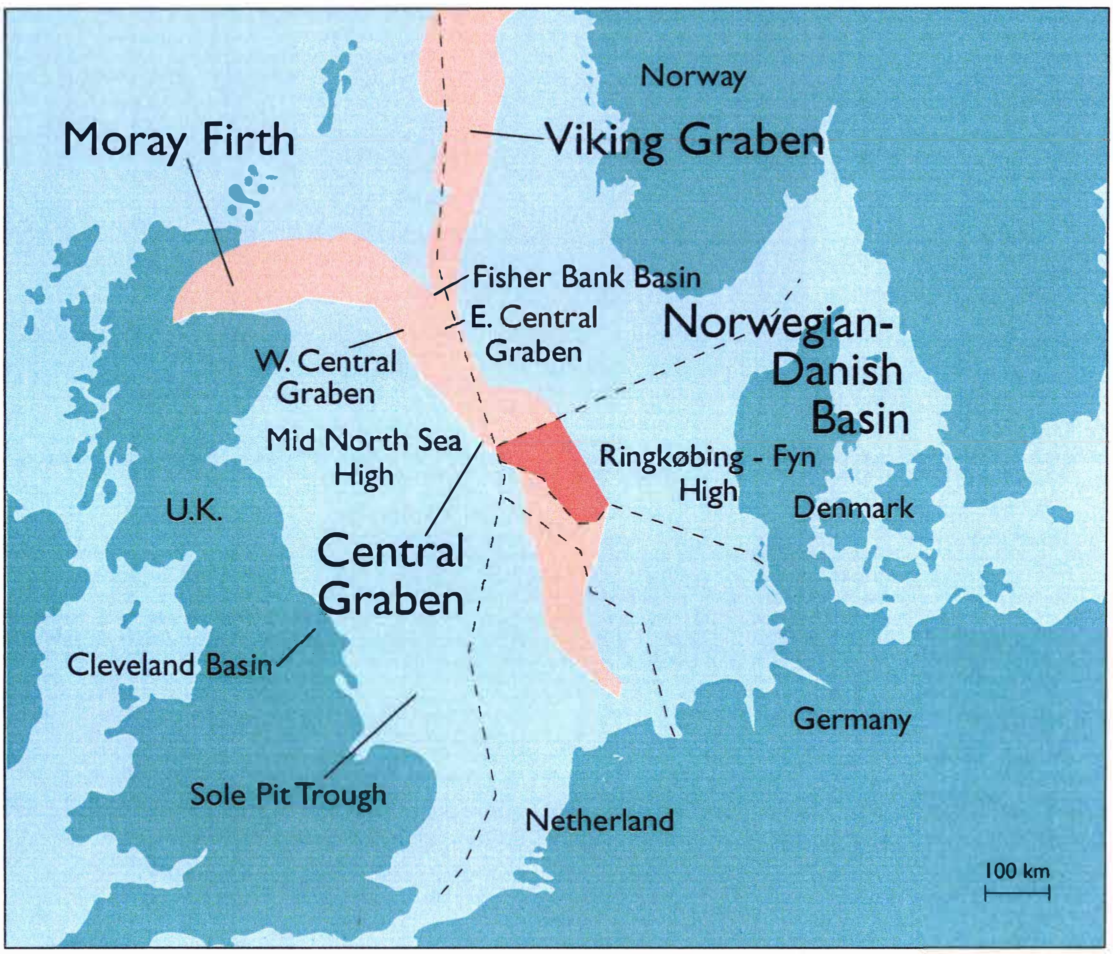
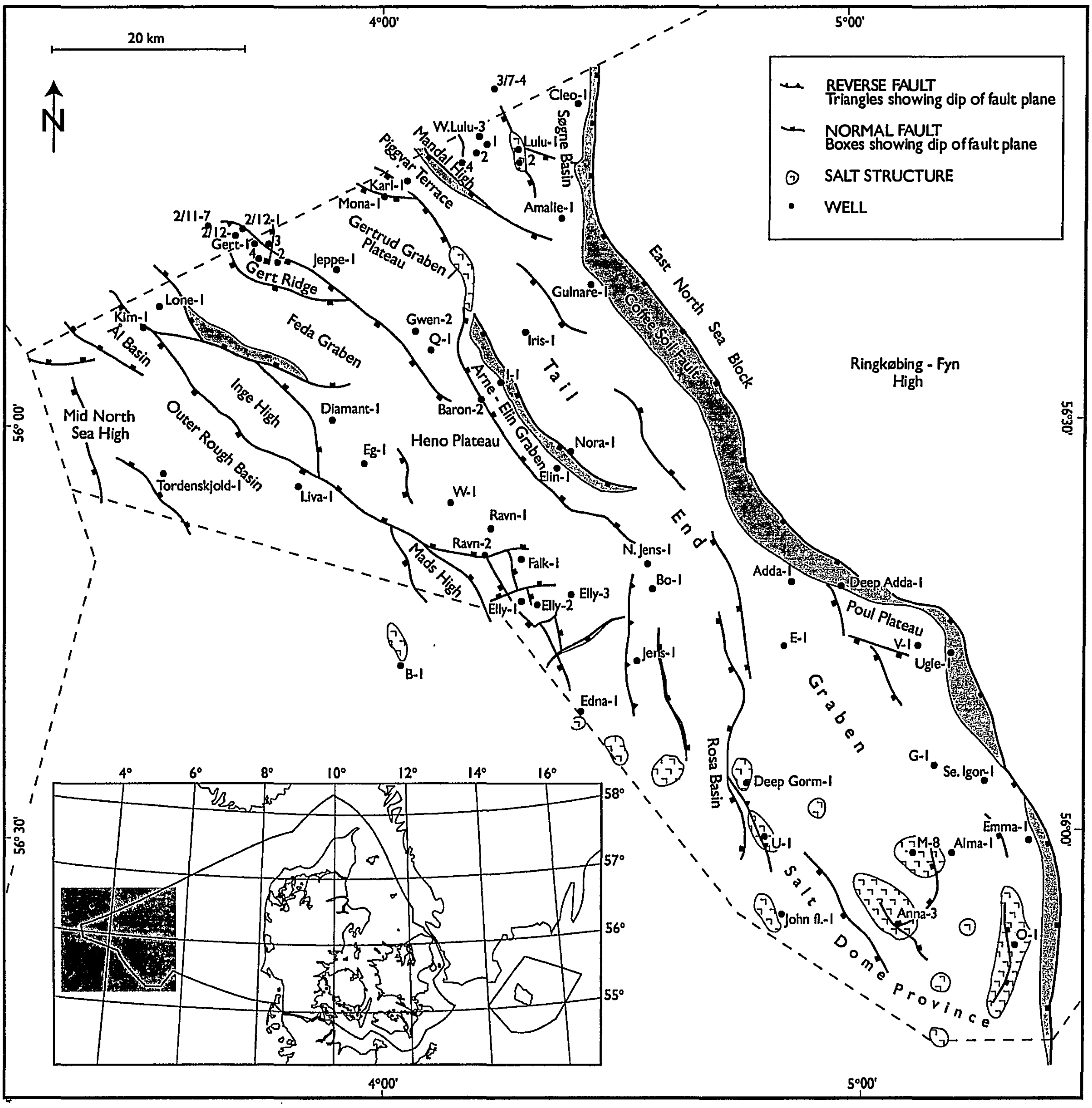
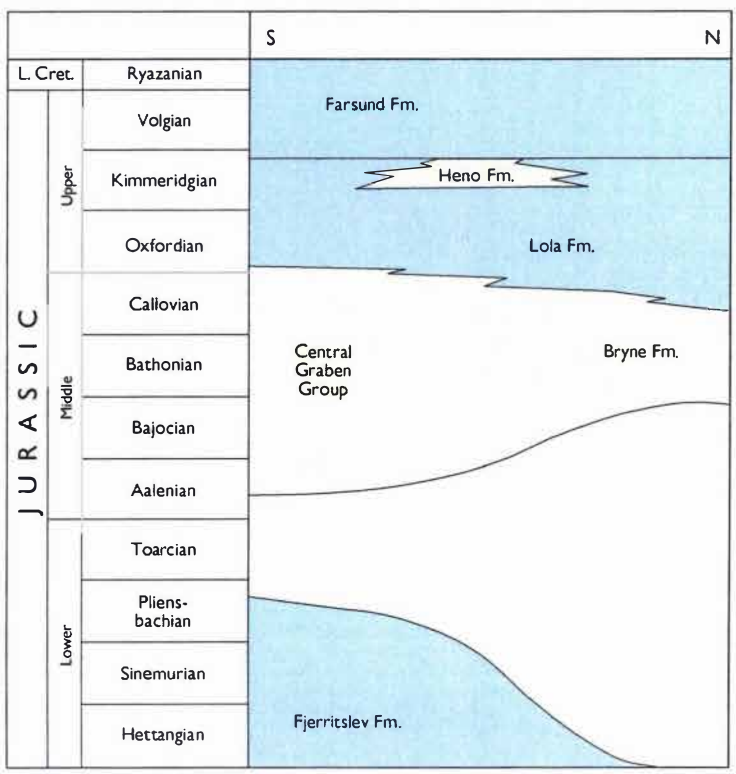

Norway
Moray Firth
Viking Graben
Fisher Bank Basin
E. Central
Graben
Norwegian-
Danish
Basin
W. Central
Graben
Mid North Sea
High
Ringkøbing - Fyn
High
U.K.
Denmark
Central
Graben
Cleveland Basin
Germany
Sole Pit Trough
Netherland
100 km

Fig. 1



4°00'
5°00'
20 km
N
REVERSE FAULT
Triangles showing dip of fault plane
NORMAL FAULT
Boxes showing dip of fault plane
SALT STRUCTURE
WELL
Ringkøbing - Fyn High
East North Sea Block
Coffee Soil Fault
Tail End Graben
Søgne Basin
Mandal High
Piggvar Terrace
Gertrud Graben / Plateau
Gert Ridge
Feda Graben
Ål Basin
Inge High
Outer Rough Basin
Mid North Sea High
Heno Plateau
Arne - Elin Graben
Mads High
Poul Plateau
Rosa Basin
Salt Dome Province
56°00'
56°30'
Fig.2

Fig.2



S
N
L. Cret.
Ryazanian
Farsund Fm.
Volgian
Upper
Kimmeridgian
Heno Fm.
Oxfordian
Lola Fm.
Callovian
JURASSIC
Middle
Bathonian
Central
Graben
Group
Bryne Fm.
Bajocian
Aalenian
Lower
Toarcian
Pliens-
bachian
Sinemurian
Hettangian
Fjerritslev Fm.


Fig.3

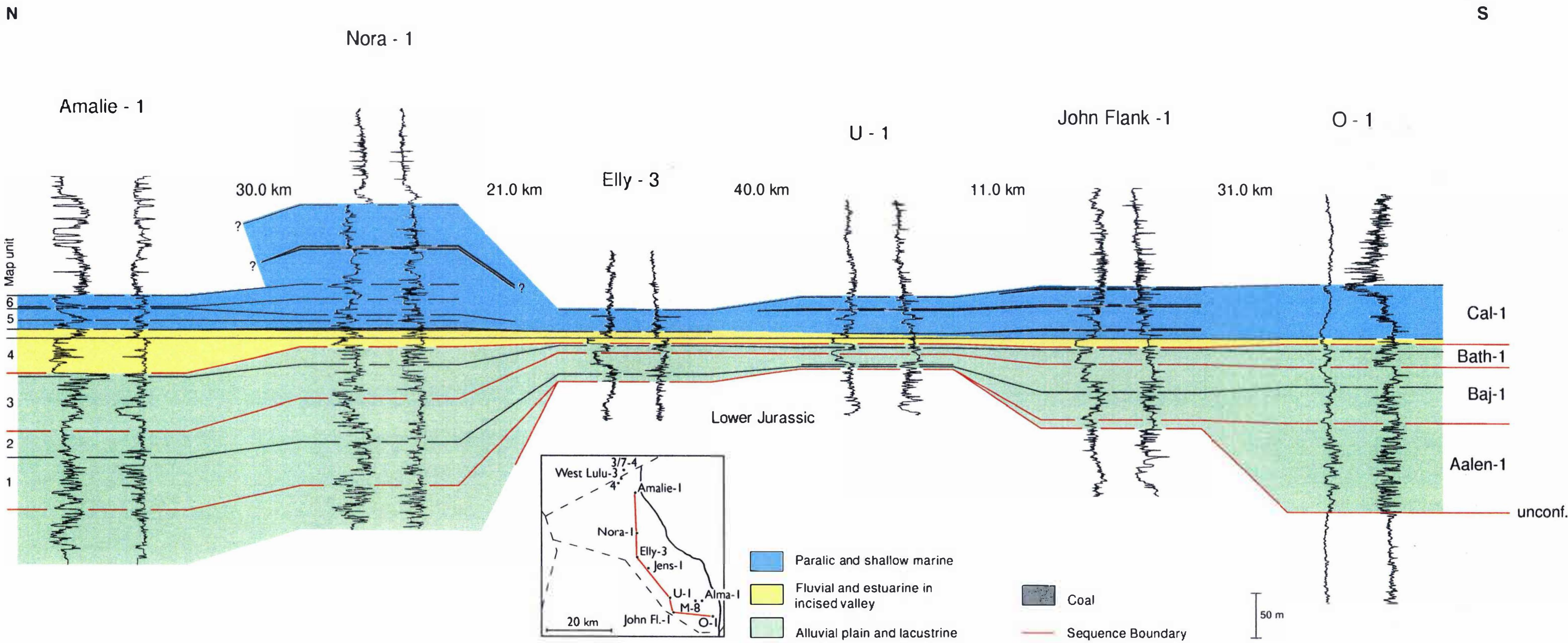

N
S
Nora - 1
Amalie - 1
30.0 km
21.0 km
Elly - 3
40.0 km
U - 1
11.0 km
John Flank -1
31.0 km
O - 1
Map unit
6
5
4
3
2
1
Cal-1
Bath-1
Baj-1
Aalen-1
unconf.
Lower Jurassic
3/7-4
West Lulu-3
4
Amalie-1
Nora-1
Elly-3
Jens-1
U-1
Alma-1
M-8
John Fl.-1
O-1
20 km
Paralic and shallow marine
Fluvial and estuarine in incised valley
Alluvial plain and lacustrine
Coal
Sequence Boundary
50 m

Fig.4

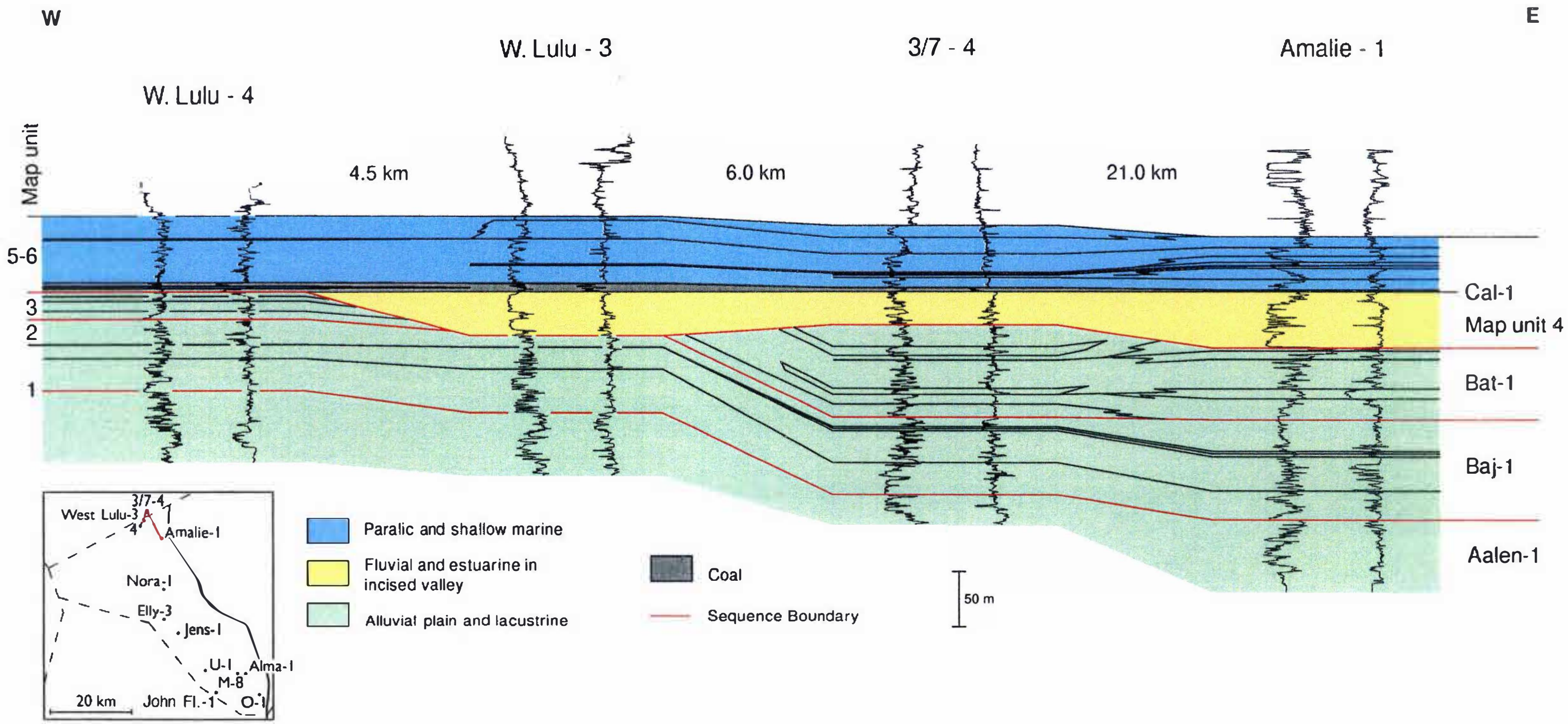

W
E
W. Lulu - 4
W. Lulu - 3
3/7 - 4
Amalie - 1
Map unit
4.5 km
6.0 km
21.0 km
5-6
3
2
1
Cal-1
Map unit 4
Bat-1
Baj-1
Aalen-1
West Lulu-3
4
3/7-4
Amalie-1
Nora-1
Elly-3
Jens-1
U-1
Alma-1
M-8
John Fl.-1
O-1
20 km
Paralic and shallow marine
Fluvial and estuarine in incised valley
Alluvial plain and lacustrine
Coal
Sequence Boundary
50 m

Fig.5

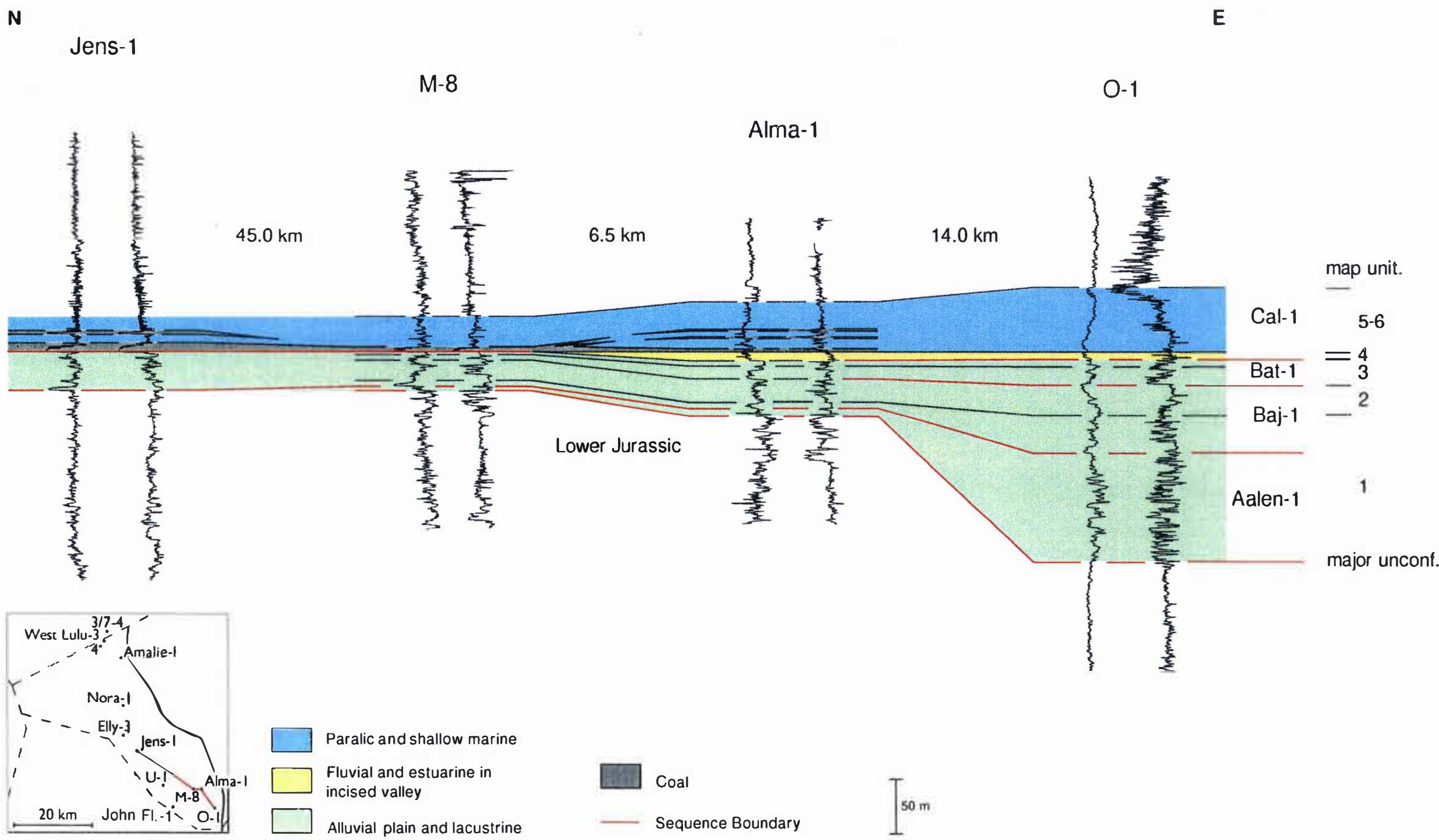

N
E
Jens-1
M-8
Alma-1
O-1
45.0 km
6.5 km
14.0 km
map unit.
Cal-1
5-6
4
Bat-1
3
2
Baj-1
Lower Jurassic
1
Aalen-1
major unconf.
3/7-4
West Lulu-3
4
Amalie-1
Nora-1
Elly-3
Jens-1
U-1
Alma-1
M-8
20 km
John Fl.-1
O-1
Paralic and shallow marine
Fluvial and estuarine in incised valley
Alluvial plain and lacustrine
Coal
Sequence Boundary
50 m

Fig.6

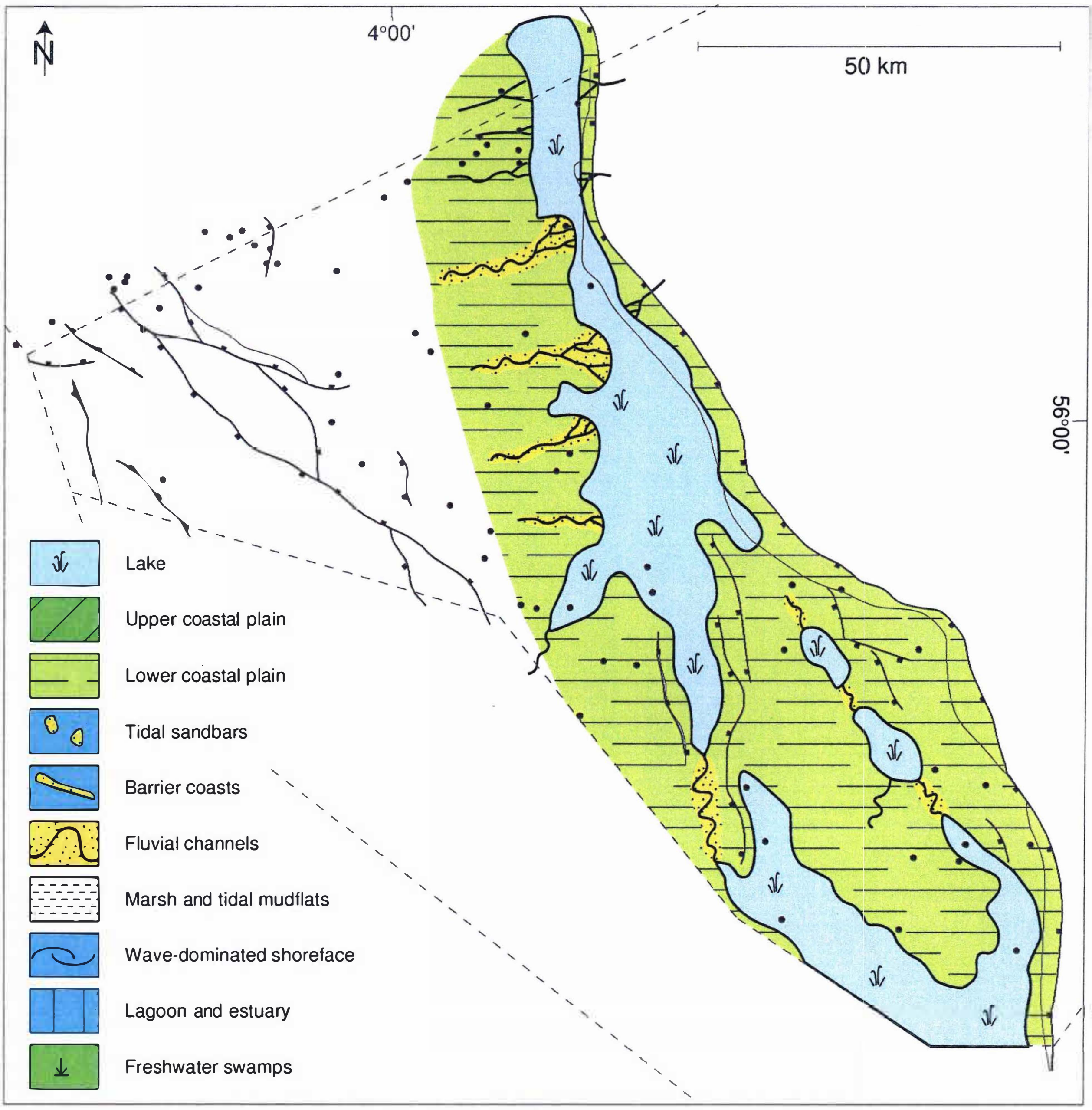

N
4°00'
50 km
56°00'
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps

Fig.7

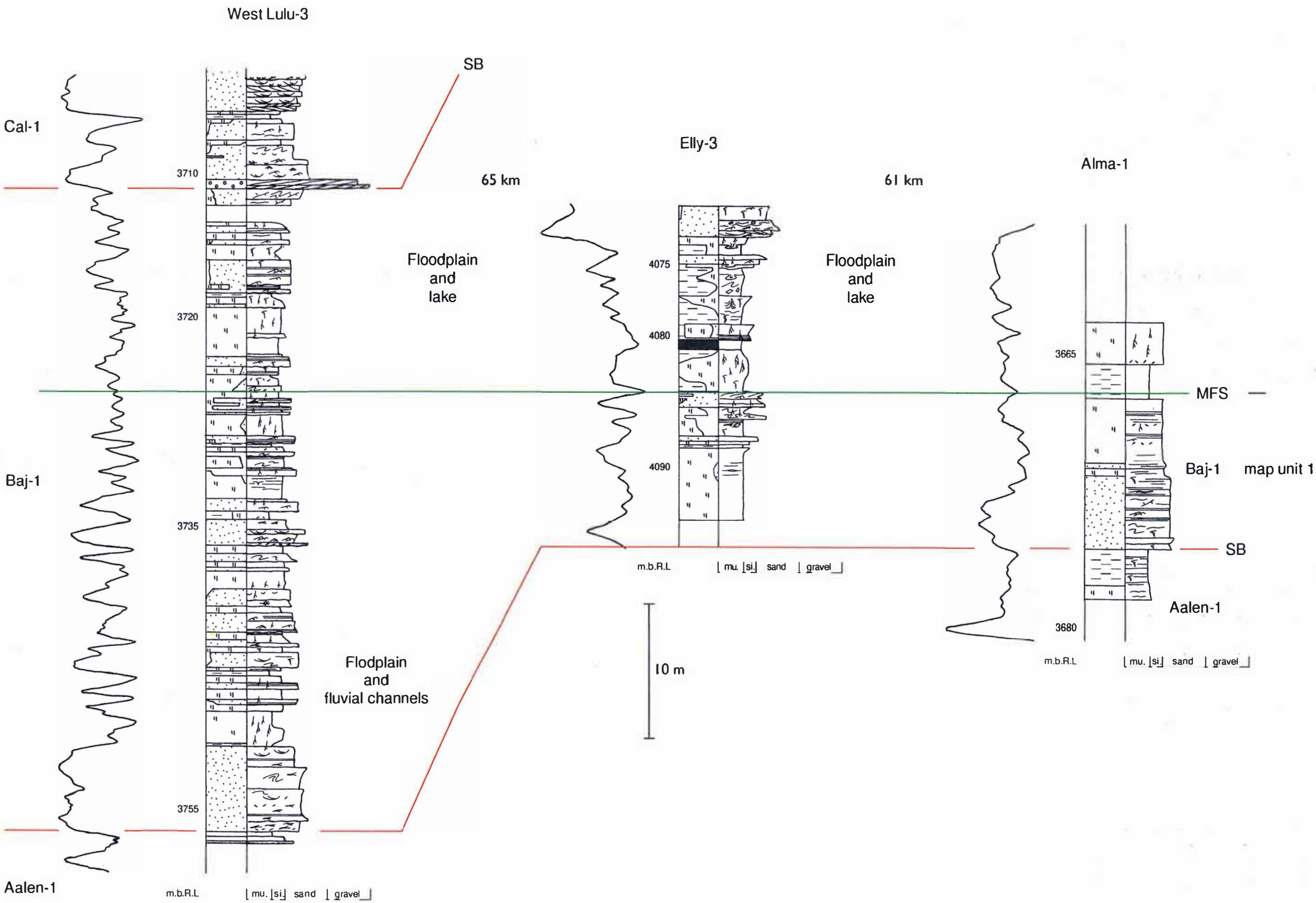
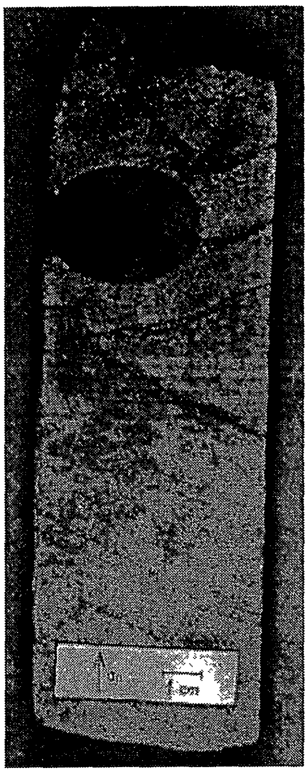
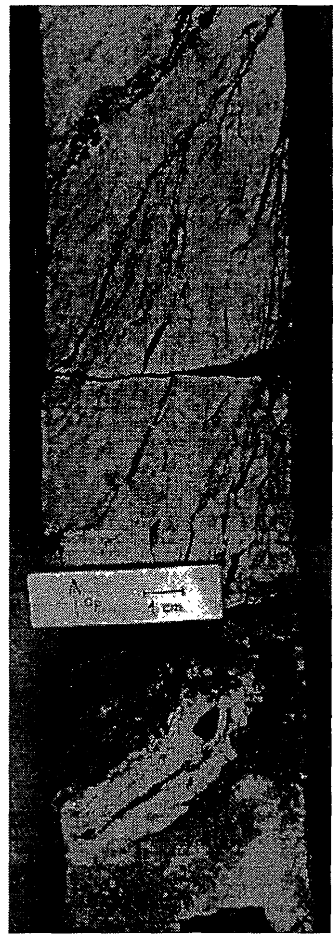

West Lulu-3
SB
Cal-1
3710
65 km
Elly-3
61 km
Alma-1
4075
Floodplain
and
lake
Floodplain
and
lake
3720
4080
3665
MFS
Baj-1
4090
Baj-1
map unit 1
3735
SB
m.b.R.L
mu. si sand gravel
Aalen-1
10 m
3680
m.b.R.L
mu. si sand gravel
Flodplain
and
fluvial channels
3755
Aalen-1
m.b.R.L
mu. si sand gravel

Fig.8



a



b

Fig.9

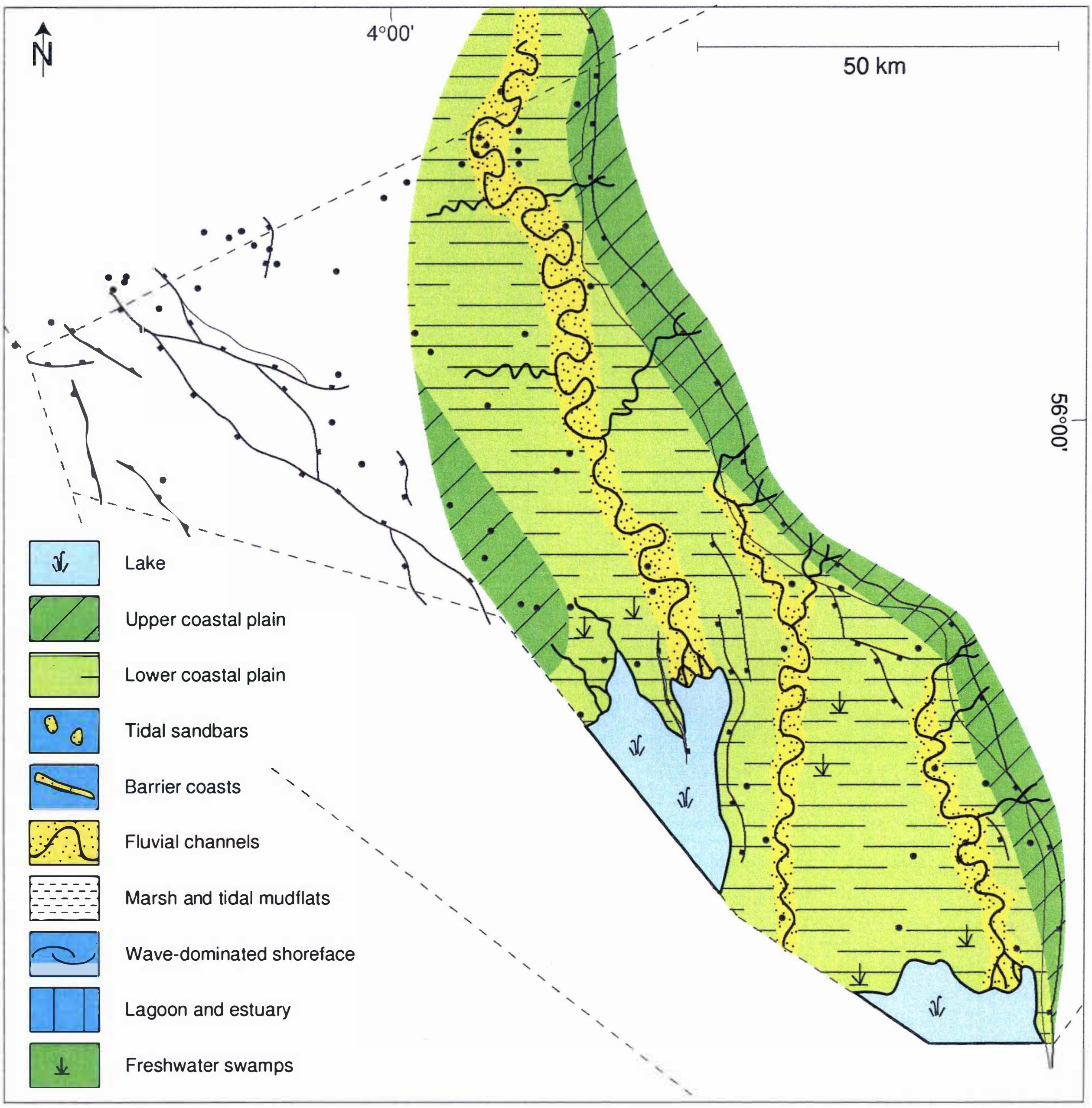
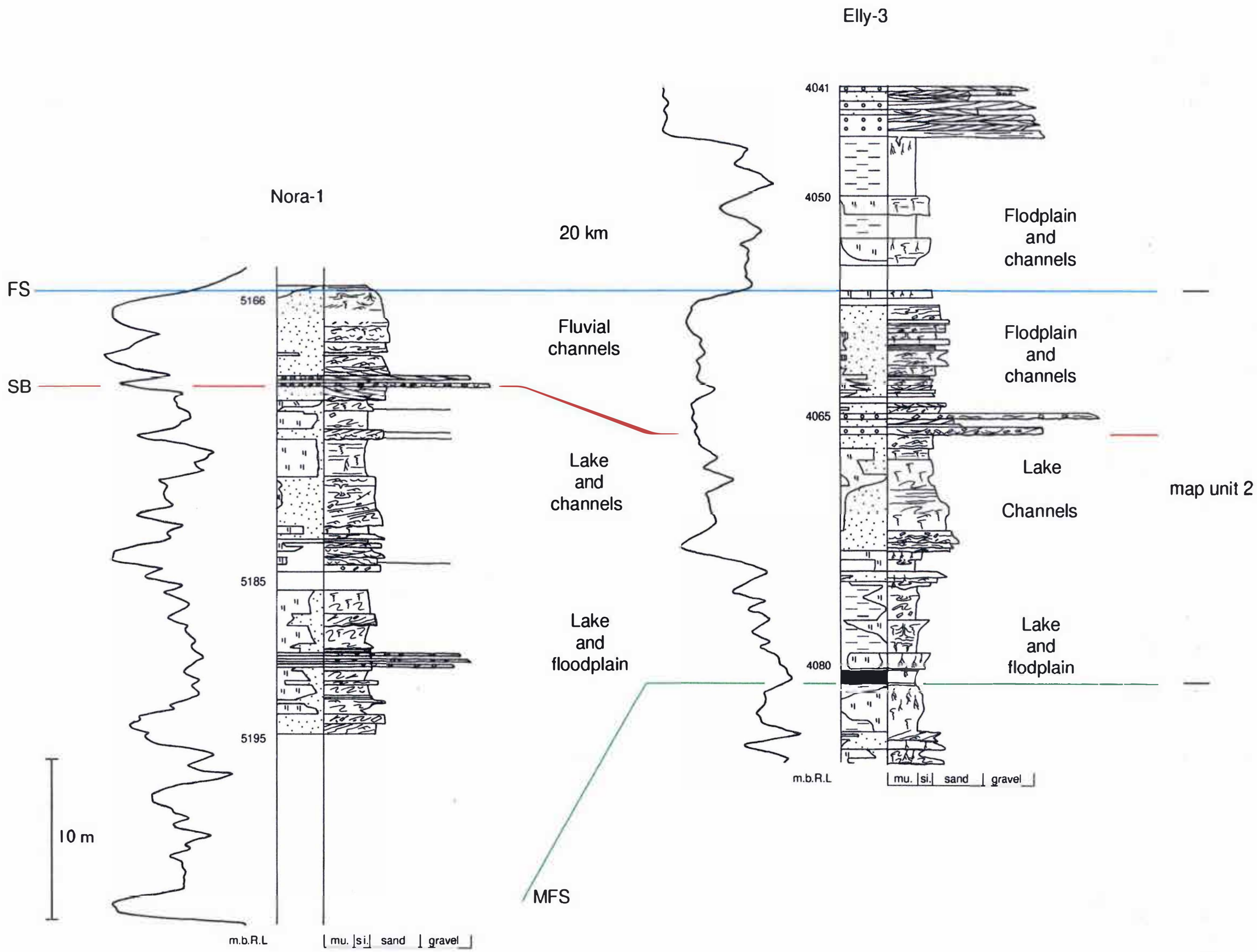

N
4°00'
50 km
56°00'
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps

Fig.10



Elly-3
Nora-1
20 km
FS
SB
MFS
5166
5185
5195
4041
4050
4065
4080
Fluvial channels
Lake and channels
Lake and floodplain
Flodplain and channels
Flodplain and channels
Lake
Channels
Lake and flodplain
map unit 2
10 m
m.b.R.L
mu. si. sand gravel
m.b.R.L
mu. si. sand gravel


Fig. 11

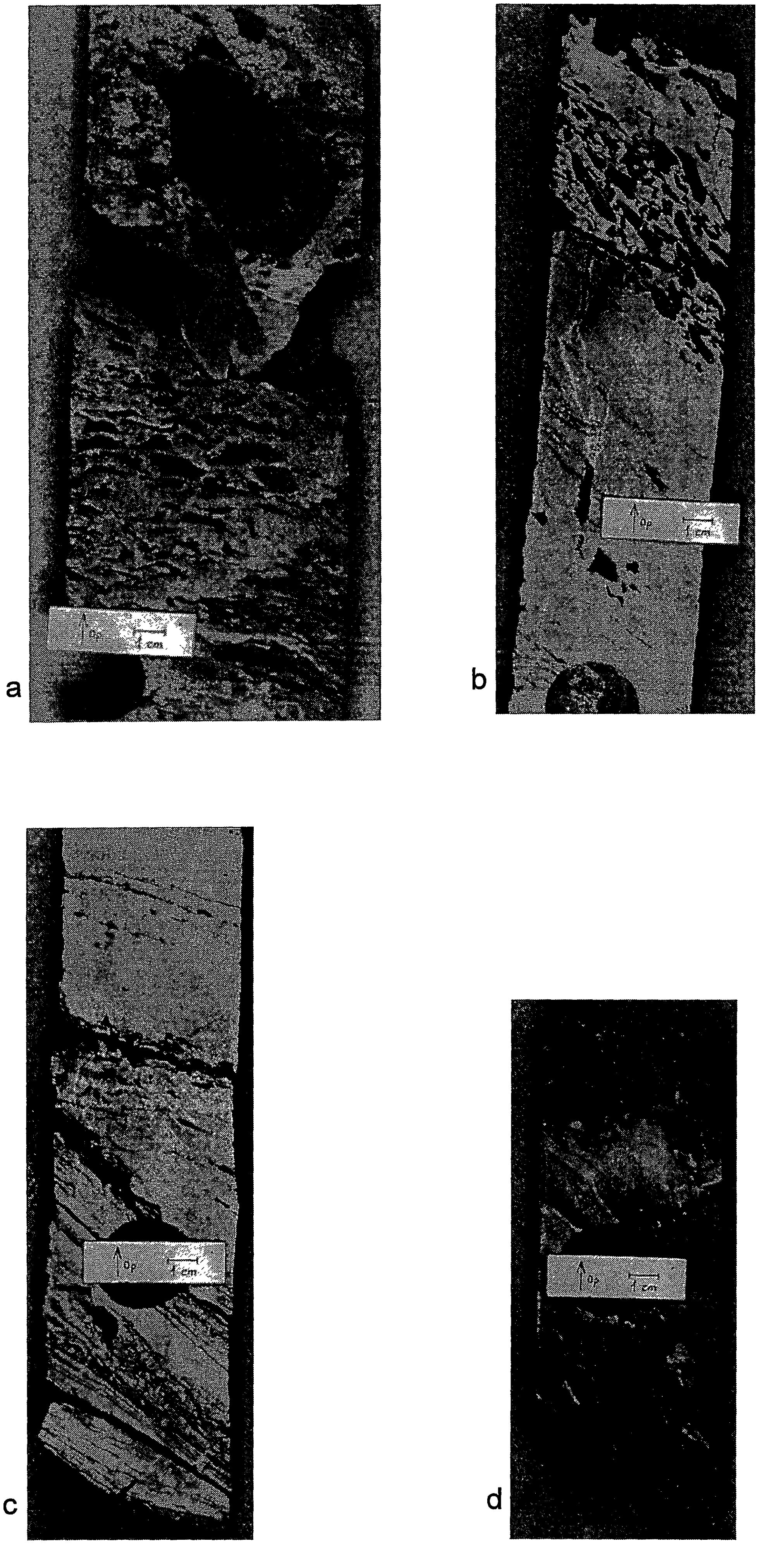



Fig.12

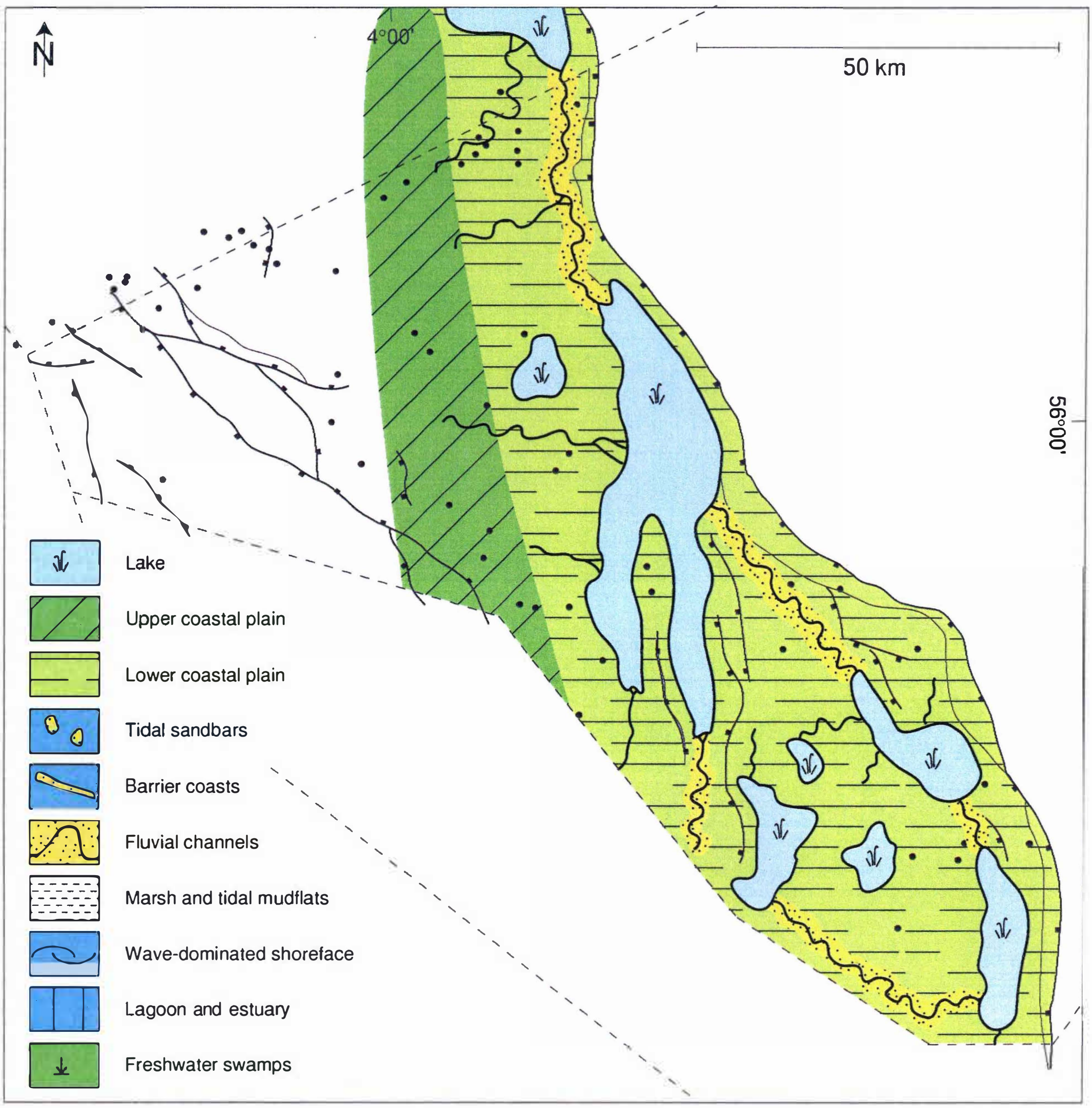

N
4°00'
50 km
56°00'
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps

Fig. 13

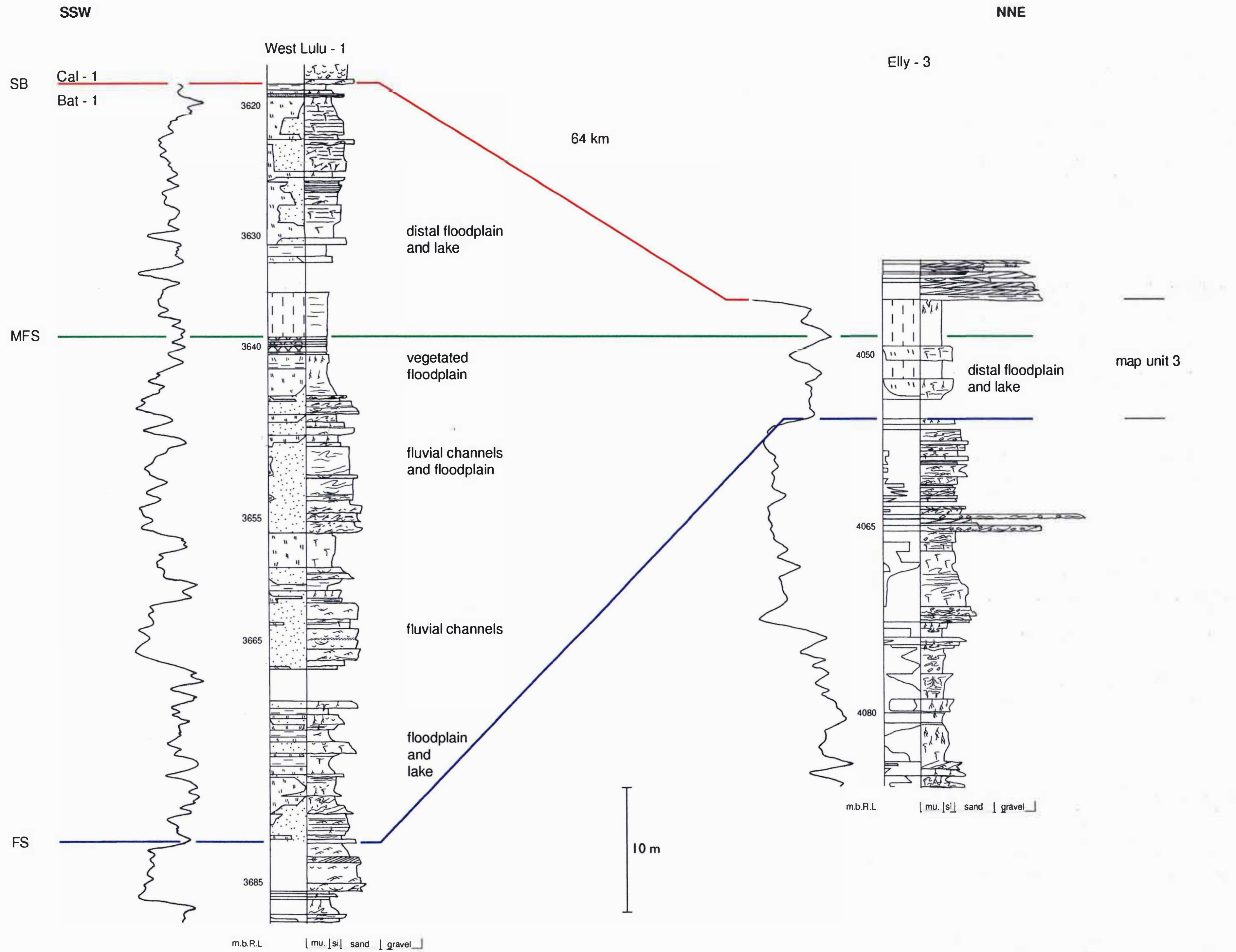

SSW
NNE
West Lulu - 1
Elly - 3
SB
Cal - 1
Bat - 1
MFS
FS
3620
3630
3640
3655
3665
3685
4050
4065
4080
64 km
distal floodplain and lake
vegetated floodplain
fluvial channels and floodplain
fluvial channels
floodplain and lake
distal floodplain and lake
map unit 3
10 m
m.b.R.L
mu. si. sand gravel
m.b.R.L
mu. si. sand gravel

Fig. 14

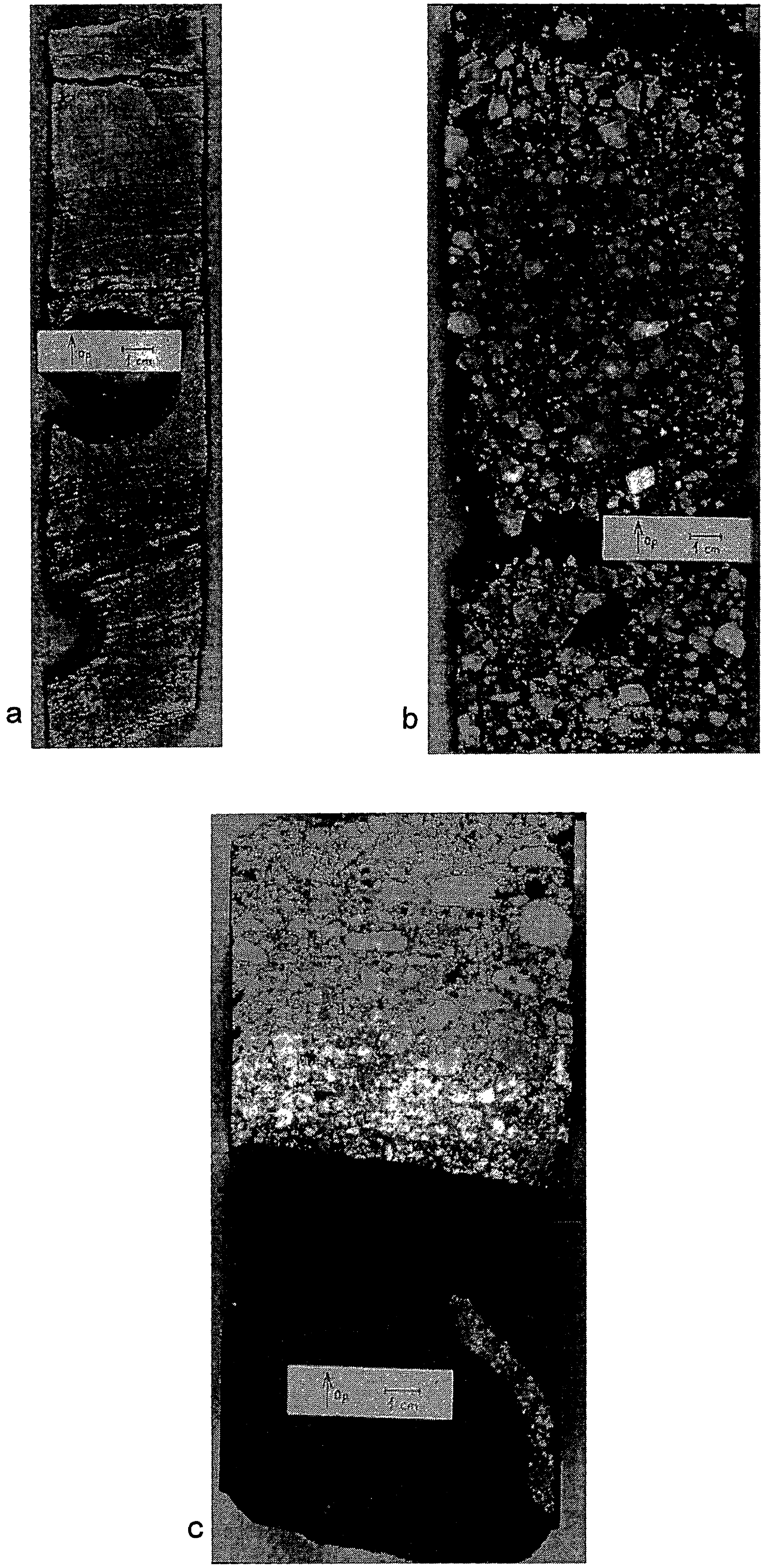
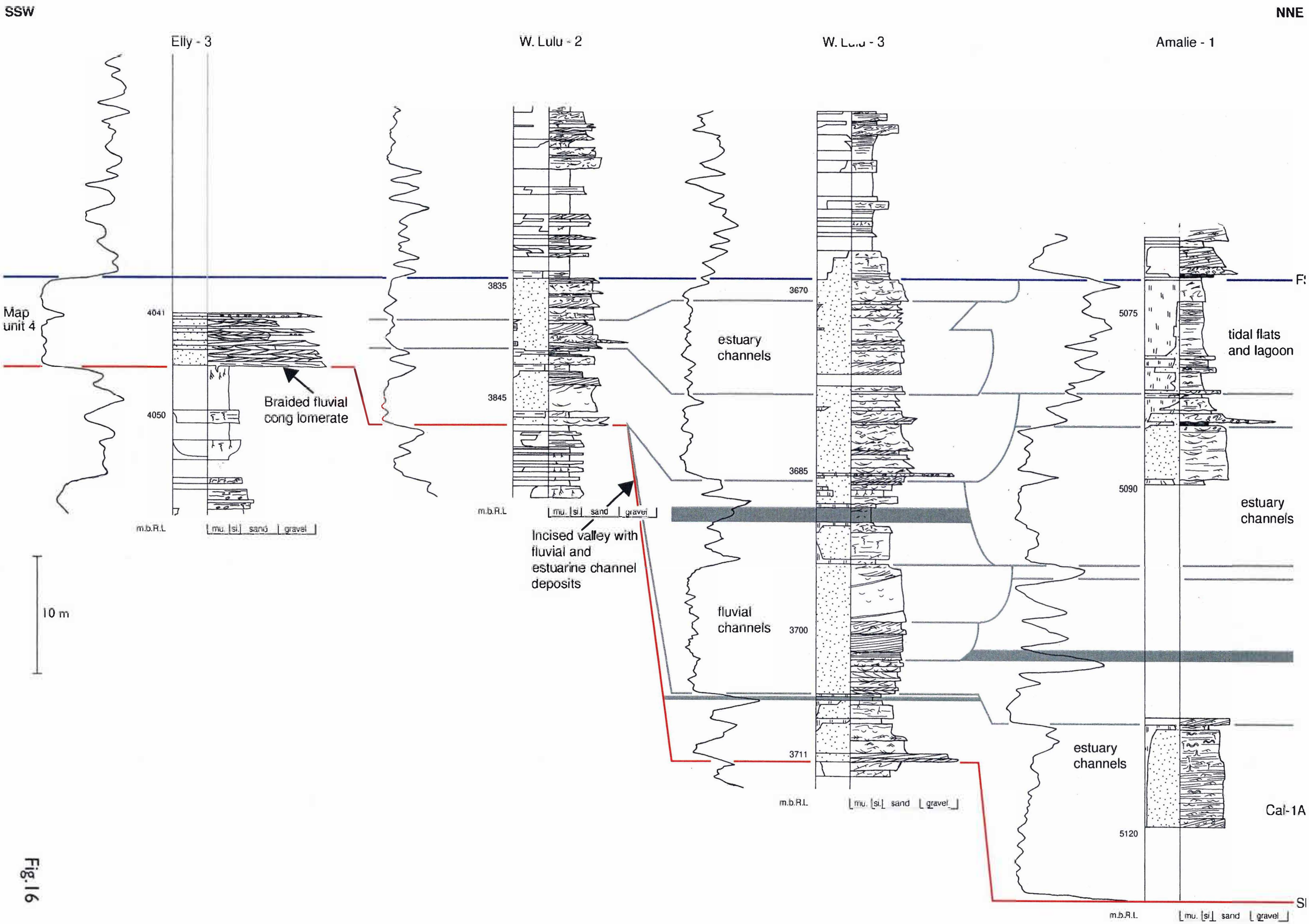



Fig.15



SSW
NNE
Elly - 3
W. Lulu - 2
W. Lulu - 3
Amalie - 1
Map unit 4
4041
4050
Braided fluvial conglomerate
3835
3845
Incised valley with fluvial and estuarine channel deposits
estuary channels
fluvial channels
3670
3685
3700
3711
5075
5090
5120
tidal flats and lagoon
estuary channels
estuary channels
Cal-1A
10 m
m.b.R.L.
mu. si. sand gravel


Fig. 16

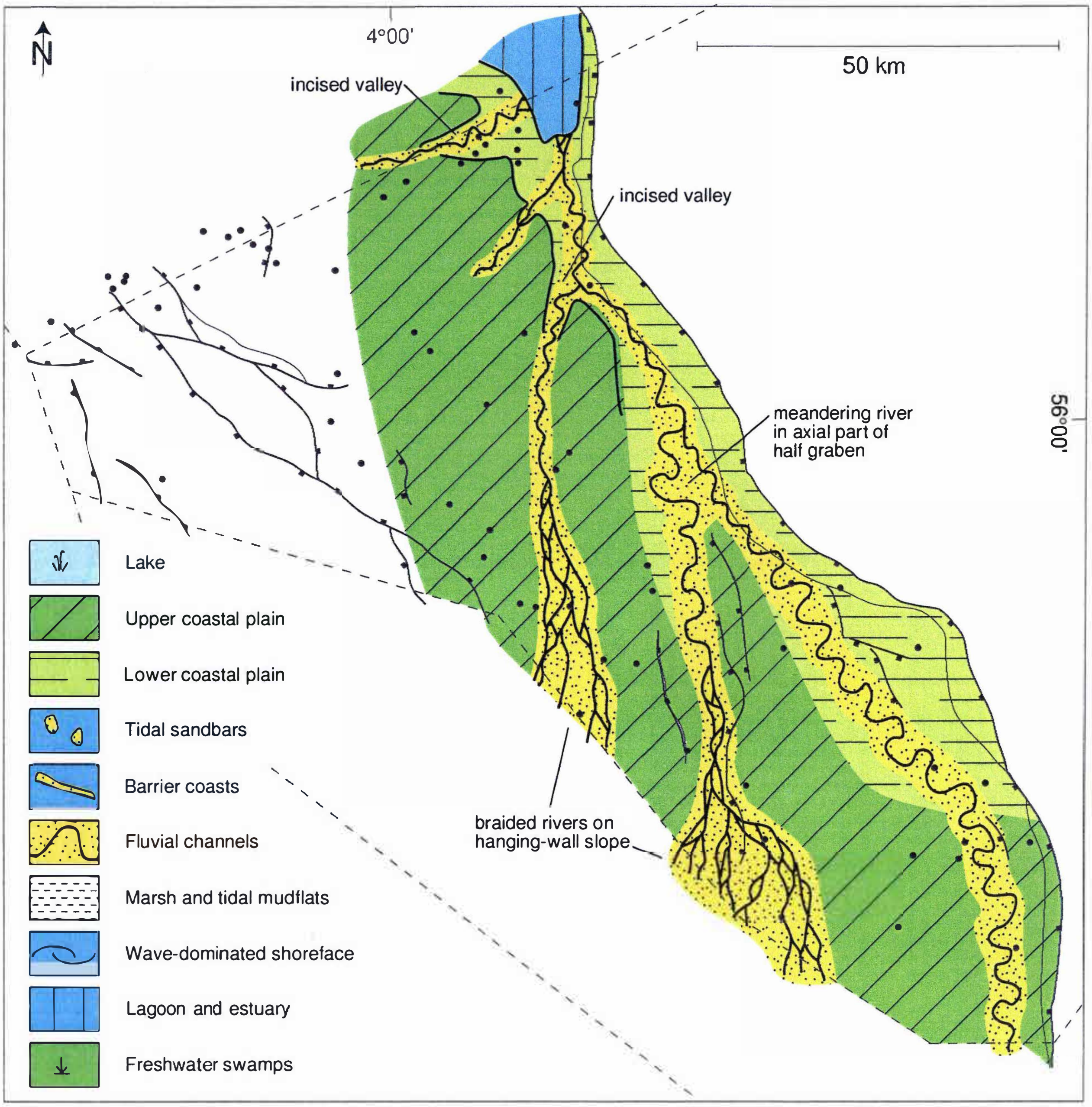
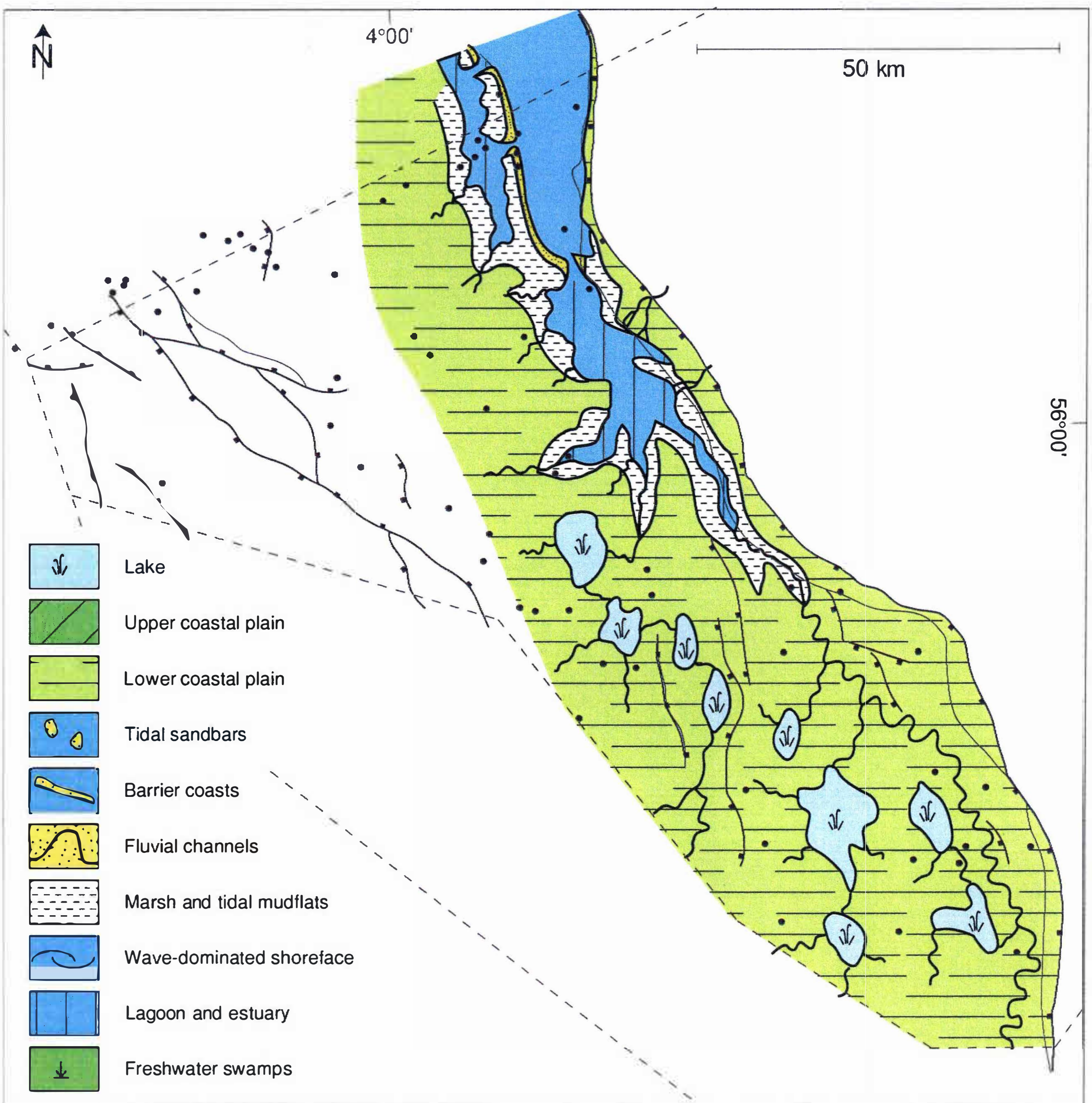

4°00'
50 km
N
incised valley
incised valley
meandering river
in axial part of
half graben
56°00'
braided rivers on
hanging-wall slope
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps

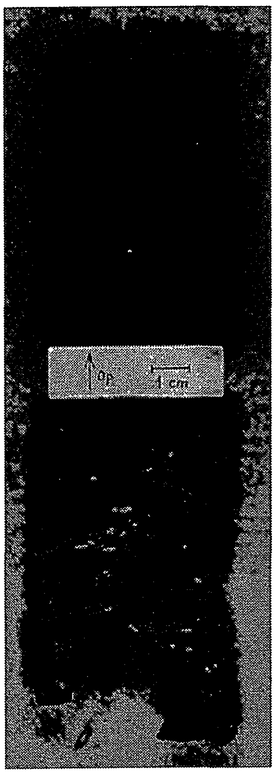
Fig. 17



N
4°00'
50 km
56°00'
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps


Fig. 18

a




b

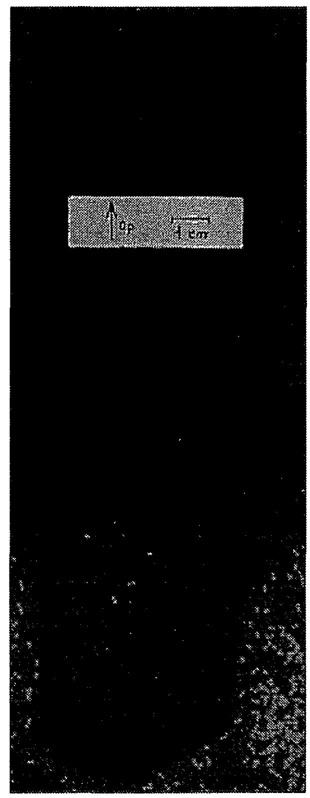



Fig.19

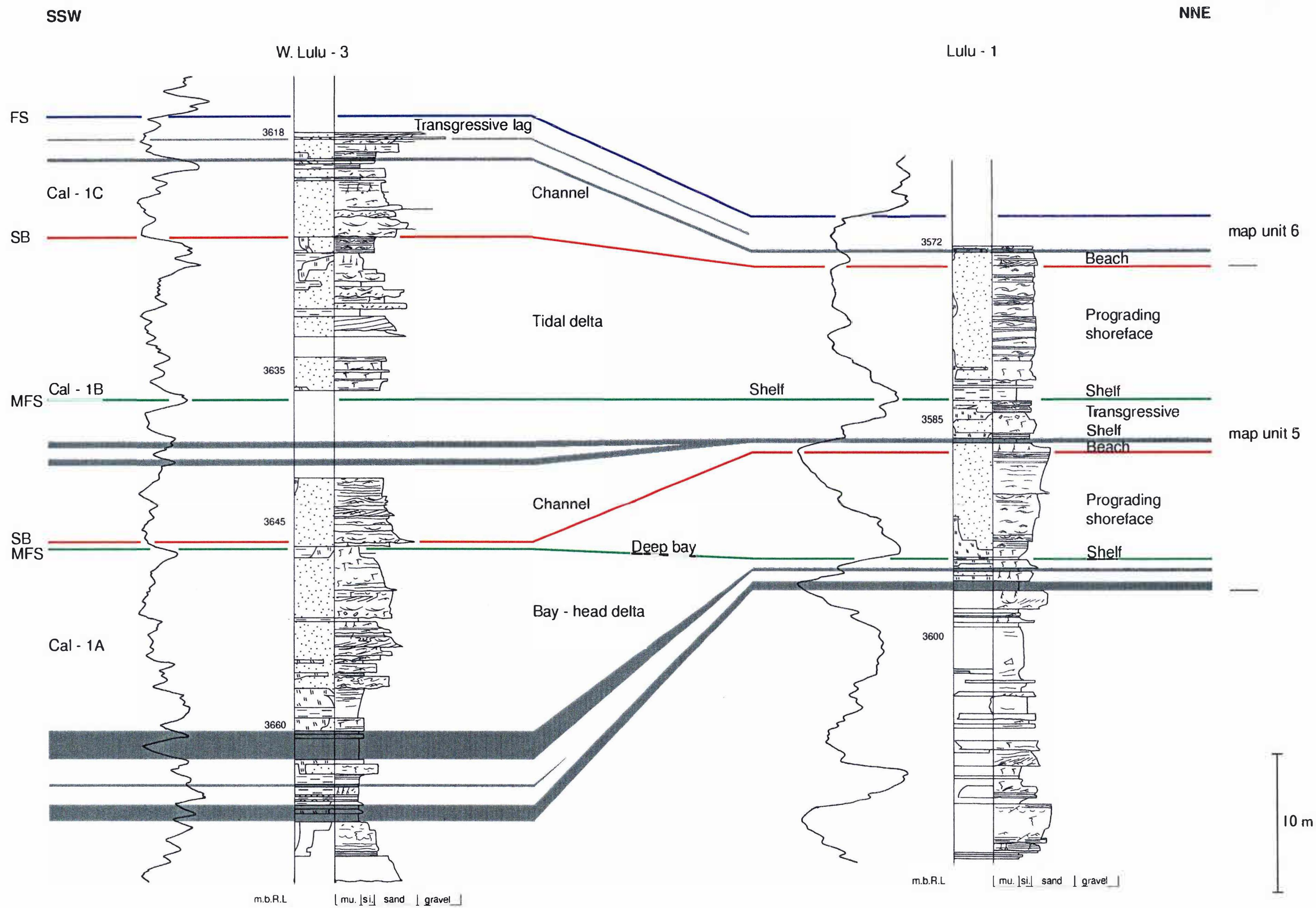

SSW
NNE
W. Lulu - 3
Lulu - 1
FS
Cal - 1C
SB
Cal - 1B
MFS
SB
MFS
Cal - 1A
3618
3635
3645
3660
3572
3585
3600
Transgressive lag
Channel
Tidal delta
Shelf
Channel
Deep bay
Bay - head delta
Beach
Prograding shoreface
Shelf
Transgressive
Shelf
Beach
Prograding shoreface
Shelf
map unit 6
map unit 5
10 m
m.b.R.L
mu. si. sand gravel
m.b.R.L
mu. si. sand gravel

Fig.20

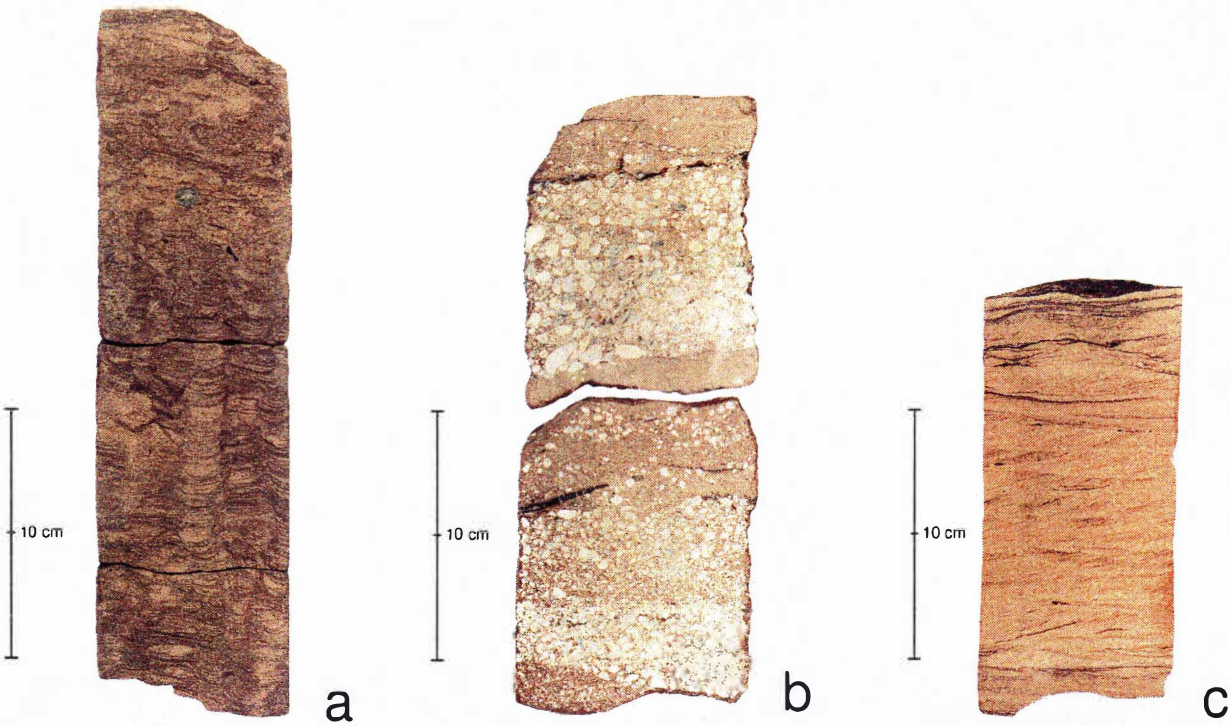



Fig.21

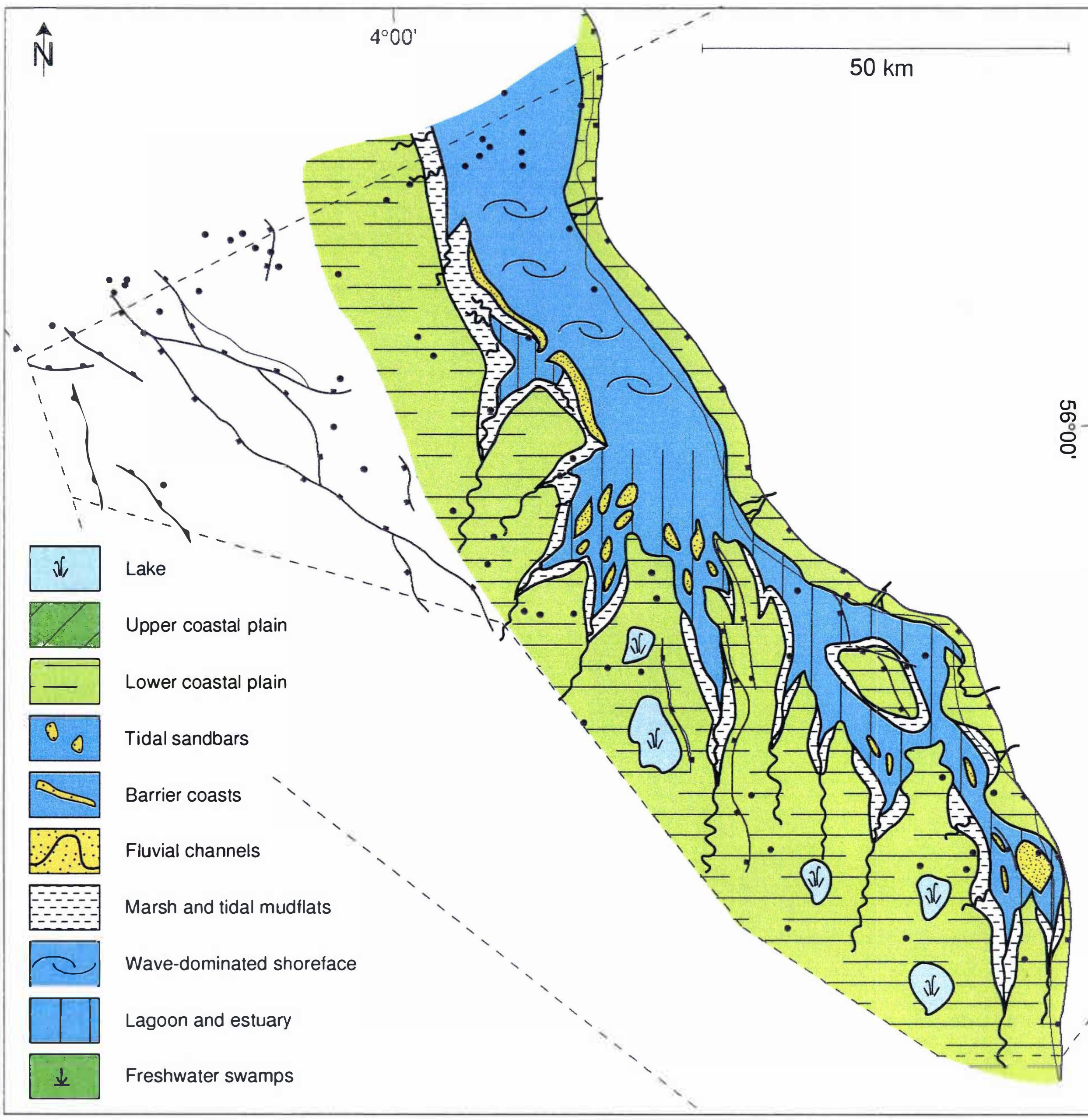
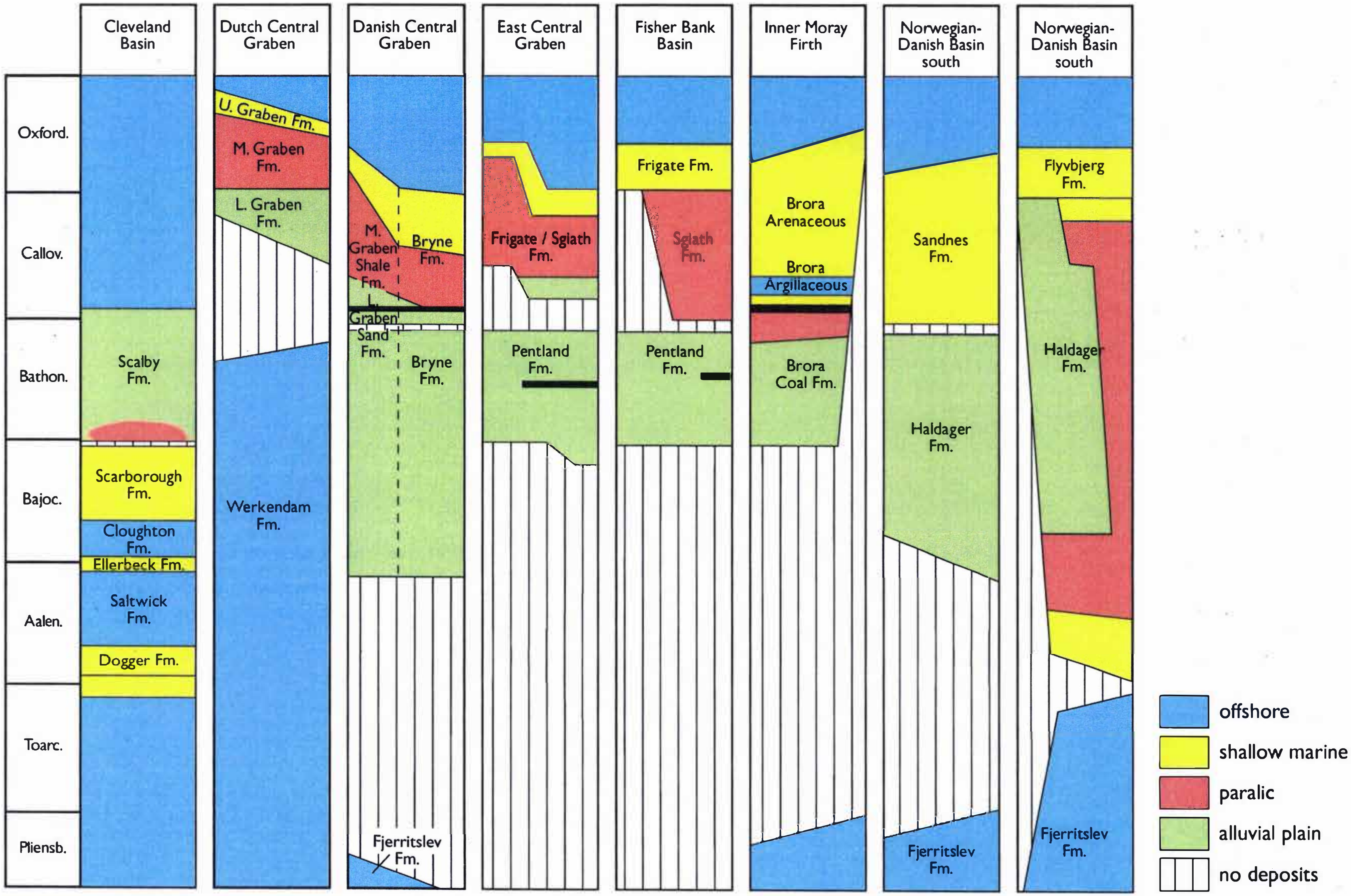

4°00'
50 km
56°00'
N
Lake
Upper coastal plain
Lower coastal plain
Tidal sandbars
Barrier coasts
Fluvial channels
Marsh and tidal mudflats
Wave-dominated shoreface
Lagoon and estuary
Freshwater swamps

Fig.22



Cleveland Basin
Dutch Central Graben
Danish Central Graben
East Central Graben
Fisher Bank Basin
Inner Moray Firth
Norwegian-Danish Basin south
Norwegian-Danish Basin south
Oxford.
Callov.
Bathon.
Bajoc.
Aalen.
Toarc.
Pliensb.
Scalby Fm.
Scarborough Fm.
Cloughton Fm.
Ellerbeck Fm.
Saltwick Fm.
Dogger Fm.
U. Graben Fm.
M. Graben Fm.
L. Graben Fm.
Werkendam Fm.
M. Graben Shale Fm.
L. Graben Sand Fm.
Bryne Fm.
Bryne Fm.
Fjerritslev Fm.
Frigate / Sglath Fm.
Pentland Fm.
Frigate Fm.
Sglath Fm.
Pentland Fm.
Brora Arenaceous
Brora Argillaceous
Brora Coal Fm.
Sandnes Fm.
Haldager Fm.
Fjerritslev Fm.
Flyvbjerg Fm.
Haldager Fm.
Fjerritslev Fm.
offshore
shallow marine
paralic
alluvial plain
no deposits


Fig.23

De Nationale Geologiske Undersøgelser
for Danmark og Grønland (GEUS)

*Geological Survey of Denmark and Greenland*

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Internet www.geus.dk

Please access the article Petersen, H.I. & Andsbjerg, J. (1996): Organic facies development within Middle Jurassic coal seams, Danish Central Graben, and evidence for relative sea-level control on peat accumulation in a coastal plain environment. Sedimentary Geology 106(3-4), p. 259-277 directly from the publisher at: https://doi.org/10.1016/S0037-0738(96)00015-2