DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/55

Sedimentological / Stratigraphic Study of the Elly/Luke license area

Peter N. Johannessen, Claus Andersen, Karen Dybkjær, Jussi Hovikoski & Rikke Weibel

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

G E U S

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Preface

This brief report was prepared to fulfil the requests described in the RFQ-16-918 of Wintershall Noordzee B.V. regarding the “Sedimentological /stratigraphic study for Elly/Luke”.

The objectives and content of the study were defined by Wintershall to focus on the lateral and vertical reservoir extent and distribution of reservoir quality.
The study comprised a wide range of geo-scientific issues including seismic interpretation, well-log interpretation and correlation, biostratigraphy, diagenesis, and a core workshop.

Results have been communicated through e-mails, telephone and videoconference and a core workshop organized by GEUS. The report summarizes the findings and proposes further work primarily regarding biostratigraphic, diagenetic and sedimentological analyses.

Contents

1 Background

The Elly-Luke gas/condensate discoveries are located in blocks 5504/05 and 5504/06, east of the Mads High on the southern part of the Heno Plateau in the Danish Central Graben. It contains the Elly Field discovered in 1984 by the Elly-1 well and appraised in a down-faulted position in 1987 and 1992 by the Elly-2 and Elly-3 wells drilled on the eastern hanging wall of the block. The adjacent Luke accumulation was found in 2009 and early 2010 when Luke-1X proved the presence Middle Jurassic sandstones close to the gas-water contact. The well was sidetracked updip closer to crest of the Luke structure, and Luke-1XA encountered gas-bearing reservoir sandstones with a better net sand content and porosities. Middle Jurassic sandstones of the Bryne Formation contain gas in structural closures under HPHT conditions, sealed by Middle–Upper Jurassic shales. Main uncertainties are reservoir development, structural and stratigraphic compartmentalization and producibility. The discoveries were relinquished by the DUC Group in 2013.

Wintershall acquired the license area at the 7th Danish license round. The content of the performed study was designed by Wintershall with the scopes of defining sedimentological and stratigraphical input to their reservoir considerations regarding the vertical and lateral extent of the reservoir and the distribution of the reservoir quality.

The necessary data for the study was provided by Wintershall according to the tender material RFQ-16-918. The study was kicked-off at a meeting held at the premises of Wintershall in Rijswijk, the Netherlands, and is concluded with this report.

2 Introduction

This study was kicked-off at a meeting held at Wintershalls premises in Rijswijk, The Netherlands the 12th October 2016 with participation of representatives from Wintershall and GEUS, where the scopes of the study were reviewed by Wintershall and discussed among the participants.

The study comprises four main topics:

- review of the structural complexity based on seismic expression;
- review of avalible biostratigraphic data;
- interpretation of the depositional evolution for generating input and constrains to a static reservoir model; and
- review of the degree of diagenesis in the reservoir sandstones.

The study has been based on material provided by Wintershall supplemented by information avalible at GEUS. The present seismic resolution, as well as the structural complexity of the study area, hinders a detailed seismic stratigraphic breakdown and identification and mapping of the distribution of the reservoirs in the stratigraphic succession of interest. In Appendix 1 a number of requested seismic profiles and maps are shown.

The existing biostratigraphic data was reviewed thoroughly in an attempt to establish the best possible stratigraphic framework for the breakdown and correlation of the succession of interest based on the well-logs. The evaluation of the existing biostratigraphy, which have been conducted by various companies over several decades, shows highly variable quality and documentation. Due to non-marine to marginal marine depositional environments, only a few stratigraphically useful palynomorphs have been recorded from the Middle Jurassic to lower Oxfordian succession. It is thus not possible at present to establish a detailed biostratigraphic framework for the succession. Firm indications of Bajocian–Bathonian are not found in the present data set. On the other hand, the possibility of a Bathonian age for the oldest parts of the succession cannot be excluded; based on the available biostratigraphy the Bryne–Middle Graben interval may thus be limited to the late Middle Jurassic-early Late Jurassic (Callovian–Oxfordian).

During the core workshop on the cores from Elly-3, Falk-1 and Luke-1X, which in combination cover most of the stratigraphic interval of interest, new crucial observations were recognized and discussed among the participants. The observations have led to minor revisions of GEUS´ preliminary core interpretations of the Elly-3 and Luke-1X cores. Detailed observations on the cores indicate occurrence of several intervals with brackish-marine influence, which probably contain sporadic dinocysts that have the potential for being of stratigraphic importance. In combination with the result of the biostratigraphic evaluation of the existing reports, the core observations have generated new insights, which are recommended to be tested in further work.

The insights concerning the presence of estuarine-brackish depositional environments and the evaluation of the age-dating have led to the construction of two new possible sequence stratigraphic models of the Bryne–Middle Graben interval, which are displayed on the enclosed well-log panels. The two proposed sequence stratigraphic models are here termed the "**layer cake model**" and the "**incised valley model**" and are both illustrated by two well logs panels that together display the nine wells included in the study. The two models represent two very different and yet possible solutions to the present data; it is thus emphasized that both models may be modified as the herein proposed well-log correlations are non-conclusive and that other correlations are possible within the presently available constrains. The presented well-log panels illustrating the "**incised valley model**" form the basis for the constructed paleographical maps and for comments regarding the correlation panels provided by Wintershall.

The cores were macroscopically inspected for lithology and cementation and the observations were compared to the sparse petrographic and diagenetic data available.

A revision of the lithostratigraphic subdivision is also suggested for the wells Elly-2 and Elly-3, in which the lower part of the Lola Formation here is regarded as the Middle Graben Formation, and in Jens-1 where the Bryne Formation is recognizes between the Fjerritslev and Middle Graben formations.

The outcome of these four topics is described in separate chapters with an attempted integration in the conclusion. It is concluded that GEUS favors the "**incised valley model**", as this accommodates the presently available data best; it is however recommended to initiate further investigations that have the potential of testing the proposed model.

3 Geological setting

The Central Graben forms the southern part of the North Sea rift system. Active rifting toke place in the Triassic and in the late Middle Jurassic–Late Jurassic with the development of a complex of NNW–SSE trending half-grabens (e.g. Andsbjerg and Dybkjær 2003 and references therein). The Coffee Soil Fault forms the eastern margin bounding fault of the approx. 150 km long Danish part of the Central Graben, whereas the Mid North Sea High forms the western limit (e.g. Japsen et al., 2003). In Early Jurassic times marine mudstones of the Fjerritslev Formation were deposited over most of the Danish area that formed a common shallow shelf area (Michelsen et al., 2003). During the latest Early Jurassic–earliest Middle Jurassic much of the Danish area was uplifted and eroded with the formation of the widespread “Mid-Cimmerian Unconformity, MCU” also called the base Middle Jurassic Unconformity (e.g. Michelsen et al. 2003; Nielsen 2003 and references therein). Deposition resumed in the Danish part of the Central Graben during the Middle Jurassic with deposition of the sandstone-dominated Bryne and Lulu formations and the mudstone-dominated Middle Graben Formation (Michelsen et al. 2003). These units are restricted to the Søgne Basin, Tail End Graben and the Salt Dome Province and deposition of flood plain – coastal plain sediments was initially focused in the eastern part as accommodation space was generated along the Coffee Soil Fault (Michelsen et al. 2003; Surlyk and Ineson 2003). A marked unconformity between the uppermost Bathonian and Callovian sediments was interpreted by Surlyk and Ineson (2003) to reflect a change in basin subsidence. An overall relative sea level rise followed, and floodplain and estuarine bay mudstones, fluvial–estuarine sandstones and common coals were deposited in an overall low-energy paralic environment during the Callovian to earliest Oxfordian. In the deepest parts of the rift-system Callovian fluvial channels became tidally-influenced estuaries (Johannessen et al., 2012).

Regional dating of the marine incursions in the Danish Central Graben demonstrates that the transgression spread from the north toward the south (Johannessen and Andsbjerg 1993). The increasingly marine influence during the Callovian–Oxfordian reflects resumed subsidence that caused overstepping of the former uplifted areas and highs to west with marine influence commencing in the east and showing a gradual westward onlap.

4 Review of the seismic interpretation of the Elly/Luke area

During the kick-off meeting at Wintershall it was suggested by Mohamed Ashtiwi and Anett Hufe that GEUS should focus the seismic review on creating at set of arbitrary profiles across the Elly/Luke structures to illustrate the structural complexity based on the Wintershall 2016 interpretation on band pass filtered data of the DUC05 3D survey. This dataset is a clear improvement compared to the original Maersk Oil processing as multiples have been considerably suppressed. It was further agreed that time isochores should be generated of the interpreted intervals.

Following material was subsequently supplied by Wintershall:
Band pass filtered DUC05 SEG-Y data covering a rectangular area of c. 20 km x 18 km. The area includes from north to south the location of the Falk-1 and Skarv-1 wells, and from west to east the Elly-1 location and the Jens-Valdemar inversion fault zone.

Three horizon files were included in the data package: *T_Bryne_Time_2016, Mid_ Cimmerian_Un_2016* and *T_Triassic_Time_2016*. The horizons are interpreted in a dense grid (every 4 lines and traces) in the core area of the Elly and Luke discoveries. Outside the interpretation density is less and variable.

The data were loaded on GEUS' Landmark system.
In addition PNG-files of Ant Attribute at top Bryne sst. and Spectral Decomposition (10-15-24 Hz) were supplied.

4.1 Structural profiles

Seven (7) structural profiles (SeisWorks screen dumps) are shown in appendices 1a–1g. The arbitrary lines have been selected to give a general overview of the structural complexity of the mapped area with emphasis on the core area and on well ties. On each profile the Wintershall horizon interpretation of the three markers is carefully traced and visual fault cuts are marked. For reference the BCU reflector is marked in purple. The location of the arbitrary lines through the seismic volume is indicated on the inset map of the SeisWorks *T*_Bryne time structure map on each section. The exact position (in UTM-coordinates) of each profile is given in Appendix 2.

It is noteworthy that the wellbores of Elly-2, Elly-3 and Luke-1X appear to be close to minor fault traces cutting the Bryne Fm. interval. These observations are in line with the ant attribute map generated by Wintershall. Dipmeter analyses also suggest presence of possible faults in Elly-2, Elly-3 and Falk-1

(Erikfiord 2006) The Mid_Cimmerian_Un marker is clearly shown as an unconformity surface in profiles 4, 5 and 7 (appendices 1d, 1e and 1g).

Profile No 1

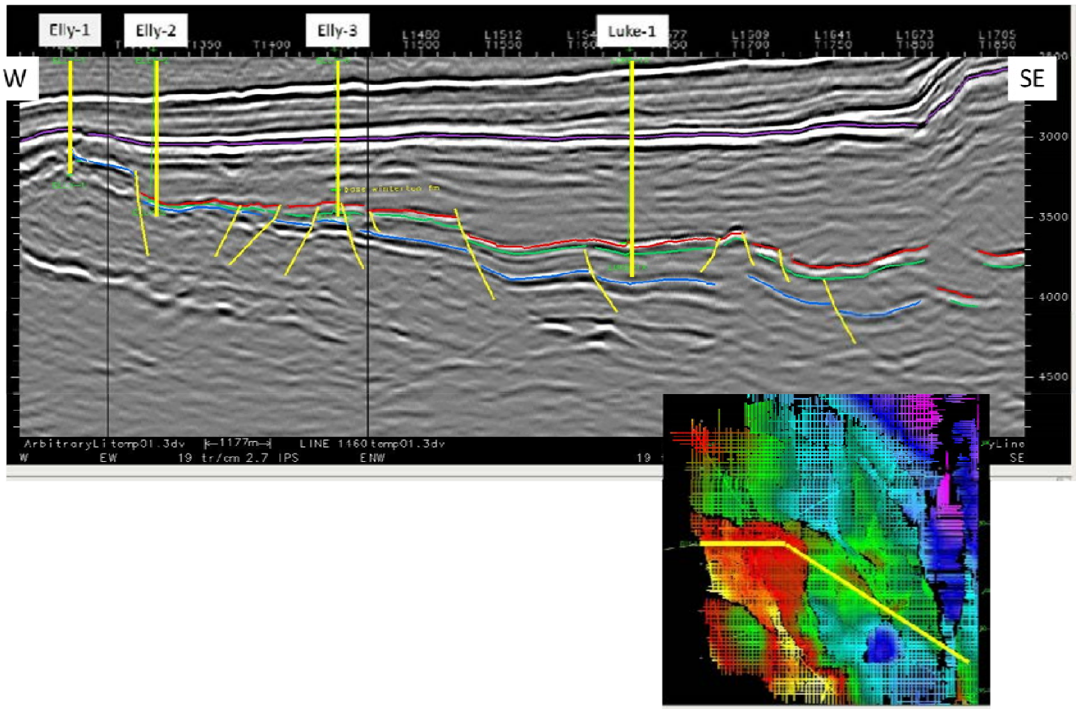


Fig. 4.1. Example of structural profile.

4.2 Time isochore maps

The time isochores of the Bryne Fm. and Lower Jurassic have been calculated by subtraction of the horizon files of *T_Bryne* from *Mid_Cimmerian_Un* and *Mid_Cimmerian_Un* from *T_Triassic*, respectively (appendices 1i–1j). The overall wedge-shaped Jurassic intervals with increasing thickness towards east are well illustrated on the SeisWorks maps. Maximum time thickness of the Bryne Fm. interval up to 80 ms on the Elly-segment is found south of the Elly-3 location. Similarly max time thicknesses of 80 ms exist in a broad depocenter situated structurally down-dip SW of Luke-1X (see Fig. 1). The Lower Jurassic seismic interval has a wider range in thickness (up to 200 ms) with the depocentres confined to NW-SE-trending halfgraben-like features truncated by the Mid Cimmerian unconformity.

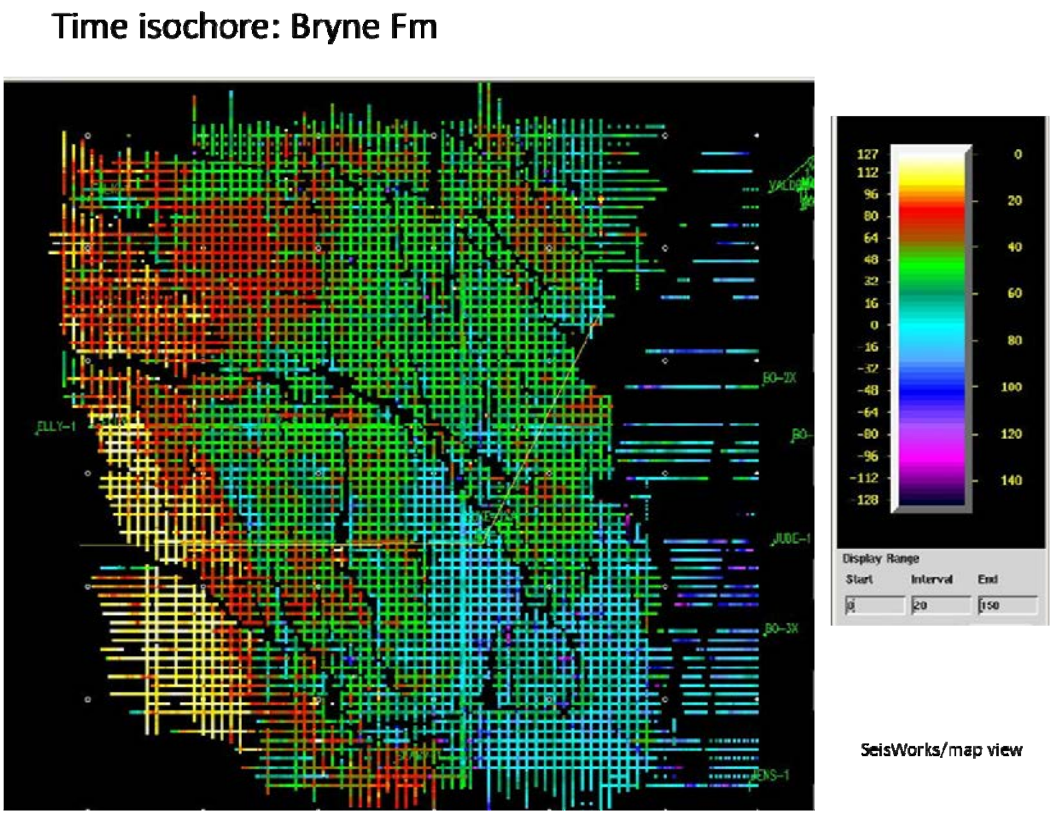


Fig. 4.2. Example of time isochore map.

4.3 Attribute maps

An edge detection attribute map on an interpolated *T_Bryne* surface is given in Appendix 1k. The Wintershall horizon file on the surfaces was prior to running the attribute extraction in SeisWorks interpolated with a gap of 5 between traces and lines. The resulting map clearly exhibits the major fault traces and confirm the location of major faults also depicted on the ant attribute.
In order the check if some geological trends could be localized crossing the dominant fault patterns amplitude extractions of the Bryne Fm. interval were attempted. Unfortunately neither the RMS-amplitude nor the max negative amplitude attributes of the interval (appendices 1l and 1m) show any patterns, which differ from the patterns on Wintershalls spectral decomposition attribute.

4.4 Recommendation for further work

It is our understanding that Wintershall is in the process of acquiring the PSDM-processed DUC05 data from Maersk Oil to be used for further seismic studies including AVO-work. It is our opinion that further work on the present band pass filtered data is not needed.

5 Biostratigraphy

Existing biostratigraphic studies of the Bryne, Lulu and Middle Graben formations (Middle to lowermost Upper Jurassic) in 9 wells (Edna-1, Elly-1, Elly-2, Elly-3, Falk-1, Jens-1, Luke-1X, Luke-1XA, Skarv-1) from the Danish Central Graben have been evaluated in detail to provide the best possible stratigraphic framework based on presently available data. The studies are presented in the "standard" biostratigraphic reports, see below. A comparison of the interpretations (lithostratigraphy, chronostratigraphy and bioevents) from these reports with data from the PetSys project, are presented in a series of "Stratigraphic Summary Charts"- one for each well (Enclosures 1-8). No Summary Chart was produced for Luke-1XA as no bioevents were recorded from this well.

The correlations between bioevents and chronostratigraphy are (as in the PetSys project) based on: Herngreen & Wong (1989), Batten & Koppelhus (1996), Riding & Thomas (1992), Poulsen (1996), Abbink (1998), Herngreen et al. (2000) and Poulsen & Riding (2003).

The biostratigraphic data used in the PetSys project were collected from all available consultancy reports, published studies and internal GEUS-reports. GEUS data from Elly-2 was extracted from the report by Dybkjær (2007), prepared for Wintershall Noordzee B.V.

5.1 Edna-1, 3891 m – 3900 m

Report

Bailey, H.W., Forbes, G. 1984. Edna-1. Stratigraphical/Paleontological final report – Depth interval: 340´–13.767´. Paleoservices Ltd. 44pp.

Samples analysed for palynology

DCS´s: 72 DCS were processed for palynology within the interval 3045 m – 4196 m (9.990´–13.767´), each representing 10´or 20´. There is no list of analysed DCS´s presented in the report, but in their Enclosure 2 data from a DCS with base at 3895 m (12.780´) is shown.

SWC´s: 3892 m, 3895 m, 3900m (12.766´, 12.778´, 12.796´) (See Enclosure 2).

Comments to the recorded bioevents

Nannoceratopsis pellucida appears downhole (has it´s top-occurrence) in the DCS at 3892 m – 3895 m (12.770´–12.780´). *N. pellucida* is a long-ranging taxa (Bajocian–Kimmeridgian according to Paleoservices, and Upper Bajocian to lowermost Kimmeridgian according to Riding & Thomas 1992). The recording here was (by Paleoservices) assumed to be caved. In the PetSys project this occurrence was assumed to be *in situ*. Based on a combination of log-correlation and biostratigraphy this level was interpreted as representing the Callovian–Oxfordian boundary interval.

SWC at 3898 m (12.787´): contains only spores and pollen, all long-ranging.

Interval below
The last occurrence of common *Chasmatosporites* spp. was found at 3922 m (12.866´) (SWC). This is a good marker for the Pliensbachian. The Upper Jurassic is interpreted, both by Paleoservices (1984) and by PetSys, to rest unconformably on the Lower Jurassic Fjerritslev Formation.

Interval above
The last occurrence of *Scriniodinium crystallinum* was found at 3841 m (12.600´). This level is interpreted both by Paleoservices and in the PetSys project as Oxfordian, although the last occurrence of *S. crystallinum* is in the Lower Kimmeridgian according to the literature (e.g. Riding & Thomas 1992).

Caving/reworking
See above.

Literature
Paleoservices only refers to studies of ostracods and foraminifera. As the study is from 1984 available literature presenting ranges of stratigraphically important palynomorphs were very limited.

Comments
Paleoservices writes the following for the interval referred to the Bryne Formation: “The absence of definite paleontological data through this interval makes dating very difficult”.

New/supplementary studies
There seems to be a potential for achieving a more precise dating of the interval above the Bryne Formation (down to 3901 m (12.800´)) as the recorded bioevents (e.g. the top *S. crystallinum* and the top of *N. pellucida*) are interpreted by both Paleoservices and in the PetSys project to occur too low.

5.2 Elly-1, 3388 m – 3483 m

Report

Ball, K.C., Chance, S.J., Forbes, G. 1984. Well Elly-1. Stratigraphical/Paleontological final report (Interval 280´– 12.491´). Paleoservices Ltd. 43pp.

Samples analysed for palynology (within the "?Bream equivalent" interval)

DCS´s: There is no list of analysed DCS´s presented in the report, but in their Enclosure 2 data from the DCS´s are shown.

SWC´s: 3388 m, 3405 m, 3421 m (11.114´, 11.170´, 11.224´) (See their Enclosure 2).

Comments to the recorded bioevents

Scriniodinium crystallinum has its last occurrence in the SWC at 3388 m (11.114´). The last occurrence of *S. crystallinum* occurs in the Lower Kimmeridgian according to Riding & Thomas (1992). Paleoservices uses it as indicating a basal Kimmeridgian marker.

Interval below

No stratigraphically usefull palynomorphs were recorded from the interval from 3438 m – 3517 m. In the DCS from 3517 m (11.540´) the presence of *Apiculatisporites plicatus* indicates an Anisian (Middle Triassic) age. A Triassic age is further supported by the presence of *Aequitriradites minor* below 3533m (11.590´) (in DCS´s). Paleoservices (1984) interpreted the unconformably Triassic-Jurassic boundary to be located at 3438 m, while this boundary in PetSys was interpreted as being located at 3483 m.

Interval above

The consistent occurrence of *Gonyaulacysta jurassica* from 3310 m (10.858´) and downwards indicates according to Paleoservices an Early Kimmeridgian age. In Petsys the last occurrence of common *G. jurassica jurassica* was used as indicating the top of the *Mutabilis* chronozone (Upper Kimmeridgian).

Caving/reworking

Caved Jurassic palynomorphs were recorded in the DCS´s from the Triassic interval.

Literature

Paleoservices only refer to studies of ostracods and foraminifera. As the study is from 1984 available literature presenting ranges of stratigraphically important palynomorphs were very limited.

Comments
Paleoservices indicate the top of the Triassic at 3438 m based on “regional lithological evidence”, while it was interpreted to be located at 3483 m in the PetSys project based on correlation of log-patterns.

Paleoservices writes: ”There is no paleontological evidence indicating the presence of Middle or Early Jurassic strata in this well”, and further “There is no direct evidence for the presence of Late Oxfordian sediments”. The Oxfordian interval from 3468 m – 3483 m as indicated by PetSys is based on correlation of log-patterns.

New/supplementary studies
In order to test the presence of Oxfordian as suggested in the PetSys project, and to try to locate the top of the Triassic with more confidence, a detailed study of the interval from 3505 m – 3388 m is suggested.

5.3 Elly-2, 3861 m – 4032 m

Reports
Chance, S., Shaw, D., 1988. Elly-2. Biostratigraphy interval 1.260´– 13.591,5´ TD. Paleoservices. 45pp.

Dybkjær, K., 2007. Palynological subdivision of selected wells from the Danish Central Graben. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2007/23.

Samples analysed for palynology
Paleoservices (1988): DCS´s: 7 DCS were processed for palynology within the interval 3861 m – 4032 m (12.666´–13.229´), each representing 10´. There is no list of analysed DCS´s presented in the report, but their presence is shown in the rangecharts. SWC´s: 13 SWC samples were processed for palynology within the interval 3861 m – 4032 m (12.666´– 13.229´).
Dybkjær (2007): 15 SWC samples and 2 DCS within the interval from 3861 m – 4032 m (12.666´– 13.229´).

Comments to the recorded bioevents
Scriniodinium crystallinum has last occurrence in the DCS at 3868 m (12.690´) (Paleoservices 1988). This last occurrence indicates an Early Kimmeridgian age.

Four stratigraphically important dinocysts taxa occur in the sidewall-core at 4025 m (13.204´); *Dichadogonyaulax sellwoodii*, *Compositosphaeridium polonicum*, *Rigaudella aemula* and *Gonyaulacysta jurassica* (Paleoservices

1988; Dybkjær 2007). According to Riding & Thomas (1992) these dinocyst taxa occur within the following time-intervals:
C. polonicum ranges from the earliest Callovian to the late Oxfordian.
R. aemula ranges from the latest Bathonian? – earliest Callovian to the middle Oxfordian.
G. jurassica ranges from the Bajocian to the early Volgian.

The first occurrence of *D. sellwoodii* is in Riding & Thomas (1992, their figure 2.9.) indicated in the late Bajocian, while the last occurrence is shown in fig. 2.11 to continue from the Callovian into the Oxfordian, although it is not included in fig. 2.12, showing the Oxfordian taxa. In Plate 2.8. they indicate the range of this taxa to be from late Bajocian to late Callovian. In the following, it is assumed that the continued range shown in fig. 2.11 is a drawing-mistake and that *D. sellwoodii* does not range into the Oxfordian.

In the PetSys study the co-occurrence of the four above mentioned dinocyst taxa was interpreted as indicating an Oxfordian age. However, based on the above mentioned discussion, the sidewall-core sample has to be Callovian in age.

Dybkjær (2007) further recorded the last occurrence of *Granuloperculatipollis rudis* in a SWC at 4032 m (13.229´) indicating an uppermost Triassic age.

Interval below

No stratigraphically useful palynomorphs were recorded from 4025 m (13.204´) or below, according to the study by Paleoservices. Dybkjær (2007) recorded an occurrence of *Granuloperculatipollis rudis* at 4032 m (13.229´) indicating a Triassic age.
Paleoservices (1988) located the top of the Triassic at 4032 m while in the PetSys project this unconformable boundary was interpreted to be located at 4025 m based on log-patterns and lithology.

Interval above

The last common occurrence of *Gonyaulacysta jurassica* was according to Palaeoservices recorded at 3745 m (12.286,5´). This event indicates a Late Kimmeridgian age.

Caving/reworking

Paleoservices recorded only caved palynomorphs from the DCS representing the Triassic. A single SWC was barren of palynomorphs.

Literature

For the interval of interest (Middle Jurassic to Lower Kimmeridgian), Paleoservices refers to an unpublished study by Riley (1978). Otherwise they only refer to studies of ostracods and foraminifera.

Comments

Paleoservices writes (for the interval 3917 m – 4032 m (12.850´- 13.229´)): “Due to the extremely poor quality of the cuttings samples and the occurrence of only rare age-diagnostic taxa in the sidewall core samples the precise age of this interval is difficult to determine”.

The sidewall-core at 4025 m (13.204´) from which the co-occurrence of four stratigraphically important dinocysts taxa were recorded (see above), represents a thin claystone layer within the interval referred to the Bryne Formation. The relatively diverse dinocyst assemblage in this sample, strongly indicate that the claystone layer is of marine origin and possibly represent a significant marine flooding surface. Very sporadic dinocyst assemblages were recorded from the two sidewall-cores at 13.194´ and 13173´, respectively, also located within the interval referred to the Bryne Formation. These sporadic occurrences indicate a depositional environment with a very limited marine influence.

New/supplementary studies

GEUS performed a study of SWC samples and DCS from Elly-2 for Wintershall Noordzee (Dybkjær 2007), among others 15 SWC samples and 2 DCS within the interval from 3861 m – 4032 m (12.666´– 13.229´). The bioevents recorded in this study were referred to in the PetSys project and are discussed above. As it is assumed that only very little material from the sidewell-cores (if any at all) is left, an additional study based on this material is probably not possible.

5.4 Elly-3, 3901 m – 4115 m

Report

Wood, M.E. 1992. Maersk Elly-3. Danish North Sea well: Biostratigraphy of the interval 4070´– 14.300´ TD. Simon-Robertson. Report No. 4642/Ia. 79pp.

Samples analysed for palynology

Simon-Robertson have analysed 7 DCS, 2 SWC samples and 27 core samples from this interval. There is no information about the interval each DCS represents. The location and type of the samples analysed for palynology are presented in their Enclosure 1.

Comments to the recorded bioevents

The first occurrence of *Glossodinium dimorphum* at 3984 m (13.071´) (core) indicates an age not older than middle Oxfordian.

The last occurrence of *Dichadogonyaulax sellwoodii* at 4030 m (13.220´) (DCS) indicates an age not younger than Callovian (see discussion for Elly-2).

The last occurrence of *Neoraistrickia gristhorpensis* at 4060 m (13.319.5´) (core) indicates an age not younger than Callovian/early Oxfordian. The

recovery of *Kraeuselisporites mathurii* at 4054 m (13.300.5´) (core) indicates according to Simon Robertson a Bathonian age – see discussion below.
The last occurrence of consistent *Chasmatosporites* spp. at 4094 m (13.433.04´) (core) indicates an Early Jurassic age.

Interval below
Simon-Robertson (1992) interpreted the unconformably Lower Jurassic–Middle Jurassic boundary to be located at 4092 m while this boundary was located at 4095 m in the PetSys project based on the well logs.

Interval above
The last occurrence of *S. crystallinum* at 3957 m (12.981.25´) indicates an Early Kimmeridgian age

Caving/reworking
Caving from Upper Jurassic sediments into the Lower Jurassic.

Literature
They do not refer to any literature.

Comments
Simon-Robertson writes for the interval 4049 m – 4054 m (13285.5´–13300,5´), assigned a ?Bathonian age: "Palynofloral characteristics in the two core pieces analysed from this interval are similar to those recovered from the underlying interval which have been positively dated as Bathonian. This interval has therefore been questionably assigned to the Bathonian".

The interval 4054 m – 4092 m is referred to the Bathonian based on the occurrence of *Kraueuselisporites mathurii* at 4054 m (13.300.5´/13.290.5´) (core) and the occurrences of *Neoraistrickia gristorpensis* at 4060 m (13.319.5´/13.311.5´) (core) + 4084 m (13.398.5´/13.390.5´) (core). *K. mathurii* is not well known from the literature and its stratigraphic range is not very well documented. In the paper by Stephen et al. (1993, p. 503) *K. mathurii* "…is believed to be Bathonian restricted", but there is not mentioned any references. The indicated range probably comes from an internal BP/Shell database. *K. mathurii* occurs within their "Genetic stratigraphic sequence J1bi" (Bathonian – Early Callovian). Within this sequence they also found *Nannoceratopsis pellucida* which, according to them indicates an age no younger than earliest Bathonian, and *Aldorfia aldorfensis*, which they claim should support a Bathonian age. However, in the publication by Riding & Thomas (1992), *N. pellucida* is shown to range into the lower Kimmeridgian and *A. aldorfensis* ranges into the Callovian. Therefore it must be concluded that the stratigraphic range of *K. mathurii* is not well-documented and may very well range into younger time-intervals than the Bathonian. The presence of *N. gristorpensis* indicates an age between the latest Toarcian and Callovian/early Oxfordian (Herngreen & Wong 1989; Herngreen et al. 2000; Batten & Koppelhus 1996).

New/supplementary studies

If there are sedimentological indications for marine influenced intervals within the cored parts of the Bryne Formation (e.g. MFS of Cal-1), samples for palynology should be taken from there aiming at recording stratigraphically useful dinocysts.

5.5 Falk-1, 4003 m – 4236 m

Report

Rich, B.E., 1989. Amoco 5504/6-3 Danish Central Graben well: Biostratigraphy of the interval 160m-4236 m TD. The Robertson Group plc. Report no. 4077/Ia. 45pp.

Samples analysed for palynology

Robertson have analysed 11 DCS, 2 SWC samples and 4 core samples from this interval. There is no information about the interval each DCS represents.

Comments to the recorded bioevents

4114 m: last occurrence of Quadraeculina anellaeformis (=Parvisaccites enigmatus).

The last occurrence of Q. anellaeformis is found in mid Bathonian according to Batten & Koppelhus (1996) and in the early Callovian according to Abbink (1998). In Herngreen et al. (2000) the last occurrence of Q. anellaeformis is indicated at the top Oxfordianin or possibly reaching into the early Kimmeridgian. Here the suggestion by Abbink (1998) is followed.

Interval below

The Jurassic succession unconformably overlies the Triassic. Robertson located the boundary at 4198 m based on greyish red claystone in a SWC at that depth. The boundary was suggested to be located at 4174 m in the PetSys project.

Interval above

The last occasional occurrence of *Gonyaulacysta jurassica* was according to Robertson recorded at 3830.3 m. This event indicates a Late Kimmeridgian to Early Volgian age.

Caving/reworking
Caving from Upper Jurassic sediments into the Triassic was observed by Robertson. A tetrad of *Heliosporites altmarkensis* (=*Kraeuselisporites reissingeri*) found at 4189 m was considered to be reworked. This taxa ranges from the Rhaetian (uppermost Triassic) into the Lower Jurassic. The occurrence at 4189 m supports the location of the Triassic – Middle Jurassic boundary at 4174 m suggested in the PetSys project.

Literature
Concerning palynostratigraphy in the Jurassic they only refer to unpublished internal Robertson reports.

Comments
Robertson suggests the presence of a major unconformity at 4114 m comprising the Callovian to lower Oxfordian. The presence of this unconformity is based on the downhole appearance of a miospore flora combined with the occurrence of *Q. anellaeformis* (as *P. enigmatus*) in a core sample at 4114 m, interpreted as indicating a Bajocian–Bathonian interval from 4114 m – 4198 m.
In the PetSys project no unconformity within the Jurassic succession was suggested. The lower part of the Jurassic succession (unconformably overlying the Triassic) was interpreted to be Callovian.

New/supplementary studies
If there are sedimentological indications for marine influenced intervals within the cored parts of the Middle Graben Formation, samples for palynology should be taken from there aiming at recording stratigraphically useful dinocysts.

5.6 Jens-1, 3688 m – 4298 m

Report
Bailey, H.W., Gueinn, K.J., 1982. Well Jens-1 (Interval 330´– 14.666´), Stratigraphical/Paleontological final report. Paleoservices Ltd. 35pp.

Samples analysed for palynology
Paleoservices have analysed 3 (?) DCS and 35 SWC samples. The interval each DCS represents was 10´.

Comments to the recorded bioevents
In spite of the high number and rather densely located SWC samples analysed, very few bioevents were recorded.

Interval below

The interval between 3962 m – 4267 m is by Paleoservices referred to as “undifferentiated Jurassic”. In their enclosures, they indicate a questionable unconformity at 4267 m, above the interval referred to the Pliensbachian. In the Petsys project, the Middle Jurassic (Callovian) is interpreted to rest unconformably on the Lower Jurassic (Pliensbachian), with the unconformity located at 4205 m.

Interval above

The last (?) occurrences of *Endoscrinium luridum* and *Gonyaulacysta jurassica* at 3619 m (11874´) strongly indicate an Upper Kimmeridgian to Early Volgian age.

Comments

Paleoservices write (e.g. in enclosure “Sedimentary history”: “It is not possible to define the precise stratigraphy of the section between 13.000´ and 14.000´ or the position of possible unconformities because of the absence of age-diagnostic microfossils”.

Caving/reworking

Both Late Jurassic caving and the presence of Carboniferous spores (interpreted as derived from additive) were observed in the interval referred to the Upper Triassic – Lower Jurassic.

Literature

Paleoservices only refer to studies of foraminifera. As the study is from 1982 available literature presenting ranges of stratigraphically important palynomorphs were very limited.

New/supplementary studies

Based on the high number of SWC from this interval, and assuming that there is enough material left from the SWC-samples for palynological analysis, there seems to be a high potential for achieving more precise datings.

5.7 Luke-1X, 4115 m – 4618 m

Report

Price, R.H., 2010. Maersk Luke-1X (5504/6-6) and -1XA (5504/6-6A), Danish North Sea Wells. Wellsite Biostratigraphy and Acid-based Analysis of the Intervals 8830 ft – 15166 ft TD (Luke1X) and 14690 ft – 15240 ft (Luke-1XA). Fugro Robertson Ltd. Report No. 7076/Ia. 23pp.

Samples analysed for palynology
Fugro Robertson have analysed 42 DCS and 22 core samples within this interval. Most of these samples were analysed on wellsite, using a non-acid preparation method. The interval each DCS represents was not clearly stated.

Comments to the recorded bioevents
Coreshifts resulted in minor deviations (max. +7´) of the depths of bioevents within the cored interval between the Fugro Robertson report and the Stratigraphic Summary Chart.

Only one usefull bioevent was recorded from this interval; the last occurrence of *Neoraistrickia gristhorpensis* at 4435 m (14.550.24 m/14.544.5´), indicating a Callovian/early Oxfordian age. All other bioevents were either questionably identified (e.g. the last occurrence of ?*Gonyaulacysta jurassica* at 3947 m (12950´)), long-ranging spore-taxa (e.g. *Deltoidospora* spp., *Lycopodiumsporites* spp., *Densoisporites* spp.) or just variations in the assemblage of organic particles (downhole increase in vitrinite at 4404 m (14450´)).

The presence of *Verreticulisporis giganteus* is not stratigraphically useful as this taxa is not well-known from the literature and its stratigraphically range is therefore likewise not well-known.

Interval below
Fugro Robertson Ltd. (2010) interpreted an unconformity at 4541 m (14.897´), separating the Lower Jurassic (?Hettangian – Toarcian) from the Middle Jurassic. The presence of Lower Jurassic deposits below are mainly based on a shift in lithology. The questionable *Trochammina gryci* (foraminiferid) recorded at 4587 m (15.050´) support an Early Jurassic age, but the poor preservation precluded a positive identification. In the PetSys project an unconformity located at 4536 m (14.882´), separating the Lower Jurassic (Sinemurian) from the overlying Middle Jurassic (Callovian).

Interval above
The last occurrence of *Endoscrinium luridum* at 3789 m (12.430´) strongly indicates an Upper Kimmeridgian to Early Volgian age.

Comments:
Non-acid palynology of 131 DCS over the interval 3589 m – 4623 m were made on wellsite.

Postdrilling, acid-based analyses were made of 11 DCS (4493 m – 4623 m) and 15 core samples (4420 m – 4491 m. According to Fugro Robertson, the good recovery of well-preserved palynomorphs in the core-samples from the Bryne and Middle Graben formations indicates that the very poor palynomorph recovery from the ditch cuttings samples within this interval are the result of the drilling methods in this HTHP part of the well.

Caving/reworking
11 DCS form the interval 4623 m – 4493 m (Bryne and Fjerritslev formations) were analysed post drilling. The samples were almost barren and the preservation of *in situ* material was poor. Samples which had some recovery were often dominated by cavings from the Farsund Formation.

Literature
Partington et al. (1993).
Andsbjerg & Dybkjær (2003).

New/supplementary studies
The interval from 3589 m – 4420 m have been analysed on wellsite, using a non-acid preparation method. An inspection of the distribution chart (their Enclosure 4) reveals that this procedure resulted in a very low number of identifiable palynomorphs, seldom more than 20 dinocysts per sample. In the interval 4008 m – 4420 m a total of only 4 dinocysts were recorded from 35 DCS! Based on this extremely poor result, a supplementary study, including acid based preparation, of this interval must be recommended. As a part of such a new study a thorough, supplementary study of the underlying succession (especially the cored intervals) could possibly result in better age-constrains for this interval as well.

5.8 Luke-1XA, 4478 m – 4645 m

Report
Price, R.H., 2010. Maersk Luke-1X (5504/6-6) and -1XA (5504/6-6A), Danish North Sea Wells. Wellsite Biostratigraphy and Acid-based Analysis of the Intervals 8830 ft – 15166 ft TD (Luke1X) and 14690 ft – 15240 ft (Luke-1XA). Fugro Robertson Ltd. Report No. 7076/Ia. 23pp.

Samples analysed for palynology
32 DCS representing the interval 4478 m – 4645 m were analysed onshore by Fugro Robertson.

Comments to the recorded bioevents:
No bioevents was recorded from this side-track. On p. 17 Fugro Robertson explains why it was not possible to differentiate this interval, which they referred to as “undifferentiated Jurassic”. Palynomorphs are scarce, poorly preserved and often dominated by cavings. *In situ* occurrences are doubtful;

several samples are barren of palynomorphs. The recorded dinocysts may be caved and the miospores long-ranging. No evidence of pre-Jurassic age.

Reworking/caving
The recorded (poor) palynomorph assemblages are often dominated by cavings.

Comments:
As no bioevents, and thus no stratigraphic information, was recorded from this deviated well, no Stratigraphic Summary Chart has been produced.

5.9 Skarv-1, 3729m – 3887m

Report
Bailey, H.W., Gallagher, L.T., Forbes G.A., 1993. Well 5504/10-2 (Skarv-1), Biostratigraphy of the interval 500m – 3.972m (T.D.). Paleoservices. 39pp.

Samples analysed for palynology
Paleoservices have analysed 5 DCS and 16 SWC samples. The interval each DCS represents was 6m.

Comments to the recorded bioevents
In spite of the high number of SWC samples analysed, very few bioevents were recorded. *Aldorfia dictyota* was recorded (as *Scriniocassis dictyota*) at 3770 m.

Interval below
The interval below 3840m is by Paleoservices referred to the Hettangian – early Sinemurian, based on a combination of a gamma-log shift, and the highest occurrences of *Involutina liassica* (foraminiferid), *Ogmoconcha hagenowi* (ostracod) and *Dapcodinium priscum* (dinocyst) in the SWC at 3851m. In the PetSys project the unconformity between the Lower and Middle Jurasssic was placed at 3842 m.

Interval above
The last occurrence at 3716m of *Endoscrinium luridum* strongly indicates an Upper Kimmeridgian to Early Volgian age.

Comments:
Paleoservices (1993) suggested the presence of a major hiatus at 3809m (at a log break) between the interval they refer to Lower Kimmeridgian and the interval they refer to the Middle Oxfordian. They further suggest that the Middle

Oxfordian Lola claystones rests unconformably on Middle Jurassic marginal marine carbonates at 3833m. Finally, they interpreted a hiatus at 3840m, between the Middle Jurassic and the underlying Lower Jurassic (Hettantian to lower Sinemurian) deposits. The PetSys project only suggests one hiatus (at 3842m), between the Lower Jurassic (Sinemurian) and the Middle Jurassic (Callovian).

Caving/reworking

Caving of upper Jurassic deposits into the Triassic was observed as one specimen of the Lower Kimmeridgian dinocyst taxa *Scriniodinium crystallinum* was recorded from a DCS at 3950 m.
The presence of one specimen of *Heliosporites altmarkensis* (as *Krauselisporites reissingeri*) at 3837m was interpreted as being due to reworking.

Literature

Paleoservices do not refer to any studies of dinocysts within the relevant stratigraphic intervals.

New/supplementary studies

Based on the high number of SWC from this interval, and assuming that there is enough material left from the SWC-samples for palynological analysis, there seems to be a potential for achieving more precise datings of the intervals referred to the Oxfordian and to the Middle Jurassic.

5.10 Discussion

5.10.1 Quality of samples and previous analyses

In general, the studied interval (Bryne, Lulu and Middle Graben formations) comprises very few stratigraphically useful palynological bioevents. The reasons for this are multiple:

- The deep burial of these deposits, resulting in high temperature and high pressure, have degraded the palynomorphs to a degree where identification to genus or species level is often difficult or not possible.
- The general fluvio-deltaic depositional environments of the studied interval result in very sporadic recordings of the stratigraphically important dinocysts, while the more common spore/pollen taxa are long-ranging forms.
- The cored intervals are most often the most coarse-grained, and as palynomorphs have a density comparable with clay and silt, palynomorphs occur only sporadically in these deposits.
- The palynological studies of most of these wells are from a time where only sparse literature on dinocyst taxa and their stratigraphical ranges

were available. Not much literature presenting stratigraphic ranges of Jurassic dinocysts existed in the 1980th and the early 1990th, before e.g. the publication by Riding & Thomas (1992). The knowledge about the ranges of the different dinocyst taxa has improved considerably since then, and therefore the interpretations of the correlations between palynological bioevents and the chronostratigraphy have also changed considerably.

The quality of the biostratigraphic analyses is very variable. The study of Luke-1X and Luke-1XA is especially poor, reflecting that most samples were prepared (using a non-acid preparation method) and analysed on well-site. It is expected that modern high quality sample processing performed in a laboratory with emphasis on concentrating dinocysts will provide better results.

5.10.2 Stratigraphically useful bioevents

The stratigraphically useful bioevents within the Bryne, Lulu and Middle Graben formations (and lowermost Lola Formation) recorded from the nine wells comprise:

Edna-1: Last occurrence of *Nannoceratopsis pellucida* at 3892 m (12770´) (indicating an age not younger than early Kimmeridgian).

Elly-2: The co-occurrences of *Dichadogonyaulax sellwoodii*, *Composito-sphaeridium polonicum*, *Rigaudella aemula* and *Gonyaulacysta jurassica* at 4025 m (13204.0´).
D. sellwoodii ranges from the late Bajocian to the late Callovian.
C. polonicum ranges from the earliest Callovian to the late Oxfordian.
R. aemula ranges from the latest Bathonian/earliest Callovian to the middle Oxfordian.
G. jurassica ranges from the Bajocian to the early Volgian.

Elly-3: Last occurrences of *N. pellucida* and *Aldorfia dictyota* at 3971 m (13028.5´) (indicating an age not younger than early Kimmeridgian), last occurrence of *Endoscrinium galeritum* at 3974 m (13037.5´) (indicating an age not younger than early Kimmeridgian), first occurrence of *Glossodinium dimorphum* at 3984 m (13071.0) (indicating an age not older than middle Oxfordian), last occurrence of *D. sellwoodii* at 4030 m (13220´) (indicating an age not younger than Callovian), last occurrence of *Neoraistrickia gristhorpensis* at 4062 m (13327.70´) (indicating a Callovian/early Oxfordian age).

Falk-1: Last occurrence of *Quadraeculina anellaeformis* at 4115 m (indicating an age not younger than Callovian).

Jens-1: Occurrence of *G. dimorphum* at 3923 m (12870´) (indicating an age not older than middle Oxfordian).

Luke-1X: Last occurrence of *N. gristhorpensis* at 4435 m (14550.24´) (indicating an age not younger than Callovian/early Oxfordian).

Skarv-1: Last occurrence of *N. pellucida* at 3802m (indicating an age not younger than early Kimmeridgian), last occurrence of *Chasmatosporites hians* at 3836 m (indicating an age not younger than Callovian).

The presence of Bathonian in Elly-3 according to Simon Robertson (1992) is strongly based on the presence of a spore-taxa, *Krauselisporites mathurii*, which is not well-documented in the published literature and neither is its stratigraphic range. It may be an internal BP/Shell taxa. The presence in Skarv-1 of one specimen of *Heliosporites altmarkensis* (as *Krauselisporites reissingeri*) at 3837m within the interval referred to the Middle Jurassic, was by Paleoservices (1993) interpreted as being due to reworking. *H. altmarkensis* is well-known to occur commonly in uppermost Triassic (Rhaetian) and Lower Jurassic deposits. The Lower Jurassic succession was - due to regional doming in the Central Graben area during the Aalenian - eroded partly or totally from large areas within the Danish Central Graben and there are thus a large potential for finding reworked Lower Jurassic palynomorphs within the Middle Jurassic deposits. This may explain the presence of *Krauselisporites*-type spores (registered as *K. mathurii* and used as a Bathonian marker) within the Middle Jurassic fluvio-deltaic deposits in Elly-3.

5.10.3 Dating of the Bryne and Middle Graben formations

The oldest stratigraphically useful bioevents recorded from this interval are the last occurrences of *Quadraeculina anellaeformis*, of *Chasmatosporites hians*, of *Dichadogonyaulax sellwoodii* and of *Neoraistrickia gristhorpensis*. These bioevents have been recorded in Elly-2, Elly-3, Falk-1, Luke-1X and Skarv-1.

The last occurrence of *Quadraeculina anellaeformis* is according to Batten & Koppelhus (1996) found in the mid Bathonian, according to Abbink (1998) it is found in the earliest Callovian and according to Herngreen et al. (2000) it is found in the early Kimmeridgian. As it has not been recorded from the Kimmeridgian in the Danish sector, the suggestion by Abbink (a last occurrence in the earliest Callovian) is followed here.

The last occurrence of *Chasmatosporites hians* is found in the Bathonian according to Batten & Koppelhus (1996) and in the earliest Callovian according to Abbink (1998).

The last occurrence of *Dichadogonyaulax sellwoodii* is found in the late Callovian according to Riding & Thomas (1992).

The last occurrence of *Neoraistrickia gristhorpensis* is in the early Oxfordian according to Abbink (1998), Batten & Koppelhus (1996) indicate a ?Callovian age, while Herngreen et al. (2000) indicate an early or possibly Middle Oxfordian age.

No trustworthy bioevents proving ages older than Callovian have been recorded.

The occurrence of *D. sellwodii* at 4030 m (13220´) in Elly-3, just above the interval referred to the Bryne Formation, indicates an age not younger than the Callovian for the Bryne Formation. Likewise, the last occurrence of *Quadraeculina anellaeformis* at 4115 m in Falk-1 in the uppermost part of the Middle Graben Formation indicates an age not younger than Callovian for the Middle Graben Formation.

5.10.4 Unconformities

The interpretations from the PetSys project show the presence of a regional unconformity between the Triassic or Lower Jurassic deposits and the overlying Callovian/Oxfordian deposits, in all the wells, but no unconformities have been suggested internally in the Middle Jurassic – Lower Kimmeridgian succession. The evaluated reports likewise show an unconformity between the Triassic or Lower Jurassic deposits and the overlying Middle Jurassic/Oxfordian deposits and, in addition, unconformities internally within the Middle Jurassic – Lower Kimmeridgian interval in 3 wells; Falk-1, Skarv-1 and Luke-1X.

5.11 Biostratigraphic conclusions

- Stratigraphically useful palynomorphs (dinocysts) are so far only recorded very sporadically within the interval referred to the Bryne, Lulu and Middle Graben formations, hindering a detailed correlation based on biostratigraphy.
- Firm indications of Bajocian–Bathonian are not found in the present data set. On the other hand, the possibility of a Bathonian age for the oldest parts of the succession (without any stratigraphically usefull bioevents) cannot be excluded.

- A re-evaluation of the literature concerning the interpretation of the last occurrence of *D. sellwoodii* suggests a Callovian age, rather than an Oxfordian age as used in the PetSys project. This event was recorded from Elly-2 and Elly-3.

- The youngest parts of the Bryne and Middle Graben formations in these wells are dated as Callovian.

- Attention should be made to a relative diverse dinocyst assemblage in the a SWC at 4024.6m in Elly-2, in the lowermost Bryne Formation, indicating the presence of a marine flooding surface at this level.. This potentially significant flooding event was not emphasized in the PetSys project.

- It is likely that a new biostratigraphic study will provide new important data, if it is performed consistently by specialists at GEUS on samples cautiously selected from identified marine influenced levels after common core inspection by involved biostratigraphers and sedimentologists. The samples should further be processed very carefully with emphasis on extracting dinocysts. Such study should also take advantage of modern literature with documented range of the identified dinocysts.

6 Depositional development

Owing to the general non-marine to marginal marine/paralic character of the Middle Jurassic deposits in the Danish Central Graben and the relatively deep burial, biostratigraphic dating is in general poor hampering detailed reconstructions of the depositional developments. In order to provide a general overview of the Jurassic stratigraphy and its subcrop in the nine wells included in this study, two well-logs panels, using the well-logs supplied by Wintershall and applying the stratigraphic framework from the fairly recently concluded GEUS PetSys project dealing with the Jurassic petroleum system of the Danish Central Graben area, are presented (Figs 6.1 & 6.2; Encl. 9 & 10). The shown stratigraphy encompasses the Fjerritslev, Bryne, Middle Graben and Lola (in part) formations. The successions of particular interest for this study is subdivided into the sequences Cal-1 and Ox-1, which are tied to the larger database of the Central Graben area and thus providing regional constrains on the interpreted stratigraphy.

In addition to the two well-log panels, three regional paleogeographic maps from the PetSys project have been selected to illustrate the general depositional development through Bathonian–Oxfordian times by displaying the distribution of the sequences Bat-1, Cal-1 and Ox-1 (Figs 6.3–6.5).

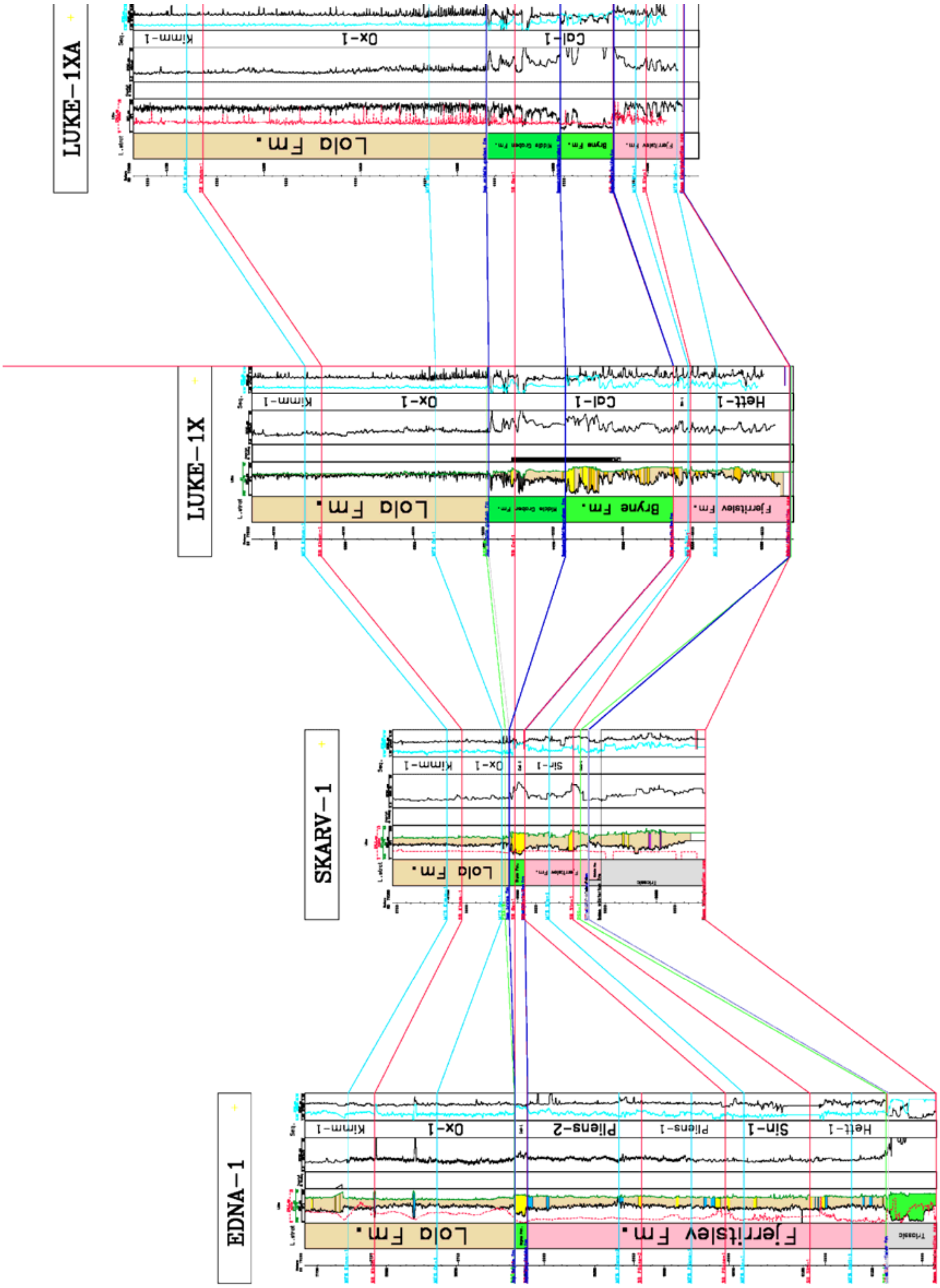


Fig. 6.1. Well log-correlation panel displaying the subcrop to the Bryne and Middle Graben formations, the two formations and parts of the overlying Lola Formation in Edna-1, Skarv-1, Luke-1X and Luke 1XA (Encl. 9). The petrophysical well logs were provided by Wintershall; the stratigraphic subdivision is based on GEUS´ PetSys project.

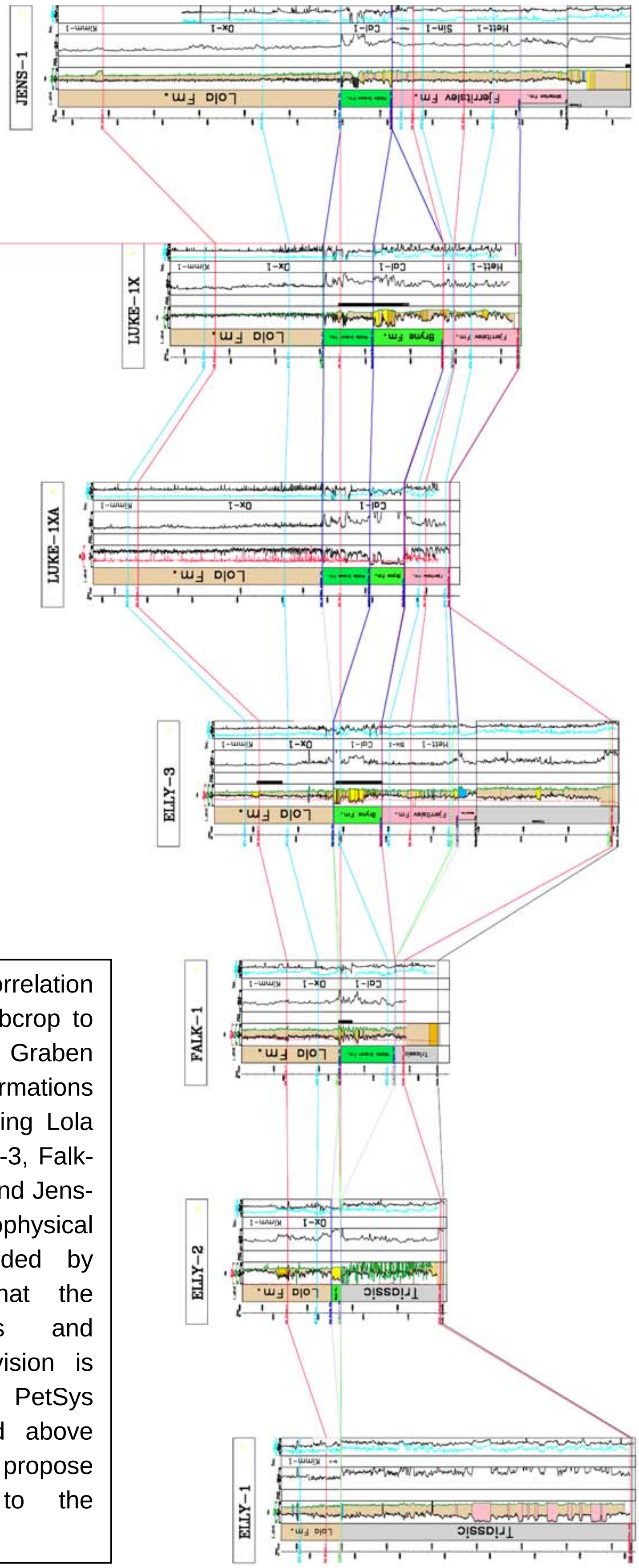


Fig. 6.2. Well log-correlation panel displaying the subcrop to the Bryne and Middle Graben formations, the two formations and parts of the overlying Lola Formation In Elly-1, -2, -3, Falk-1, Luke-1XA, Luke-1X and Jens-1 (Encl. 10). The petrophysical well logs were provided by Wintershall. Notice that the indicated correlations and lithostratigraphic subdivision is according to the PetSys database; as indicated above the results of this study propose some modifications to the PetSys database.

6.1 Palaeogeographic development

The three palaeogeographic maps (Bat-1, Cal-1 and Ox-1) depict the overall development of the depositional environments from Bathonian through Callovian to Oxfordian in the Danish Central Graben and adjacent areas.

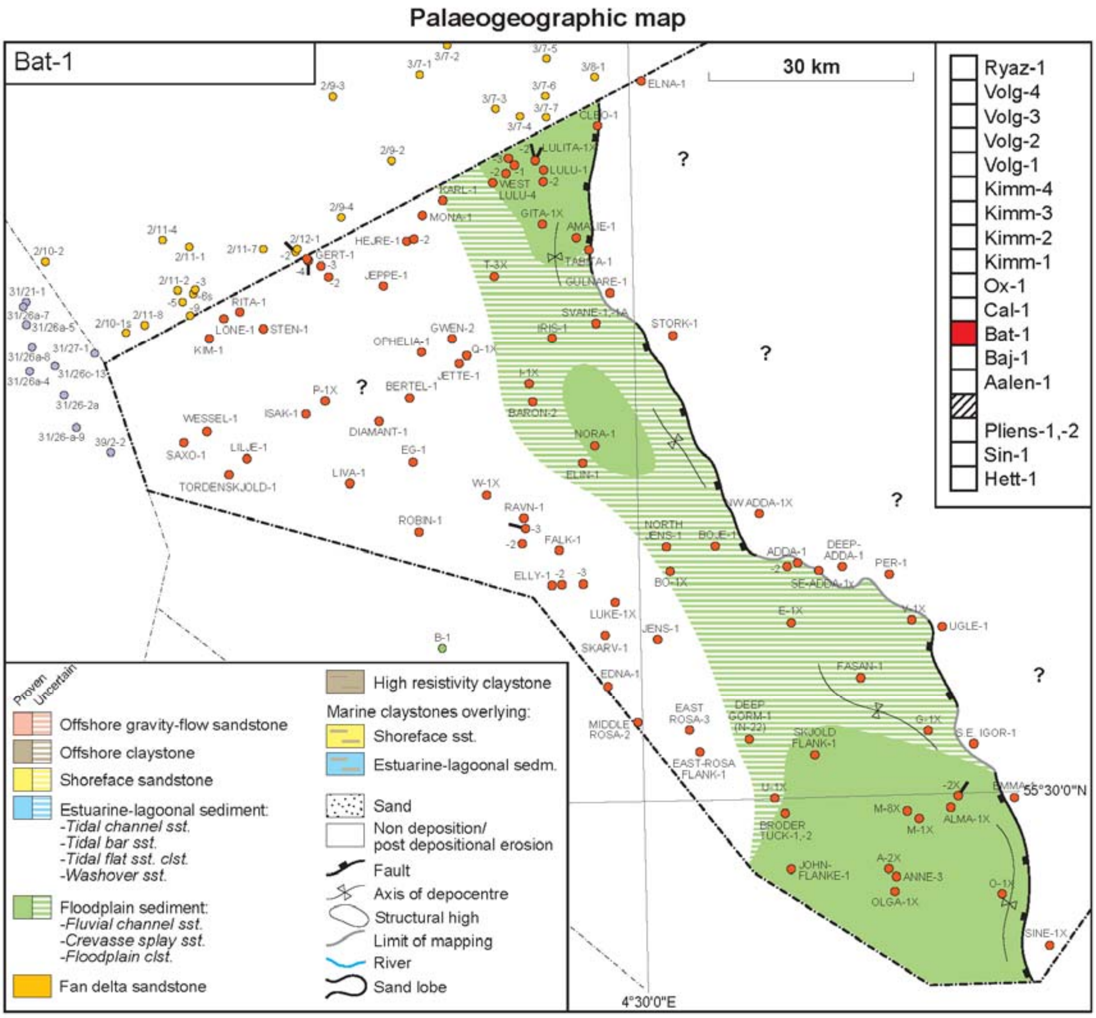


Fig. 6.3. Sequence Bat-1 emphasizing the dominance of floodplain deposition in the subsiding Central Graben surrounded by large areas of non-deposition and erosion east of the Coffee Soil Fault and to the west including the Mid Nord Sea High, Heno Plateau etc.

6.1.1 Bathonian

Bathonian sediments are not proved to be present in any of the wells in this study (**Profile-1**: Elly-1-2, Falk-1, Elly-3, Luke-1Xa, Luke-1X and Jens-1 and **Profile-2**: Edna-1, Skarv-1, Luke-1X and Luke-1Xa) (Figs 6.1 & 6.2). The study area may have been a land area with no significant sediment deposition/preservation. East of this area in the deeper part of the half-graben, floodplain sediments are preserved in several areas in the actively subsiding blocks along the eastern graben margin. These sediments were deposited in an overall floodplain environment including: Fluvial channel sandstones, crevasse splay sandstones, and floodplain mudstones. Further towards east the eastern graben margin fault (Coffee Soil Fault) limits the floodplain extension towards the Ringkøbing Fyn High (Fig. 6.3).

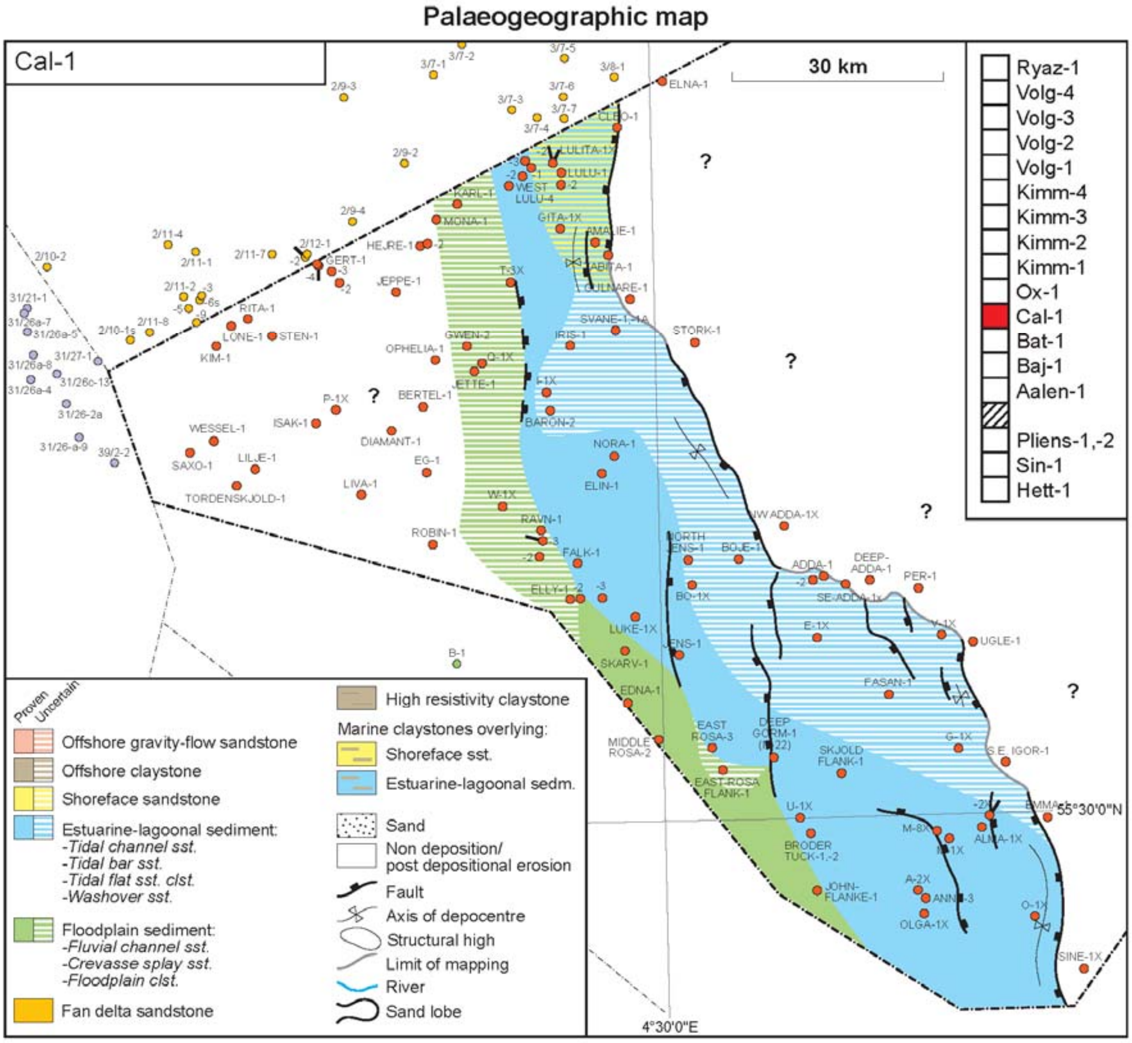


Fig.6.4. Sequence Cal-1 showing that the general floodplain environment dominating the Bathonian was gradually replaced by estuarine, lagoonal and brackish bay environments in the subsiding Central Graben including parts of the study area. East of the Coffee Soil Fault non-deposition and erosion still prevailed while the depositional area gradually expanded towards the west with floodplain sediments accumulating over parts of the Heno Plateau etc.

6.1.2 Callovian

During the Callovian estuarine-lagoonal sediments were accumulating in large parts of the Central Graben (Fig. 6.4). The estuarine-lagoonal environments include: Tidal/estuarine channel sandstones, tidal bar sandstones, tidal flat sandstones and claystones, which are represented in variable amounts in the wells of this study. This general distribution of depositional environments indicates a general base level rise, i.e. a “transgression” that facilitated establishment of Callovian estuarine-lagoonal environments to the east on top of Bathonian floodplain sediments and formation and preservation of floodplain deposits in the western area from the Bathonian to the Callovian (Figs 6.3 & 6.4).

Palaeogeographic map

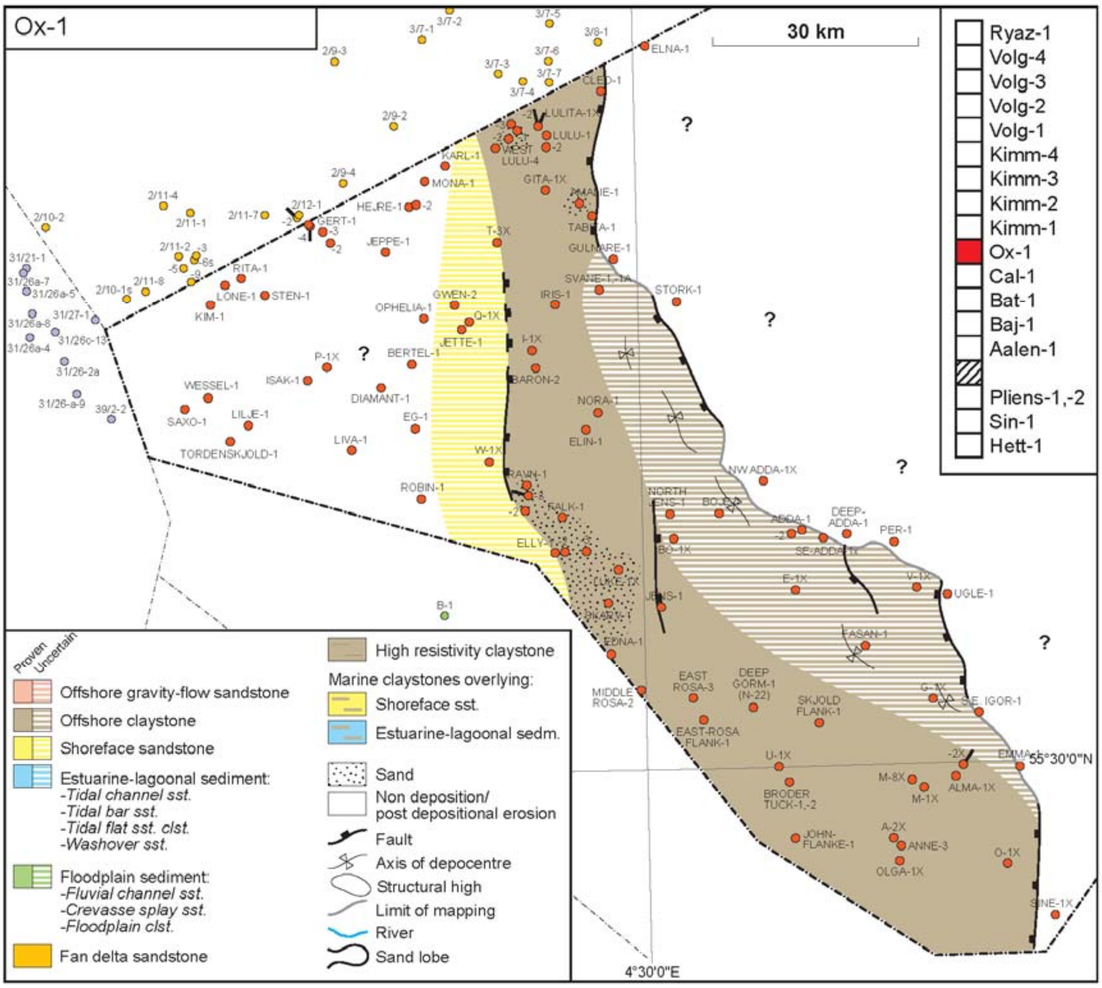


Fig. 6.5. Sequence Ox-1 showing that deposition of offshore fine-grained sediments prevailed in large areas illustrating the continued base level rise from Bathonian through Callovian and Oxfordian times. On parts of the Heno Plateau shoreface sands accumulated while non-deposition and erosion still prevailed east of the Coffee Soil Fault.

6.1.3 Oxfordian

During the Oxfordian the entire study area was flooded and offshore marine claystones are preserved in all the studied wells (Fig. 6.5). All of the well-sections, except Edna-1 and Jens-1 wells, contain sand-grains within the marine claystones, which may suggest that there was a land area closely to the west (Fig. 6.5).

6.1.4 Regional transgression from east to west

The enclosed palaeogeographic maps and the well-log panels (Edna-1, Skarv-1, Luke-1X, Luke-1XA, Fig. 6.1; Elly-1-2, Falk-1, Elly-3, Luke-1XA, Luke-1X, Jens-1, Fig. 6.2) show that the area was influenced by an overall base level rise involving a regional transgression from east to west, starting from the Bathonian through the Callovian to the Oxfordian.

6.2 Detailed well-log panels

For the purpose of this study, with focus on local reservoir development, two very different depositional models are proposed – here termed the "**layer cake model**" and the "**incised valley model**". The two models are illustrated by the construction of two detailed well-log panels for each of the models; the panels are zoomed in on the Bryne–Middle Graben interval to provide a stratigraphic subdivision of the zone of interest within the study area (Figs 6.6–6.9; Enclosure 15, 16, 17 & 18). The scope of the proposed subdivision has been to investigate the depositional environments and the lateral and vertical distribution of the identified reservoir sandstones as input to a reservoir model. GEUS prefers the "**incised valley model**" for reasons described below although this model implies a sequence stratigraphic solution and "numbering" of sequence stratigraphic surfaces that do not matched fully with the PetSys database.

Depths to all surfaces (sequence stratigraphic and lithostratigraphic surfaces) can be found in Enclosure 11 for those based on the PetSys database (Enclosure 11a), and for the two sequence stratigraphic models developed in this study (Enclosure 11b &c with changes relative to PetSys marked in red).

In the four new well-log panels, the lower boundary of the zone of interest is defined by the base Middle Jurassic unconformity (MCU), demarcated by the unconformity toward the Fjerritslev Formation or the Triassic. The upper boundary is defined by the transition to Lola Formation. These two surfaces embrace the interval with reservoir sandstones of the Middle Jurassic – lower Oxfordian. The interval shows a distinct overall westward thinning from a maximum thickness in the Luke-1X well, and marked thinning through Elly-3 and Elly-2 to absence in Elly-1 located most westward of the nine studied wells. The seismic sections shown in Appendix 1 clearly display this marked thinning, and it is also reflected by the SeisWorks maps showing the distinct overall wedge-shaped Jurassic interval with decreasing thickness towards west. A maximum time thickness of up to 80 ms of the named Bryne Fm. interval on the Elly-segment is found south of the Elly-3 location (Appendix 1i). Similarly max time thicknesses of 80 ms exist in a broad depocenter located structurally down-dip SW of Luke-1X. This distinct configuration is interpreted to reflect the influence on the deposition by the structural high of the Heno Plateau.

6.2.1 Layer cake model

This model contains three depositional sequences, A, B and C. These may be of local significance only, and their bounding surfaces may reflect local changes in depositional style rather than major basinward or landward shifts in depositional facies. Their possible regional implications are thus at present poorly understood and is beyond the scope of this study. At this point the defined sequences may be regarded as local depositional sequences of the Elly-Luke area with implications for the interpretations of the distribution of reservoir sandstones. Further work is needed before defining them as depositional sequences in a conventional sequence stratigraphic context.

The well-log panels illustrating this model strike roughly north–south and west-east and share the wells Elly-3, Luke-1X and Luke 1XA. A number of criteria have been applied for the construction of the well-log panels in addition to the general guidelines provided by the PetSys project database on stratigraphic subdivision and paleographic interpretation of the Jurassic succession of the Danish Central Graben and adjacent areas.

Although the seismic data may not be conclusive regarding the nature of the thinning, i.e. onlap of depositional units on the eastward dipping MCU versus overall thinning of the entire interval, it is here assumed that the marked westward thinning reflects progressive onlap of the lower depositional units toward MCU developed on a paleo-structural high. In other words the thinning is interpreted to reflect a gradually expansion of the depositional area over a structural paleo-topography during the Callovian–Oxfordian.

The two panels are flattened on the base Lola Formation surface (Figs 6.6 & 6.7; Enclosure 15 & 16). This surface is interpreted to represent a fairly horizontal marine flooding surface reflecting the drowning of the paralic to non-marine sediments of the Bryne and Middle Graben formations and the shift to deposition of widespread offshore marine mud in Oxfordian time. This surface, the initial marine flooding surface, is defined right above a small spiky gamma ray low accompanied by a sonic high and a shift on the resistivity and electric logs in several of the wells. In the Falk-1 core, the interval shows a thin cemented conglomerate overlying weakly bioturbated brackish bay mudstones with synaeresis cracks. The conglomerate may represent a by-pass surface or a marine ravinement surface; the latter interpretation is favored here as a result of the initial marine transgression subsequently leading to deposition of the Lola Formation marine mudstones. In Luke-1X, Luke-1XA and Jens-1 the surface is marked by a small spiky gamma ray and sonic low accompanied by a shift on the resistivity and electric logs interpreted to reflect a widespread coal bed (Figs 6.6 & 6.7; Enclosure 15 & 16). Below this surface occurs a mudstone dominated interval in most wells except for Edna-1 and Skarv-1 where the Lola Formation mudstones rest on Bryne Formation sandstones and in Elly-1 where the Lola Formation overlies the Triassic. In the remaining wells (Elly-2, Elly-3, Falk-1, Jens-1, Luke-1X and Luke-1XA), this mudstone interval contains scattered, thinly interbedded fine-grained sandstones and siltstones, whereas the interval also contains several marked coal beds in Luke-1X, Luke-1XA and Jens -1. The relatively uniform mudstone interval in Elly-2, Elly-3 and Falk-1 is interpreted as being deposited on a mud-dominated low relief floodplain based on the interpretation of the Falk-1 core and the absence of clear marine evidence from the biostratigraphy reports. The interval thickens toward the east in Luke-1X and Luke-1XA where it contains several coal beds and signs of estuarine influence witnessing larger accommodation space. Despite the interpreted shift in depositional environment from the floodplain sediments dominance at Elly-2, Elly-3, Falk-1 to the dominance of estuarine embayment sediments at Luke-1X, Luke-1XA and Jens -1, it seems possible to follow and correlate several minor log features and trends between the wells crossing the facies boundary marked on the panels (Figs 6.6 & 6.7; Enclosure 15 & 16).

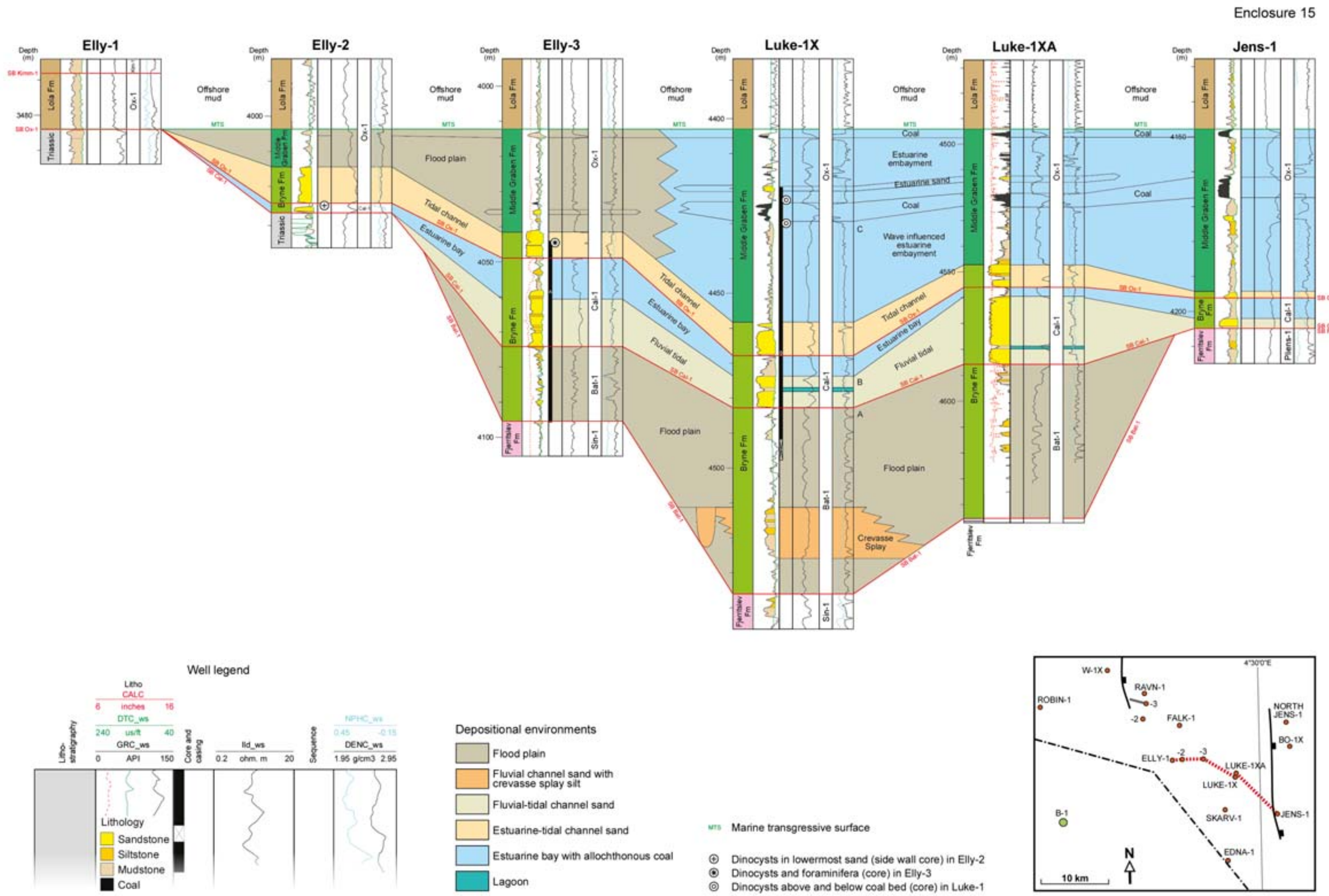


Fig. 6.6: Log panel flattened on base Lola Fm and displaying the "layer cake model. Is also included as Enclosure 15.

Local depositional sequence A

Local sequence A is only identified in the wells situated in the deep part of the study area, namely the wells Elly-3, Luke-1X and Luke 1XA. The sequence is dominated by floodplain and shallow lake mudstones with numerous roots, carbonized wood fragments, thin siltstones and very fine-grained sandstones, which in places are deformed due to slumping and occasionally containing reworked sedimentary clasts as shown by the Luke-1X and Elly-3 cores, which cover a large part of the sequence (Enclosure 15 & 16; Hovikoski and Johannessen 2016).

The well logs from Luke-1X and Luke-1XA show an interval with the occurrence of siltstones and poorly develop sandstones in the lower–middle part of the sequence; these may represent distal crevasse splays or fluvial levees suggesting the presence of a non-drilled fluvial channel system within the sequence adjacent to the wellbores. Such channel sandstones may have a reservoir potential if enveloped by floodplain mudstones. The expected net/gross ratio of reservoir sandstones in this sequence is, however very low.

Local depositional sequence B

Local sequence B is identified in the same wells as sequence A and is tentatively correlated to the Elly-2 and Jens-1 wells situated in more shallow positions. In Luke-1X the base of the sequence, here termed SB Cal-1, is defined by an abrupt shift in lithology from the floodplain mudstones with signs of pedogenic processes in sequence A to overlying, erosively-based cross-bedded, clasts supported, fine-grained conglomerate with medium-grained sand in matrix. The conglomerates are interpreted as estuarine channel deposits (Facies association FA 2 of Hovikoski and Johannessen 2016; Ichron 2010). This marked erosion surface is correlated to a similar abrupt facies change at the base of a rather thick blocky sandstone package in Luke-1XA; the surface is traced further to Jens-1 to the south where it amalgamates with the MCU surface (Enclosure 15). To the northwest the surface is correlated to the base of the lower sandstones in Elly-3. In this well, both the core and the well logs seems to suggest a gradual, less marked change from floodplain mudstones with paleosoils to muddy fluvial sandstones with weak evidence for tidal activity. The surface is further traced to Elly-2 to the base of the basal 1–2 m thick sandstone bed overlying the MCU. In Elly-1 it is replaced by the younger SB Ox-1 surface.

The sandstones in the wells Elly-3, Luke-1X and Luke-1XA (and Jens-1) is topped by a succession of mudstones. In the Luke-1X cores, the sedimentary structures in the upper part of the sandstones, including mud-draped sigmoidal cross-stratification and double muddrapes and a low-diversity, low-density ichnofacies, indicate that the sandstones were formed in tidally influenced channels (Facies association FA 2 of Hovikoski and Johannessen 2016; Ichron 2010), and that the overlying mudstones were formed in an estuarine bay environment (Facies association FA 3 of Hovikoski and Johannessen 2016; Ichron 2010). In Luke-1XA, the bay mudstones form a thin unit on top of the thick blocky sandstone package. Toward the northwest to Elly-3 the estuarine bay mudstones seem to pass into a mudstone succession with almost no indications for marine-tidal influence. The sedimentological interpretation of the cores indicates a dominant floodplain environment with paleosoils and roots in places. Sporadic bioturbation occur at some levels possibly related to freshwater or terrestrial organisms. In Elly-2 an assemblage of four stratigraphically important marine dinocyst taxa were found in a SWC (4025 m; 13.204´)

from a thin mudstone bed closely above the basal thin sandstone. Based on these ambiguous data from Elly-2 and Elly-3, the mudstones are correlated between the Elly-2, Elly-3, Luke-1X, Luke-1XA, and Jens-1 (Fig. 6.7; Enclosure 16), although the precise relation between the thin marine mudstone in Elly-2 over the mainly floodplain mudstones in Elly-3 and further southeast to the bay mudstones in Luke-1X is unclear.

The sandstones of this sequence B are thus interpreted as estuarine channels or tidally influenced fluvial channels overlain by fine-grained bay-floodplain mudstones. As channel sandstones are present in all the three wells Elly-3, Luke-1X and Luke-1XA, this may suggest that lateral migration of sinuous fluvial-tidal channels swept the area, eroded and removed contemporaneous coastal fine-grained deposits, and thereby forming a fairly coherent sheet of channel sandstones. From modern lagoons it is shown that lateral migration of tidal channels tends to remove all the fines leaving behind stacked and coherent channel sands (e.g. Fruergaard et al., 2011). Whether the 1-3 m thin sandstones in Jens-1 and Elly-2 directly overlying the amalgamated MCU-SB Cal-1 are related to the proposed channel belt is not clear. The upward-fining trend in Jens-1 may suggest this; however, the sandstones may also be interpreted as transgressive marine sandstones (Elly-2) and bay shoreline sandstones (Jens-1).

The here proposed interpretation of a possible coherent channel sandstone belt provides a high net/gross sandstone ratio for the reservoir model with an intraformational seal of bay mudstones. However, this interpretation probable requires minor subsidence of the Luke-1X section relative to the other well-sections after deposition of the channel sand to accommodate the thicker section of the overlying sequence C, i.e. the slightly deeper position of the channel sandstones in Luke-1X relative to the two other wells.

Local depositional sequence C

This sequence oversteps the areas of the former two sequences shown by the wells Falk-1, Skarv-1 and Edna-1; the very thin B sequence in Elly-2 is probably is cut by SB Ox-1 and overstepped by sequence C closely west of the well. The Elly-2, Elly-3 and Luke-1X well-logs indicate a very remarkably lithology shift at SB Ox-1. The Luke-1X core shows a sharp erosional surface where mud-draped, fine-grained small scale ripple cross-laminated sandstones with roots deposited at an estuarine bay margin are erosively overlain by cross-stratified, clast-supported fine-grained conglomerates and pebbly sandstones formed in tidal channels or an estuarine channel. The sandstone interval consists of two units separated by c. 1 m of bay mudstones with the lower sandstone being c. 7 m thick and the upper sandstone c. 1 m thick. The surface seems equally sharply developed in the Luke-1XA well, where the overlying sandstones also are divided into two beds of c. 2–3 m of thickness. Further southeast-ward the basal surface is correlated to thin gradationally based sandstones in Jens-1.

In Elly-3 the B sequence floodplain mudstones with indications of paleosoil are erosively overlain by very coarse-grained pebbly sandstones interpreted as tidal or estuarine channel sand forming two units of 4–5 m in thickness separated by few tens of cm of mudstones (Enclosure 14 b). A similar marked lithology shift is indicated by the Elly-2 well-logs, where the 10–11 m thick sandstone interval showing a gamma ray trend indicating an overall upward fining trend may be interpreted as a channel fill. In detail, the well-logs seem to subdivide the sandstone interval into three parts, where the lower c. 2–3 m shows a weak upward fining trend, whereas the two overlying parts of c. 5 and c. 3 m show upward coarsening trends. Two SWC samples contain very sparse dinocysts suggesting a weak marine influence.

In the Skarv-1 and Edna-1 wells the logs indicate a sandstone interval of c. 11m and 7 m in thickness, respectively. These are tentatively interpreted as tidal channel sand directly overlying the amalgamated Ox-1 and MCU surface. Channel sandstones are absent in Falk-1 where floodplain deposition prevailed.

Thus the channel sandstones, marked on the well-log panels as tidal channel sandstones in Figs. 6.6 and 6.7 and Enclosure 15 and 16, show a relatively uniform amalgamated thickness of c. 5–11 m, with individual channel sandstones being up to 7 m thick. Following the same rationale as for sequence B, the presence of channel sandstones in all the wells Elly-2, Elly-3, Luke-1X, Luke-1XA, Skarv-1 and Edna-1 (and possibly Jens-1) suggests that lateral migration of sinuous tidal channels swept the area, eroded and removed contemporaneous fine-grained tidal flat or bay deposits, and thereby forming a fairly coherent sheet of channel sandstones.

This interpretation offers a medium net/gross ratio of potential reservoir sandstones; however, as for sequence B differential faulting and subsidence is probably required after channel deposition and before the formation of the base Lola Formation marker. The sandstones are overlain by thick intraformational flood plain and estuarine embayment mudstones and/or marine mudstones of the Lola Formation providing top seal.

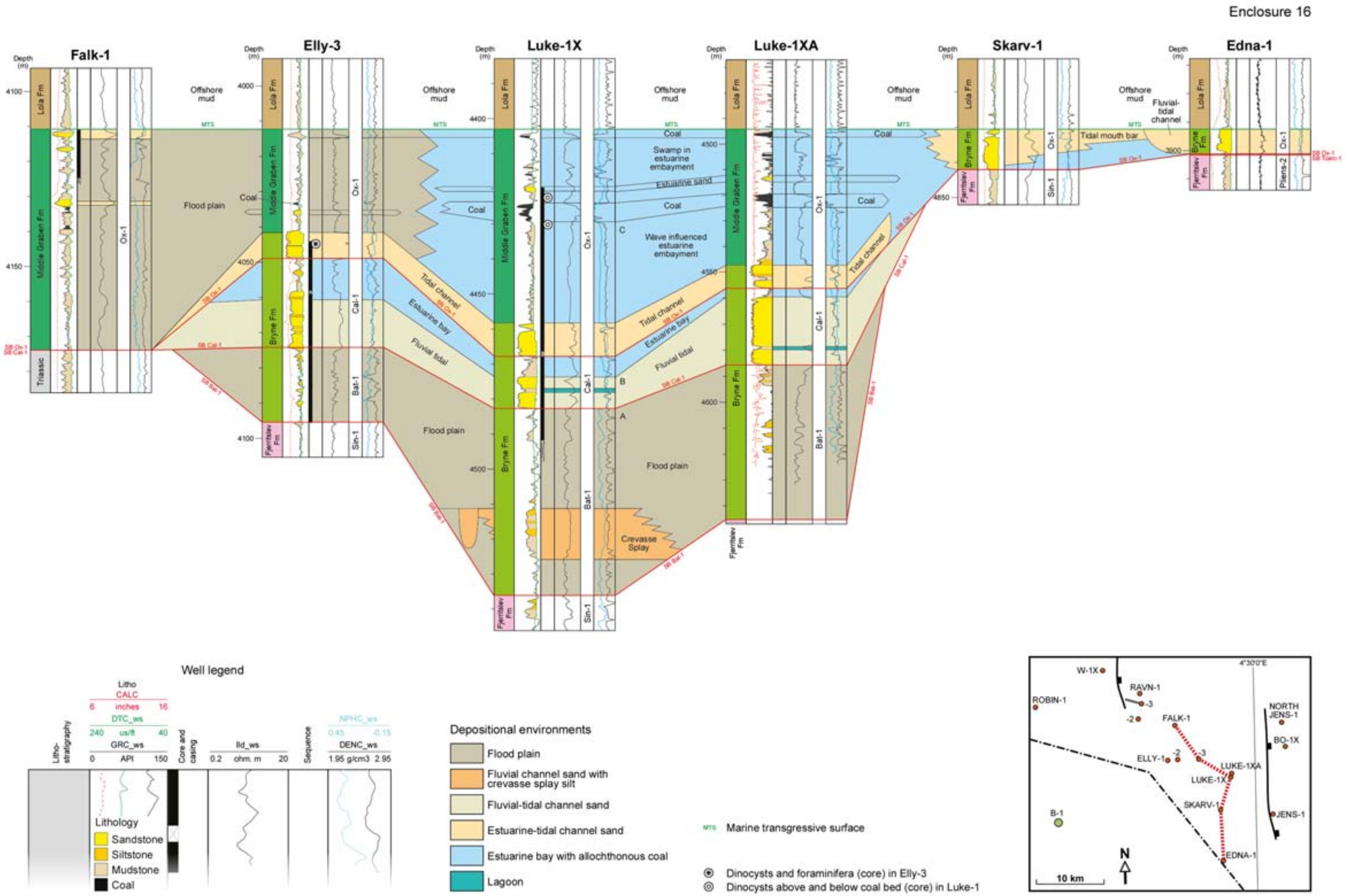


Fig. 6.7: Log panel flattened on base Lola Fm and displaying the "layer cake model. Is also included as Enclosure 16.

6.2.2 Incised valley model

An alternative model to the "**layer cake model**" is the "**Incised valley model**", which is flattened on the same log marker defining the base Lola Formation and is also bounded below by MCU; however, the core information and the well log patterns are used to define a much different solution (Figs 6.8 & 6.9; Enclosure 17 & 18). This model is preferred by GEUS, and the primary observations and rationales favoring this model compared to the "**layer cake model**" are:

i) The significant facies break at the lower sandstone interval in Luke-1X, where floodplain mudstones with indication of soil formation are erosively overlain by cross-bedded, clasts-supported conglomerates of fine-gained pebbles and medium-grained sand. This break signifies a dramatic shift in the depositional systems with erosion and possible incision by a fluvial system. The surface is easily correlated to the closely located Luke-1XA; it is further correlated to a very similar surface below the upper sandstones in the Elly-3 core where similar conglomerates as in Luke-1X are observed (Figs 6.8 & 6.9; Enclosure 17 & 18 SB Cal-1). It is further correlated to a sandstones in the Falk-1 core with signs of pedogenic processes at c. 4102 m (c. 2 m below core top) overlain by bay mudstones topped by a very significant conglomerate bed (Enclosure 12).

ii) The presence of comparable conglomerates with extra-formational clasts in Falk-1 (uppermost in core), in Elly-3 (at the base of the upper sandstone interval) and in Luke-1A (at the base of the lower sandstone interval) indicates a common causal event for their formation; the proposed correlation groups the conglomerates at the base of the same sequence in contrast to the "layer cake model", where the conglomerates are separated into two sequences and occurring at two different sequence stratigraphic levels, i.e. at the basal sequence boundary of sequence B and C and at the transgressive surface of sequence C.

iii) The different genesis of the mudstone succession in Falk-1 compared to the mudstone successions of Luke-1X and Luke-1XA. The former is interpreted as floodplain mudstones (Falk-1 core; Enclosure 12), whereas the latter are interpreted as estuarine embayment coal bearing mudstones (Luke-1X cores; Enclosure 13 and Hovikoski & Johannessen 2016). This difference in depositional environments is interpreted to be significant, and thus "overruling" the apparent similarity of the well-log patterns between Falk-1 and the Elly-3 and Luke-1X, and thus indicating that the mudstone successions belong to two different depositional settings and sequences.

iv) The significant difference in depositional facies between the mudstone successions in the lower one third of the interval of interest (lower Bryne Formation) compared to the mudstone successions in the upper one third of the interval (Middle Graben Formation). The lower mudstone succession is interpreted as deposited on a floodplain which experience pedogenic processes at several levels (the lower parts of Elly-3 and Luke-1X cores; most of the Falk-1 core; Fig. 6.8; Enclosure 17), whereas the upper mudstones in the Middle Graben Formation are interpreted as formed in an estuarine embayment with wave-activity, bioturbation, fluctuations in salinity (synaeresis cracks) and deposition of fluid muds (upper half of the Luke-1X core; Figs 6.8 & 6.9; Enclosure 17 & 18).

v) In Elly-2 the presence of c. 1 m of marine mudstones with a relatively diverse dinocyst assemblage (in a SWC at 4024.6m) indicating a Callovian age is overlain by sandstones from which two SWC with sparse dinocysts indicate brackish/marine influence conforming to the presence of overlying and adjacent bay mudstones rather than floodplain mud as indicated in the "**layer cake model**".

vi) Comparison of the well-log patterns of the Middle Graben Formation in Elly-3 to the patterns in Luke-1X, Luke-1XA and Jens-1 suggests a possible correlation of subtle log changes and patterns also involving the correlation of the thin coal bed in Elly-3 with to the thicker coals in the other wells (Figs 6.8 & 6.9; Enclosure 17 & 18).

Following these principal arguments and rationales, the interval of interest has been subdivided into two sequences; here termed the "Lower Sequence" possibly of (?)Bathonian age, and the Upper Sequence of Callovian–early Oxfordian age.

Lower Sequence – (?)Bathonian

The Lower Sequence overlies the MCU and is bounded below by its lower sequence boundary here termed SB Bat-1 (Figs 6.8 & 6.9; Enclosure 17 & 18). At the top the lower sequence is bounded by SB Cal-1, which in the Elly-3 and Luke-1X cores is marked by the dramatic shift in lithology from floodplain mudstones to overlying fine-grained conglomerates and very coarse-grained pebbly sandstones (mentioned above under bullet "i and ii").

The sequence comprises primarily floodplain mudstones with several levels with roots and paleosoil development (lower part of the Elly-3 and Luke-1X cores; Enclosure 13 & 14a; Facies association FA 1 of Hovikoski and Johannessen 2016; Ichron 2010). In the Luke-1X and Falk-1 cores the presence of slumped sandy siltstones and sandstone-siltstone heteroliths suggests possible fluvial bank collapse or crevasse splays from nearby located, undrilled fluvial channels. The Elly-3 cores shows an interval, c. 50 ft. thick (c. 15.3 m) dominated by fine-grained sandstones and heteroliths showing ripple-cross lamination, parallel lamination, wavy lamination, slump structures, synaeresis cracks and some bioturbation. The interval seems to consist of 3 or 4 channel successions, c. 4–5 m thick separated by scoured channel bases. The interval seems to have formed under weak tidally influence (Enclosure 14). The overlying mudstones are similarly to the underlying also interpreted as floodplain mudstones; however weak marine influence is not precluded. The stacking of 3–4 channel-fills may suggests lateral migration of fluvial-tidal channels eroding the contemporaneous floodplain/coastal plain fine-grained sediments similar to the process known from recent lagoons (e.g. Fruergaard et al., 2011).

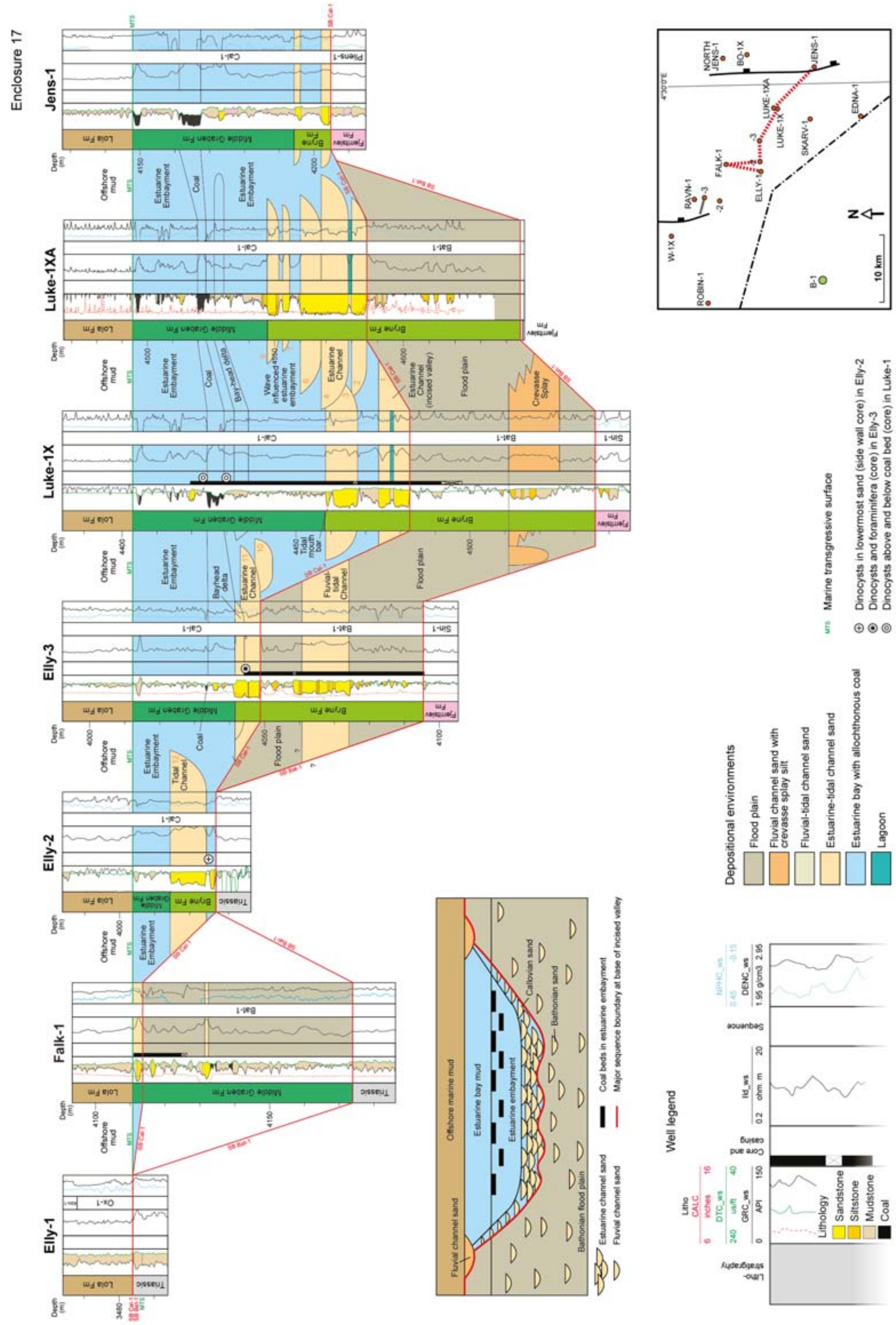


Fig. 6.8: Log panel flattened on base Lola Fm and displaying the “incised valley model”. Is also included as Enclosure 17. Notice the proposed time-stratigraphic position of the channel sandstones indicated by numbers.

No conclusive age evidence is found in the presently available data (se biostratigraphic review above); however, based on regional considerations involving the assumption of a regionally occurring hiatus between the upper Bathonian and the Callovian (e.g. Ineson and Surlyk 2003), a Bathonian age is assumed for the lower sequence.

The drilled Lower Sequence (?Bathonian) provides a low net/gross reservoir ratio with thin channel sandstones encased in intraformational floodplain mudstones. However, the suggestion of nearby channel margins in the Luke-1X and Falk-1 cores may together with the encountered channel-fills in Elly-3 suggest more reservoir potential than revealed by the drilled wells.

Upper Sequence – Callovian–early Oxfordian

The base of the Upper Sequence is defined by the significant facies change in the Elly-3 and Luke-1X cores where fine-grained conglomerates and very coarse-grained, pebbly sandstones showing cross-bedding and a low diversity, low density trace fossil assemblage indicating marine influence erosively overlie floodplain mudstones of the lower sequence (Facies association FA 2 of Hovikoski and Johannessen 2016; Ichron 2010). This marked erosion surface is correlated to a similar abrupt facies change at the base of the thick blocky sandstone package in Luke-1XA. It is further correlated to the uppermost part of the Falk-1 cores, where estuarine bay mudstones with thin coarse-grained, partly conglomeratic layers with abundant small quartz pebbles similar to those seen above the sequence boundary in the Elly-3 and Luke-1X cores occur. The surface is further correlated to the base of the Bryne Formation in Elly-2, Skarv-1, Edna-1 and Jens-1.

This correlation indicates a very significant erosional relief of the basal sequence boundary most probably reflecting a significant fall in relative sealevel after the deposition of the Lower Sequence in the (?)Bathonian, and possible involving regional changes in basin subsidence (Ineson and Surlyk 2003). It is most likely, that fluvial erosion deeply incised the floodplain deposits during the base level fall and forming an incised valley through which significant amounts of sand and gravel bypassed and was deposited further basinward as lowstand deposits. Owing to a subsequent base level rise in the Callovian, the incised valley was gradually back-filled. Whether fluvial deposits are preserved in the valley in the Elly-Luke area is uncertain. The fluvially formed valley floor was probably scoured by tidal currents during the transgression generating the cross-bedded conglomerates and pebbly sandstones probably formed by downstream migrating bars. The associated intervals with trace fossils in the Luke-1X cores indicate estuarine-tidal influence. Also in the Elly-3 cores the conglomerates are interpreted as estuarine-tidal channel deposits; thus it seems unlikely that lowstand fluvial deposits form parts of the incised valley-fill in these wells. The very blocky appearance of the sandstones in the Luke-1XA section shows that fine-grained tidal-estuarine deposits are almost absent in the lower of part of sequence here, suggesting that coarse-grained fluvial or tidal channel sandstones dominates.

The individual estuarine channel sandstone-fills occurring in the wells Elly-3, Luke-1X and Luke-1XA are thin with thicknesses of c. 3–7 m, maybe up to 13 m in Luke-1XA if not amalgamated here, and they are separated by thin estuarine bay mudstones. Above the sandstones occurs a thick succession of bay mudstones with interbeds of siltstones and allochthonoues coal beds. The bay mud is interpreted to have formed in a wave-influenced estuarine bay (Facies association FA 3 & 4 of Hovikoski and Johannessen 2016; Ichron 2010) established in the incised valley due the continued transgression that eventually led to a full marine transgression and changed to deposition of marine mudstones of the Lola Formation.

The sandstones are generally concentrated closely above the basal sequence boundary, and based on the correlations displayed in Enclosure 17 and 18 is seems unlikely that the estuarine channel sandstones are widely distributed over the entire width of the incised valley. The individual channel sandstones may to some extent be connected due lateral migration and intersection of the different episodes of channel-fill. However, the large difference between the two closely situated well sections of Luke-1X and Luke-1XA clearly demonstrates that the lateral distribution of some of the channel sandstones is limited and that the bay mudstones dominate the valley fill.

On the northwestern margin of the incised valley in Elly-2, the interval consists of 1–2 m of sandstones overlain by c. 1 m of marine mudstones with a relatively diverse dinocyst assemblage followed by a 10–11 m thick sandstone interval. The gamma ray trend indicates an overall upward fining trend that may be interpreted as a channel fill. In detail, the well-logs seem to subdivide the sandstone interval into three parts. Two SWC samples from the sandstone interval contain very sparse dinocysts suggesting a weak marine influence. The evidence from three SWC may thus reflect that slightly more marine conditions prevailed at the flank of the valley compared to the central part at Elle-3, Luke-1X and Luke-1XA.

On the southeastern flank of the incised valley, the interval of interest is thin and dominated by sandstones in the Skarv-1 and Edna-1 wells. These sandstones are interpreted as possible tidal channel sandstones and related mouth bar sandstones, but may as well represent shoreface sandstones formed on the flank when it was flooded prior to the final Oxfordian marine transgression that led to deposition of widespread Lola Formation mudstones. It is here assumed that these two well-sections are related to the incised valley; this may be verified by seismic data.

The Upper Sequence thus provide a medium net/gross ratio of reservoir sandstones, with the sandstones concentrated along the incised surface in the central parts of the valley fill and on the flanks. The channel sandstones may amalgamate vertically in places, as possibly seen in Luke-1XA, and channel bodies may to some extent amalgamate laterally due to lateral migration/meandering and cross-cutting. An optimistic “end member” input for the reservoir model may be based on the assumption that the incised valley received sandy sediments trough several contemporaneous and sinuous fluvial channels terminating into estuarine-tidal channels that migrated laterally and formed a coherent sandstone belt along the valley floor. However, the occurrence of the above mentioned interbedded bay mudstones suggests that the individual channels are partly separated (individual channels are numbered in apparent stratigraphic order on Enclosure 17 and 18 to ease the visualization). Thus a pessimistic “end member” input for the reservoir model may be based on the assumption that the individual channel sandstones mostly are separated by mudstones and primarily have a NE–SW trending (wide) shoestring appearance. A schematic cross-section of the valley is shown on Figs 6.8 and 6.9 and Enclosure 17 and 18; in Fig. 6.10 and Enclosure 19 three schematic paleogeographic maps display the situation during (?)Bathonian time with floodplain deposition, Callovian with the initial valley back-filling, and the subsequent late Callovian–early Oxfordian transgressive estuarine bay development.

In order to provide better constrains on the amount of channel sandstones versus non-reservoir bay mudstones, it will probably be beneficial to conduct a decompaction exercise to compensate for the differential compaction of the mudstones and the sandstones. After construction of decompacted vertical sections, a renewed correlation exercise should be performed with flattening on horizons much closer to the targeted sandstones, i.e. below the base Lola Formation surface. This exercise may reveal in greater detail the temporal and spatial relationship between the channel sands and the bay muds.

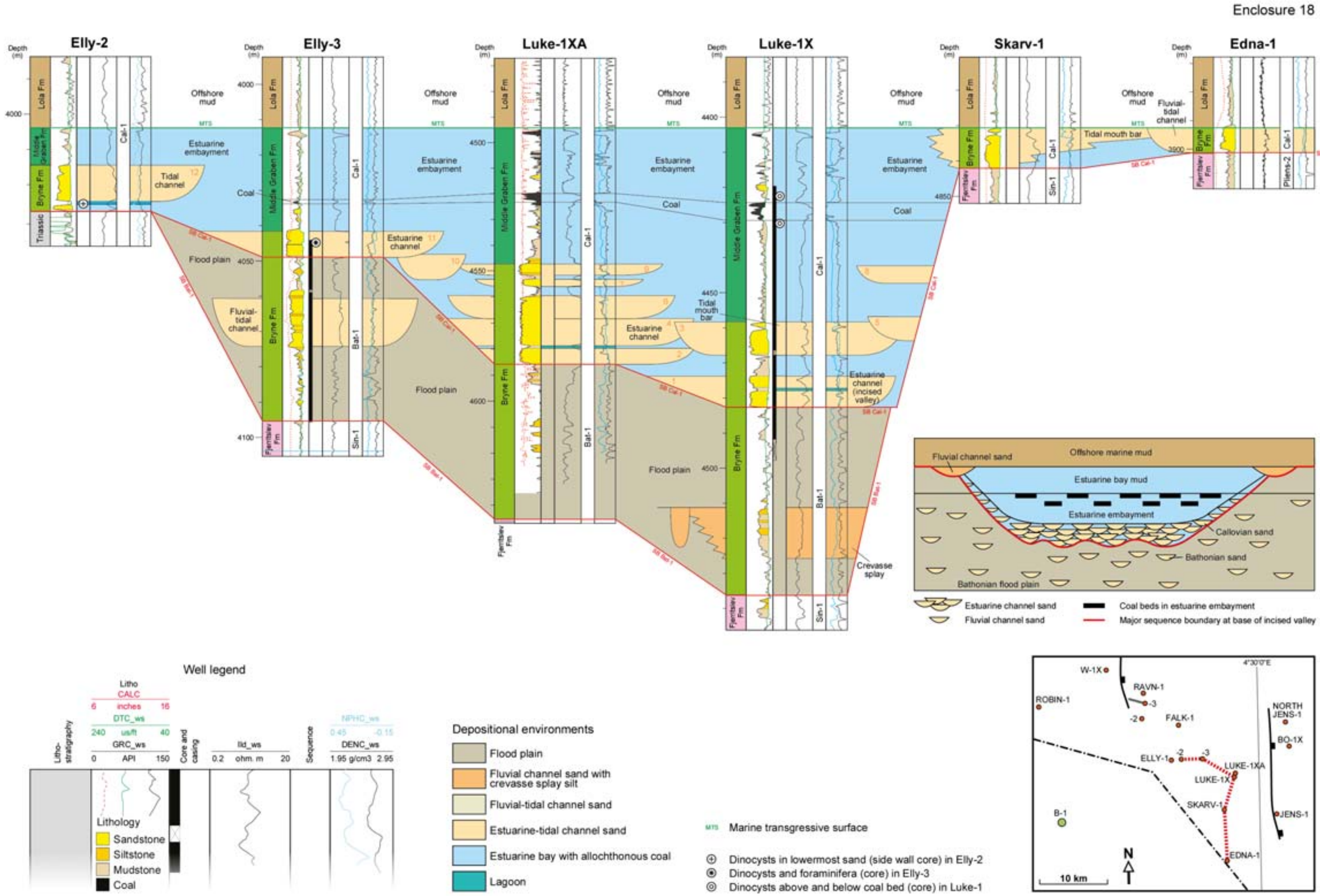
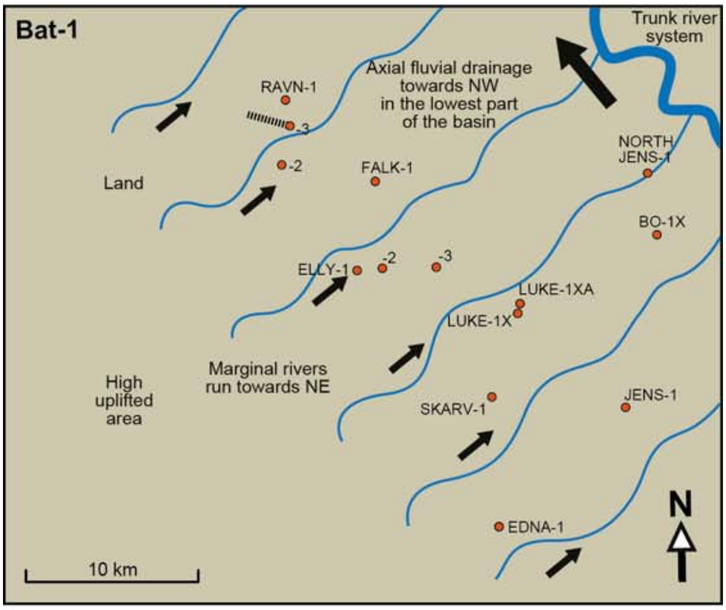
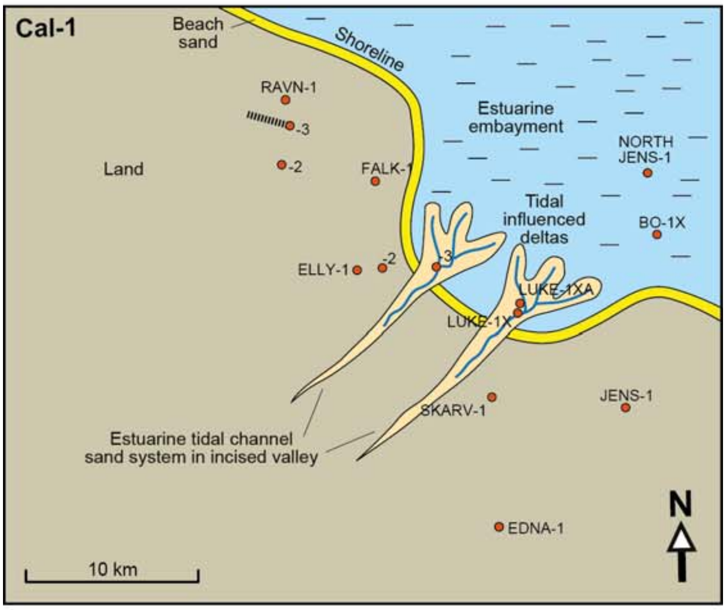


Fig. 6.9: Log panel flattened on base Lola Fm and displaying the "incised valley model. Is also included as Enclosure 18. Notice the proposed time-stratigraphic position of the channel sandstones indicated by numbers.





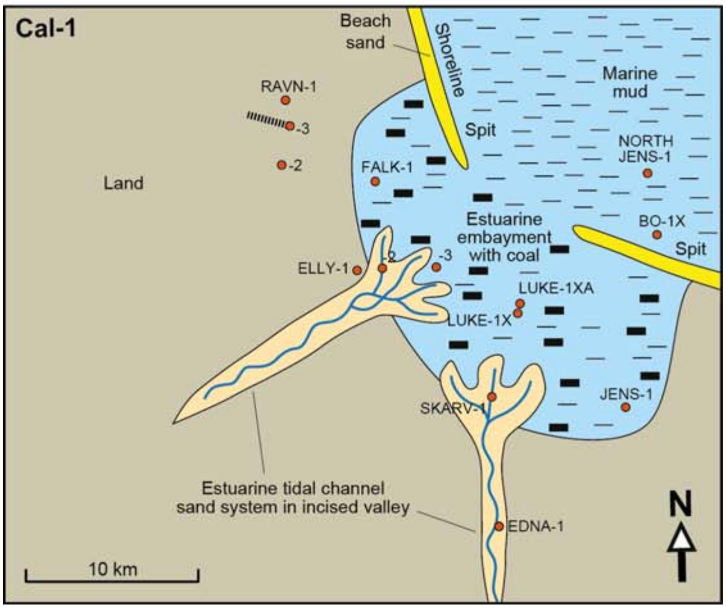


Fig. 6.10: Three schematic paleogeographic maps showing (?)Bathonian floodplain deposition followed by Callovian–early Oxfordian transgressive infill of a valley incised during the (?)late Bathonian–early Callovian.

6.3 Comparison of the GEUS models with well-log scenarios provided by Wintershall

Three well-log scenarios were provided by Wintershall. The scenario 1 and 2 encompasses Elly-2, Elly-3, Luke-1XA, Luke-1 and Skarv-1, whereas the scenario 3 includes Falk-1, Elly-2, Elly-3, Luke-1XA and Luke-1X. The Wintershall stratigraphy of the Skarv-1 well differs from the PetSys data, as GEUS interpret a thin Middle Jurassic overlying the Fjerritslev Formation at 3842.2 MD. In the Final Well Report for Skarv-1, the interval from 3834m-3891m is referred to the Callovian “Mid Graben Sandstone”, while the interval from 3891-3922m is referred to the Lower Jurassic Fjerritslev Formation. The interpretation in PetSys was based on solid biostratigraphic evidence (both dinocysts, pollen and foraminifera) for a Sinemurian (Early Jurassic) age of a SWC at 3851 m and a Rhaetian (uppermost Triassic) age of a SWC at 3888.5m (Paleoservices 1993).

The approach used by Wintershall for the scenario 1 and 2 is based on correlating marked shifts in lithology at the top of relatively thick sandstone beds. This approach, by nature aligns sandstone intervals that may be of significantly different genesis and age, i.e. sandstones that may have different stratigraphic positions within a succession are correlated. However, if sandstone intervals, which have a limited lateral distribution owing to their depositional genesis (i.e. “one-dimensional” channel sandstones), are correlated using the “top of sand approach”, a false input to the sedimentological-stratigraphic solution is provided and wrong estimates of reservoir distribution and continuity is a likely result. This rational is one of the reasons why GEUS disregard the “layer cake model” presented above. If it is further considered that the bay mudstones are much compacted and reduced in thickness compared to the sandstones, the “correlation of sandstone tops approach” is even more challenged.

The correlation in scenario 2 acknowledges the importance of the cored conglomerates in Elly-3 and Luke-1X, and in this way the erosional surface at the base of the conglomerates (a good candidate for a sequence boundary) is correlated in a similar manner as in GEUS´ “incised valley model”. However, as shown in Figs. 6.7 and 6.8 Enclosure 17 and 18 is seems unlikely that the sandstones encountered in Luke-1X and Luke-1XA are connected to the sandstones in Elly-3 as they appear to be positioned at different stratigraphic levels within the valley fill. To be connected probably requires that the base of the sequence marked as SB Cal-1 In Enclosure 17 and 18 is *not* a deeply incised erosional surface (as indicated by the facies shift across it); instead the marked relief shown by the SB Cal-1 surface, when the base Lola Formation datum is used for flattening, need to be related to differential subsidence of the well locations occurring during the time of the formation of the stratigraphic interval embraced by SB Cal-1 and the datum.

The correlation scenario 3 seems highly unlikely, as it assumes deposition of channel sands at stepwise higher stratigraphical levels moving from Elly-2 toward Luke-1x. This correlation contradicts the large similarity of the bay mudstone interval with coal beds, which seem to correlate nicely from well-section to well-section. Generally, bay – and marine mudstones – tend to be much more lateral persistent than sandstones; thus priority is given to the correlation of mudstone patterns rather than the sandstones.

The above discussion is built on the premise, that the base Lola Formation maker and the underlying coal-bearing bay mudstones showing numerous subtle log changes and log patterns are laterally persistent and correlated correctly in the Enclosure 17 and 18. If this assumption is incorrect, i.e. if the correlation is misguided and fooled by the presence of several allochthonoues(!) coal beds occurring at different stratigraphic levels, then the proposed “incised valley model” is challenged. The comparable thickness of the Lower Jurassic Fjerritslev Formation in Elly-3, Luke-1X and Luke-1XA preserved under the base of the incised valley also needs to be considered; it is remarkable that the erosion seems to have cut equally deep at the three wells; this configuration could suggest tilting of the underlying fault block rather than erosion and incision.

6.4 Sand transport direction and orientation of the incised valley

The general paleogeographical reconstruction performed in the PetSys project indicates a general NNW–SSE trend of the Callovian–Oxfordian coastline (Figs. 6.4–6.5). The well-log panels presented here indicate that the incised valley was deepest in the Luke-1X area with it flanks located at the Elly-1 and Elly-2 wells to the northwest and at Skarv-1 to the southeast. The likely trend of the valley is thus ENE–WSW with the opening to the contemporaneous sea to the NE; this may be verified by seismic data. The interpreted transport direction toward NNE–NE based on the dipmeter data an OBMI borehole image log conforms to this (Eriksfiord 2006; Ottesen 2009).

6.5 BHI data from Luke-1XA and dipmeter data from Elly-1, -2, -3 and Falk-1

Luke-1XA

A report on geological interpretation of an electrical OBMI borehole image log acquired in Luke-1XA over the interval of interest was supplied by Wintershall (Ottesen 2009) and the results are here compared with the sedimentological core logs of Ichron and GEUS (Hovikoski & Johannessen 2010).

The OBHI report subdivides the investigated succession into a Lower and an Upper Sand interval that are further subdivided into units. The notations on the depths are misleading with confusing typos and marked discrepancies between the depths intervals in the text and on the figures. Furthermore, the BHI depths seem to be approx. 7–9 ft. off the core depths. This complicates a detailed comparison between core log and the OBHI data. In addition, the text is somewhat inconsistent.

However, the descriptions of the interpreted structures and lithologies in the report seem to suggest a distal fluvial system with channels, overbank and passive channel-fill. This suggestion fits reasonable well with the Ichron and GEUS interpretation of the cores. Thus the interpreted directional data from cross-beds may still be used for interpreting transport directions, assuming that the measured depositional planes represent down-stream accreting cross-bedding reflecting the dominant fluvial direction, and not, lateral accreting surfaces on for instance a point bar surface. Based on this assumption the main transport was toward N–E from the cross-bed data. The report further suggests a direction toward the NNE–NE based on identification of assumed channel axial trends. Based on axial trends, lithofacies and directions of cross-beds, a fluvial system is visualized, flowing to NNE–NE.

The interpreted fluvial transport direction toward the NNE–NE of Ottesen (2009) is more or less perpendicular to the interpreted NNW–SSE trending coastline of GEUS (Figs 6.4–6.5). Thus the OBHI interpretation is accordance with GEUS' overall palaeogeographic understanding, as it is likely that the lower distal range of a low-gradient fluvial-estuarine system is in general oriented perpendicular to the contemporaneous coastline.

Elly-1, -2, -3 and Falk-1

Dipmeter data from Elly-2 suggest a depositional trend toward E–NE in assumed Callovian sandstones (Eriksfiord 2006). The data from both Elly-3 and Falk-1 is much more ambiguous with influence of nearby faults or well-cutting faults, but a NE–ENE transport direction also for the Callovian sand may be interpreted from these wells (Eriksfiord 2006).

7 Diagenesis

7.1 Diagenesis in the Elly-3, Luke-1X and Falk-1 cores

The evaluation of the diagenesis in based on macroscopic inspection of the cores and a description of the background diagenesis in the Elly-3 core (Rowe and Knipe 1999). Consequently, the measured porosities and permeabilities are not related to specific diagenetic changes.

The highest porosities and permeabilities clearly occur in the sandstone interbedded with conglomerates in the Elly-3 core (Routine core analysis). However, in the Luke-1X core there is no direct relationship between the grain size, and the porosities and permeabilities (Ichron 2010). Other factors, probably diagenesis, besides the depositional environment seem to affect the porosity and permeability.

Gravel sized grains mainly comprise quartz or quartzitic clasts in the Falk-1, Luke-1X and Elly-3 cores. However, relatively large rip up mud clasts occur in mouth bar deposits and sandstone clasts occasionally occur in the Elly-3 core. One interval, possibly slump deposits, in the Luke-1X core consists of cemented mudstones, sandstones and siderite cemented areas.

The most common cement types in the Elly-3 core are kaolinite (6 – 21 %), quartz (9 – 15 %, maximum 20 %) and ankerite (0 – 11 %) (Rowe and Knipe 1999). Kaolinite comprises a mixture of detrital kaolinitic clasts and authigenic pore-filling kaolinite. Authigenic kaolinite formed at the expense of feldspar and mica, possibly by meteoric water flushing through the fluvial / tidal influenced deposits. Early diagenetic dissolution of K-feldspar may have removed the internal potassium source which could otherwise have promoted illite precipitation during deep burial diagenesis. The ankerite cement is assumed to be scattered in clusters (possibly also visible in the cores), since it is maximum 11%. In this case the ankerite cement will mainly reduce porosity and to a lesser extend the permeability.

Visual inspection of the Luke-1X core also suggests the presence of carbonate cement, possibly of ankerite and siderite. Calcite cement was not identified, though it presence was suggested by Ichron (2010). The burial depth of the sandstones is approximately 400 m deeper for the Luke-1X core (4460 – 4480 m TVD) than for the Elly-3 core (4025 – 4055 m TVD). The higher temperatures at the increased burial may have promoted diagenetic changes in the Luke-1X core.

Locally barite and ankerite cemented veins/fracture are notably, since most of the porosity is closed by late barite and ankerite cement in the nearby Ravn-2 well (PetSys webpage; Rowe and Knipe 1999). However, the Ravn-2 well is located next to a fault, which probably supplied hydrothermal fluids causing the barite / ankerite cementation. Only very thin veins have been recognised in the Elly-3 core.

Siderite cement occurs repeatedly in both sandstones and mudstones in the Falk-1 and Luke-1X wells (Ichron 2010). Siderite occurs occasionally in the previously investigated sandstones from the Elly-3 core (Rowe and Knipe 1999) and visual inspection of the cores suggests that several siderite cemented areas can be sampled. Siderite geochemistry could be applied as an indicator of terrestrial versus marine influence on the depositional environment. The chemical composition, especially the Mg and Mn content, of siderite reflects the pore fluid composition at the time of precipitation (e.g. Matsumoto and Iijima 1981; Mozley 1989; Weibel et al. 2016). The chemistry of the early siderite cement should preferably be measured by microprobe, though EDS (energy dispersive spectrum) analyses at the SEM (scanning electron microscope) could provide a first estimate. Furthermore, the oxygen isotopic composition of siderite is defined by the temperature of siderite precipitation; therefore siderite has been applied as a proxy for palaeotemperature. Since siderite typically precipitates very early during diagenesis (though this will have to be verified petrographically) its composition is typically governed by the depositional environment.

Only two samples of the sidewall cores taken in the Bryne interval in the Elly-3 well remain and they are of poor quality, mainly powder. The sidewall cores are from the depth 13184’ (4018.48 m) and 13191’ (4020.62 m) and they contain only 6 g and 7 g, respectively.

7.2 Luke-1X and Luke-1XA porosities

There is observed a marked difference in the porosity of the Bryne Formation sandstones with higher values in the Luke-1XA well than in Luke-1X (5–10 porosity units, %). On average, the hydrocarbon saturation of the reservoir sandstones is 90% in Luke-1XA, but only 40–60% in the Luke-1X well. The sediments are buried somewhat deeper in the Luke-1X well than observed in Luke-1XA (approximately 200 ft. ~ 60 m). Two possible explanations may address the observed difference in porosity and saturation between the two wells:

1. The Luke-1XA well probably represents the hydrocarbon leg, whereas the Luke-1X saturations signifies a transition zone. Hence, the diagenetic alterations may have ceased early in the Luke-1XA well and continued for a longer period in Luke-1X. The brownish stained and hydrocarbon smelling carbonate cement in Luke-1X suggests that the carbonate cement formed after hydrocarbon filling. The carbonates could have been promoted by bacteria at the hydrocarbon-water contact. Bacterial influence on the carbonate cement precipitation could be verified by oxygen and carbon stable isotopes.

2. The Luke-1XA well may be located in another block than the Luke-1X well, i.e. compartmentalisation.

7.3 Recommendations regarding petrography and diagenesis

- Petrographical investigations of sandstones in the Elly-3 core having high porosity and permeability in order to understand why high initial porosity and permeability is preserved here. Verify if the conglomeratic intervals in the Elly-3 core are of equally high permeabilities. Comparison of the conglomeratic intervals in the Luke-1X and Elly-3 cores, since these have varying porosities and permeabilities. The investigations ought to include porosity and permeability measurements of the plugs from which cut offs are used for the thin section. This will ensure that the porosity and permeability measurement can be directly correlated to the sediment composition and the diagenetic changes.

- Petrographical investigations of low density sandstone interval in the Luke-1X well. Could the low grain-density and high hydrocarbon saturation be caused by hydrocarbon inclusions in cement?

- Geochemistry and petrography investigations of siderite cement in order to obtain an independent contribution to the interpretation of the depositional environment.

8 Conclusions and recommendations for further work

8.1 Conclusions

The Elly-Luke license area shows great structural complexity that is clearly reflected by the seismic data provided by Wintershall for this study. The structural complexity including faults possibly cutting the Bryne-Middle Graben interval near (or in) for instance the wells Elly-2, Elly-3, Falk-1 and Luke-1X challenge detailed interpretation of the area. With the current seismic resolution and the, in general very limited and poor biostratigraphic resolution provided by standard consultant reports, the construction of detailed stratigraphic correlations has to rely to a great extent on the recognition of well-log patterns and interpretations of depositional environments based on the available cores from Elly-3, Falk-1 and Luke-1XA.

Our evaluation of the existing biostratigraphic data, of very variable quality and years of analysis, concludes that the sporadic and poorly documented suggestions of older Middle Jurassic – the Bajocian–Bathonian – is not trustworthy, whereas the indications of the Callovian–Oxfordian are firm. It is our expectation that a new biostratigraphic study, based on careful selected and processed core samples from intervals with brackish-marine influence pin-pointed by a sedimentologist, and performed by GEUS specialists with updated knowledge on relevant literature, will provide dinocysts with stratigraphic potential.

The marked difference between the measured porosity in Luke-1X and Luke-1XA is here proposed to be related to the much higher hydrocarbon saturation in Luke-1XA compared to Luke-1X preventing pervasive diagenesis in the Luke-1XA sandstones. Petrographic studies on selected core samples are needed to confirm this.

Two possible stratigraphic models are proposed, the "**layer cake model**" and the "**incised valley model**" which provides very different interpretations of the genesis of the reservoir sandstones and their resulting distribution and connectivity. Early proposed interpretation of the Bryne sandstones as deposited by braided fluvial rivers is not regarded valid by GEUS. GEUS favors the "**incised valley model**" based on a number of criteria of which the overall geometry of the interval of interest, presence of similar conglomerates overlying an erosion surface identified in the three cored sections and the distribution of floodplain and estuarine bay mudstones are the most important. These criteria and others are discussed in the section on depositional development.

The "**incised valley model**" developed after deposition of relatively widespread mud and silt on a low-gradient floodplain that probably feed sediments toward NE into a larger floodplain system oriented NNW– SSE, i.e. parallel to the graben axes in (?)Bathonian time. Presence of non-drilled fluvial channels in the herein defined Lower Sequence (?Bathonian) in the lower part of the Bryne-Middle Graben interval are indicated by fine-grained crevasse splays (Luke-1X and Luke-1XA well-logs) and by fine-grained, muddy channel sandstones in the Elly-3 cores. On the well-log panels the predicted presence of un-drilled channels are shown between the wells; however, the Lower Sequence contains a low net/gross ratio of reservoir sandstones encased in sealing mudstones (Figs 6.8 and 6.9; Enclosure 17 and 18).

After deposition of floodplain mudstones and scattered channel sandstones (and possibly some coastal plain sediments as well), the relative sea level fall and rivers caused deep incision in the late (?)Bathonian in response to a regional(?) change in basin subsidence. In the study area, bypass of sediments prevailed and presumably significant amounts of lowstand coarse clastics were deposited in a deeper basinward position. During early Callovian time, relative sea level rose again creating new accommodation space, and back-filling of the incised valley commenced. The initial sediments comprise conglomerates and pebbly sandstones deposited in an estuarine channel (marked with 1 in Figs 6.8 and 6.9 and Encl. 17 and 18), where fluvial-tidal currents probably scoured the valley floor. The basal erosional surface of the incised valley-fill is thus a transgressive tidal ravinement surface cutting the sequence boundary.

During continued sea level rise newly formed accommodation space was mainly filled by successive channel sands developed along the gently sloping sides of the incised valley (e.g. Elly-3 and Elly-2). In the central area successive channels stacked up partly separated by bay mudstones (e.g. Luke-1X and Luke-1XA); whether this stacking pattern was formed due to autocyclic channel migration or governed by minor fluctuations in the sea level rise comparable to the development of costal parasequences, remains unclear.

The presence of comparable pebbles in the conglomerates, cored in Luke-1X, Elly-3 and Falk-1, directly overlying the basal sequence boundary/tidal ravinement surface, but formed at different times during the gradual filling-in of the valley, presumably reflects that coarse clastics were transported by rivers to the incised valley from a nearby hinterland during the entire life time of the valley. Tidal currents reworked the coarse clastics along the valley floor and when base level rose and water depths in the bay increased, mud deposition took over centrally in the valley, while the shallower valley margins still were swept by tidal currents forming tidal channel sands. As described above, the interbedded nature of channel sandstones and bay mudstones in the well-sections suggests that the individual channels are partly separated and encased in mudstones, occurring at different stratigraphic levels (tentatively numbered in ascending order on Figs 6.8 and 6.9 and Enclosure 17 and 18). In detail, some of the thinner sandstones are interpreted as tidal mouth bar and bay head delta.

The correlation schemes, and the interpreted lateral continuity of the reservoir sandstones presented by Wintershall in the three provided scenarios, are therefore not considered as a valid input to a reservoir model. The schemes seem to overemphasize the connectivity of the reservoir units and seem to ignore their limited depositional dimensions.

At some point in the Oxfordian, the entire valley and probably also large parts of the hinterland became flooded and the deposition changed to widespread marine offshore mud of the Lola Formation. The incised valley-fill is thus regarding as a thick transgressive systems tract bounded below by a transgressive estuarine scouring surface amalgamating with the Callovian sequence boundary and bounded above by an Oxfordian marine flooding surface (marked MTS on the well log panels); the maximum flooding surface, MFS Ox occurs higher in the Lola Formation.

In the section on depositional development, the implication of the incised valley model on reservoir modelling is discussed: an optimistic approach may suggest that the dominantly estuarine channel sandstones stack-up along the valley floor in the lower 1/3 of the valley-fill and are interconnected, while a more conservative approach may suggest that several channel sandstones occur isolated and encased in mudstones. GEUS experience and a quick scan through the literature does not warrant any firm relation between valley widths and valley depths/thickness or lithological nature of the fill. A schematic cross-section of the valley-fill is shown on Figs 6.8 and 6.9 and Enclosure 17 and 18.

8.2 Recommendations

8.2.1 Seismic studies

From the discussion during the kick-off seminar it is our understanding that Wintershall is in the process of acquiring the PSDM-processed DUC05 data from Maersk Oil to be used for further seismic studies including AVO-work. It is our opinion that further work on the present band pass filtered data is not needed. If the quality of the reprocessed DUC05 data warrants the conduction of further detailed analyses including advanced seismic forward modelling and attribute studies for mapping the valley dimensions, possible trends of sand input and position within the valley-fill of reservoir bodies, possible presence and timing of faults cutting the valley fill or affecting the syn-depositional accommodation space, it is probably worthwhile with the scope of providing further constrains on the nature of the valley fill and distribution of reservoir sandstones. However, the thin nature of the sandstones being below the resolution power of the seismic data, their stacking pattern and the fairly thick coal bed above the reservoir interval provide major obstacles.

8.2.2 Biostratigraphy and palynofacies

Our recommendations for further biostratigraphic studies are discussed in detail for each well in the chapter on Biostratigraphy. During the core-workshop held for the Wintershall-team, the need for better constrained correlations and possible subdivision of the Bryne-Middle Graben interval was discussed intensely. The cores were thus examined carefully for indications of marine/brackish influence as GEUS know from studies of similar paralic depositional settings that dinocysts often can be recorded from such sporadic intervals following detailed sedimentological facies analyses. It is thus expected that careful sampling of the core sections with weak marine influence followed by very cautious processing with the objective of revealing useful paralic–marine dinocysts will provide new important stratigraphic data; this has been done with great success by GEUS in similar depositional settings in the Jurassic and the Cenozoic (e.g. Johannessen et al. 1996; Dybkjær 2004; Rasmussen and Dybkjær 2005; Koppelhus and Nielsen 1994; Surlyk et al. 1995; Nielsen 2003). Palynofacies analysis may further strengthen the interpretation of depositional environment by providing crucial input. In total 19 sample positions were marked on the cores from Elly-3, Luke-1X and Falk-1.

In combination with this additional biostratigraphic study, attention should be made to the marine flooding surface in the basal part of the Bryne Formation in Elly-2, which was not emphasized in the PetSys project. In particular, it is mandatory to investigate if this event can be traced to the cored mudstone successions in Elly-3 and Luke-1X, as this may provide a firm fundament for subdivision of the Bryne Formation in the wells Elly-2, Elly-3, Luke-1X and Luke-1XA. Both the Elly-3 and the Luke-1X core contain sporadic dionocysts as indicated on the well-log panels in enclosure 15, 16, 18 and 19.

8.2.3 Sedimentology

The GEUS PetSys project provides a robust regional stratigraphic scheme, which has been used as framework and starting point for this study. However, based on the specific needs for a detailed subdivision of Bryne-Middle Graben interval with focus on reservoir development and distribution it is recommended that GEUS undertakes a detailed and integrated sedimentological facies analyses backed-up by palynofacies analyses and the above mentioned new biostratigraphic study. Below the sedimentological part of such a study is pinpointed:

The cores from the three wells cover in combination the entire interval of interest. Future sedimentological work should thus establish detailed facies associations (FA) and sub-associations of all cores. A new FA scheme aims to provide high-resolution paleoenvironmental data that allows robust delineation of sequence stratigraphic trends, refined interpretation of sequence stratigraphic surfaces, as well as correlation between the wells and a strengthened understanding for the distribution, dimensions and connectivity of the reservoir bodies. The starting point for this is the Ichron report, considered to be of good quality, and the preliminary GEUS descriptions of the Elly-3 and Luke-1X cores; GEUS has not previous to this Wintershall study examined the Falk-1 core.

As the Wintershall well-log panels, shown in the provided three scenarios, seem to overestimate reservoir connectivity, the potential for improving the input to a reservoir model seems great and crucial.

The preliminary sedimentological descriptions of the (?)Bathonian sequence have revealed that the so-called “flood plain” strata may, in fact, contain channel bodies being weakly tidally-influenced. The distinction between fluvial and tidal control is essential for a valid interpretation of the channel body geometry (e.g., fluvial point bar vs. tidal creek). To address this, the channel units (Elly-3) would be re-examined sedimentologically and ichnologically in detail. In addition, palynofacies analyses of selected intervals, as well as their microfossil content and total Sulphur content should be tested with 2 to 4 strategically selected samples.

The herein proposed “**incised valley model**” for the reservoir carrying Callovian–early Oxfordian succession needs to be further constrained regarding type of channel sandstones versus other sandstone beds (e.g. mouth bar sands, bay head deltas etc.), the position of the channel sandstones in the transgressive systems tract, dimensions of channel sandstones, interconnectivity of channel fills etc. Furthermore, it may be worthwhile considering to which extent syn-depositional tilt/differential subsidence after the formation of MCU and prior the base Lola Formation, i.e. during the time of formation of the Callovian–early Oxfordian incised valley succession possibly affected the distribution and position of the channel sandstones. Clues to the detailed filling history of the valley – and possibly the distribution of reservoir sandstones versus non-reservoir mudstones – may for instance be obtained by conducting a detail analysis of the fill after decompaction of the interval of interest and construction of a series of decompacted well-log correlations panels flattened on horizons closer to the reservoir bodies than the here used base Lola Formation. Post base Lola Formation tectonic tilt is removed by flattening on base Lola Formation as done in this study, but tilting during the valley-filling may have been important.

8.2.4 Petrography and por-perm measurements

Recommendations for further work are described in the section on petrography. The main suggestions include investigations of the Elly-3 sandstones in order to understand why high initial porosity and permeability is preserved in places, and comparison of the conglomeratic intervals in the Luke-1X and Elly-3 cores as these show varying porosities and permeabilities. The investigations shall include measurements of porosity and permeability of the plugs from which cut offs are used for the thin section to ensure that the measurements can be directly correlated to composition and diagenetic changes.

It is further suggested to perform petrographical investigations of low density Luke-1X sandstones to reveal if the low density and high hydrocarbon saturation reflects hydrocarbon inclusions in cement?

As an independent contribution to the interpretation of the depositional environment it is proposed to investigate geochemistry and petrography of siderite cement.

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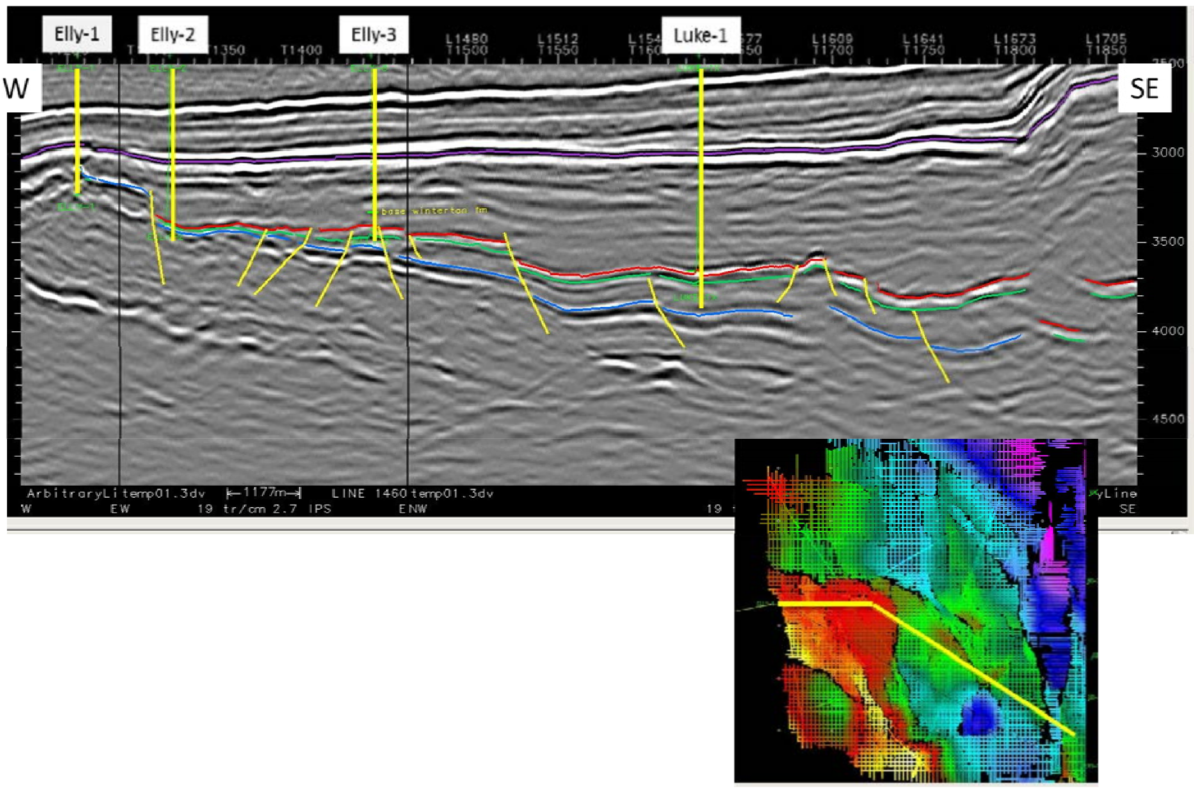
10 Appendices

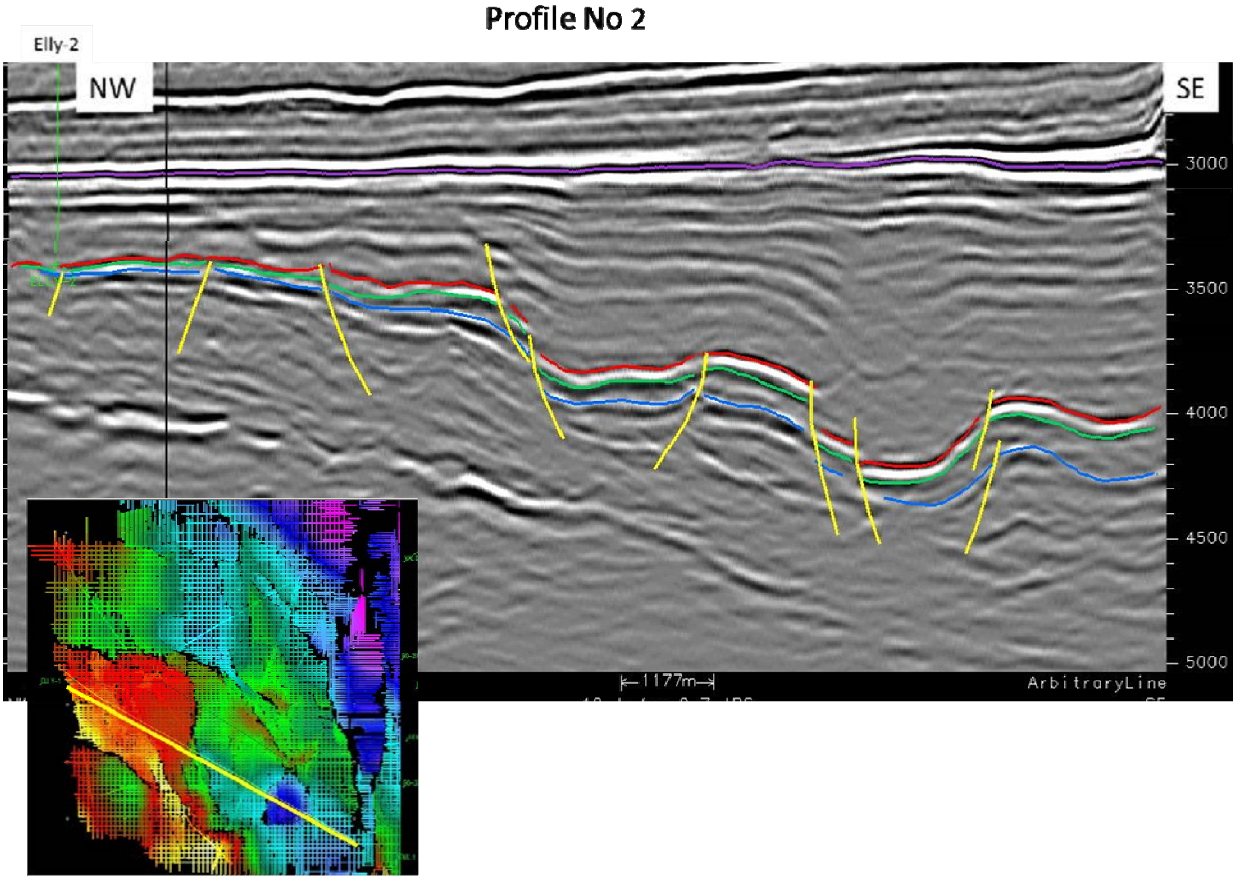
Appendix 1: Structural profiles, time isochore maps, attribute maps

Appendix 1a

Profile No 1



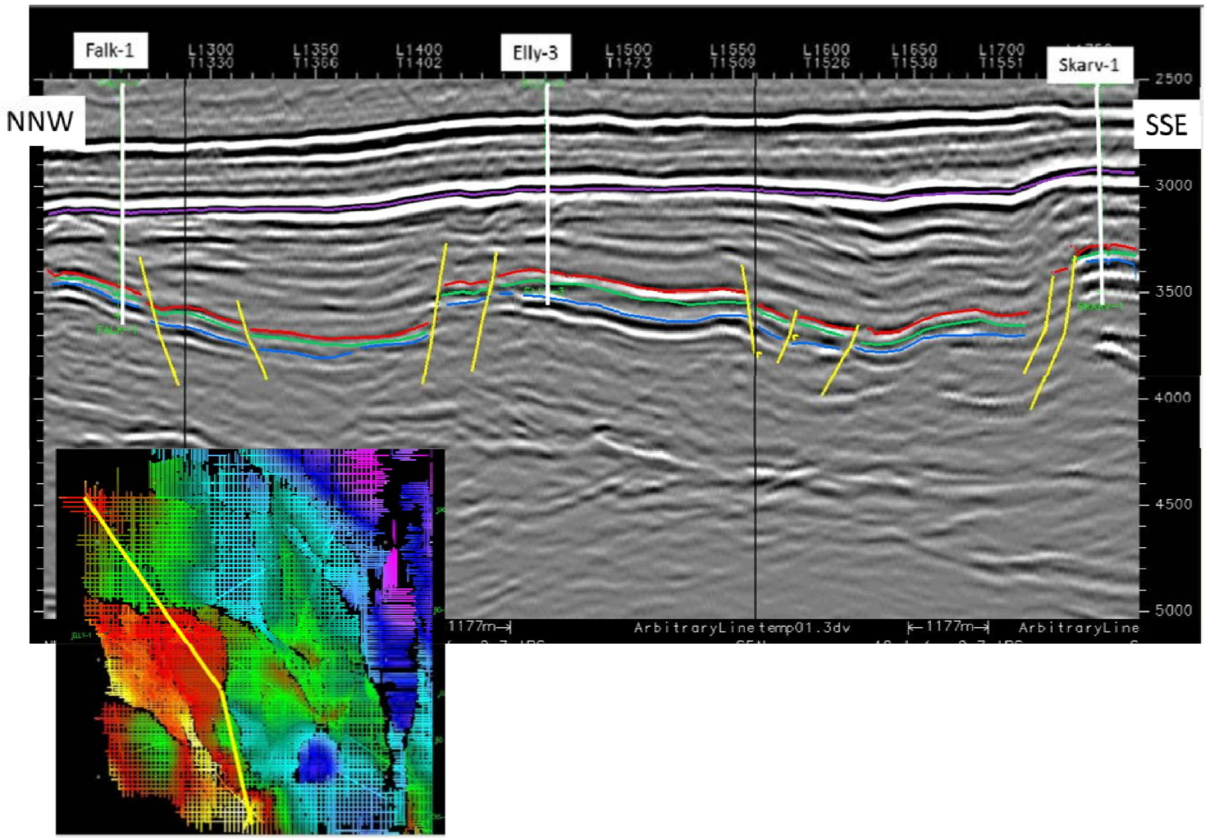
Appendix 1b



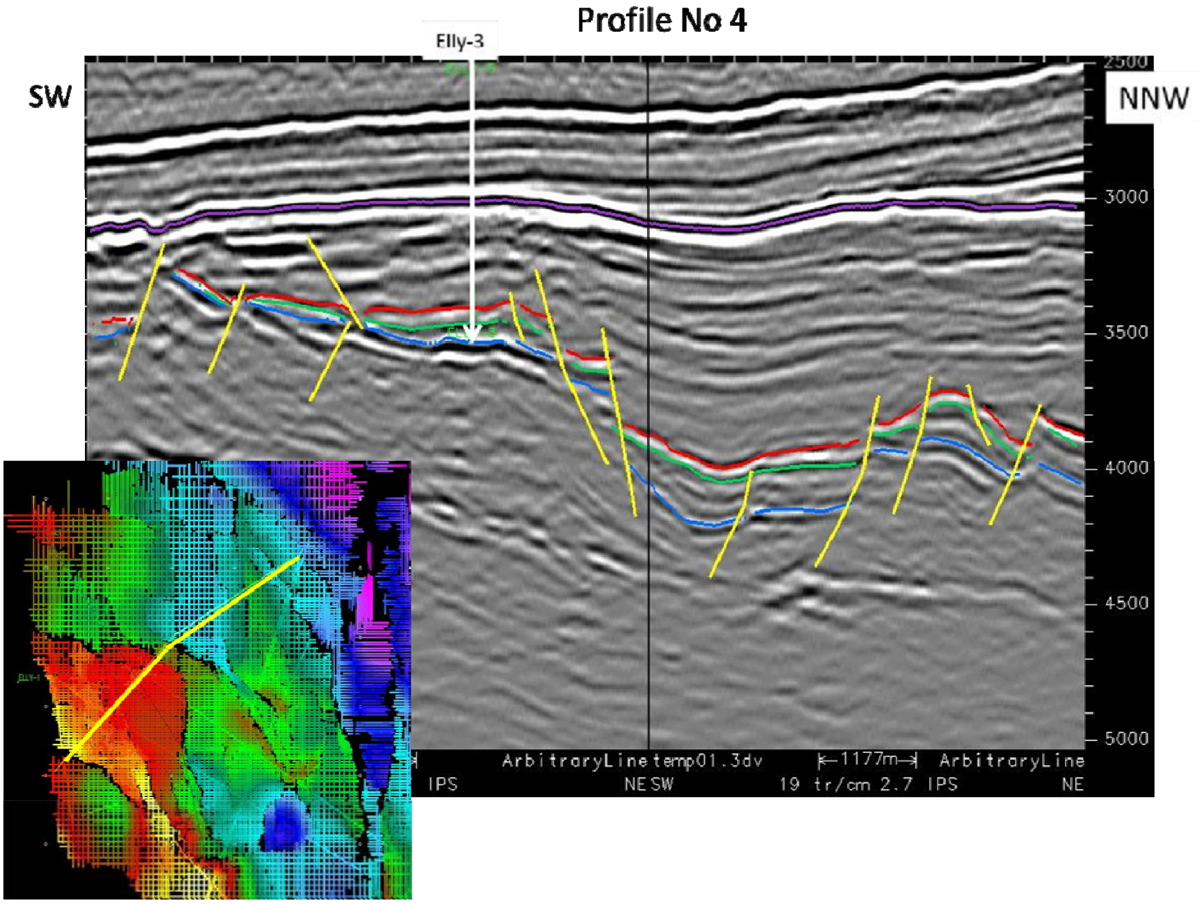
Profile No 2
Elly-2
NW
SE
3000
3500
4000
4500
5000
1177m
ArbitraryLine

Appendix 1c

Profile No 3

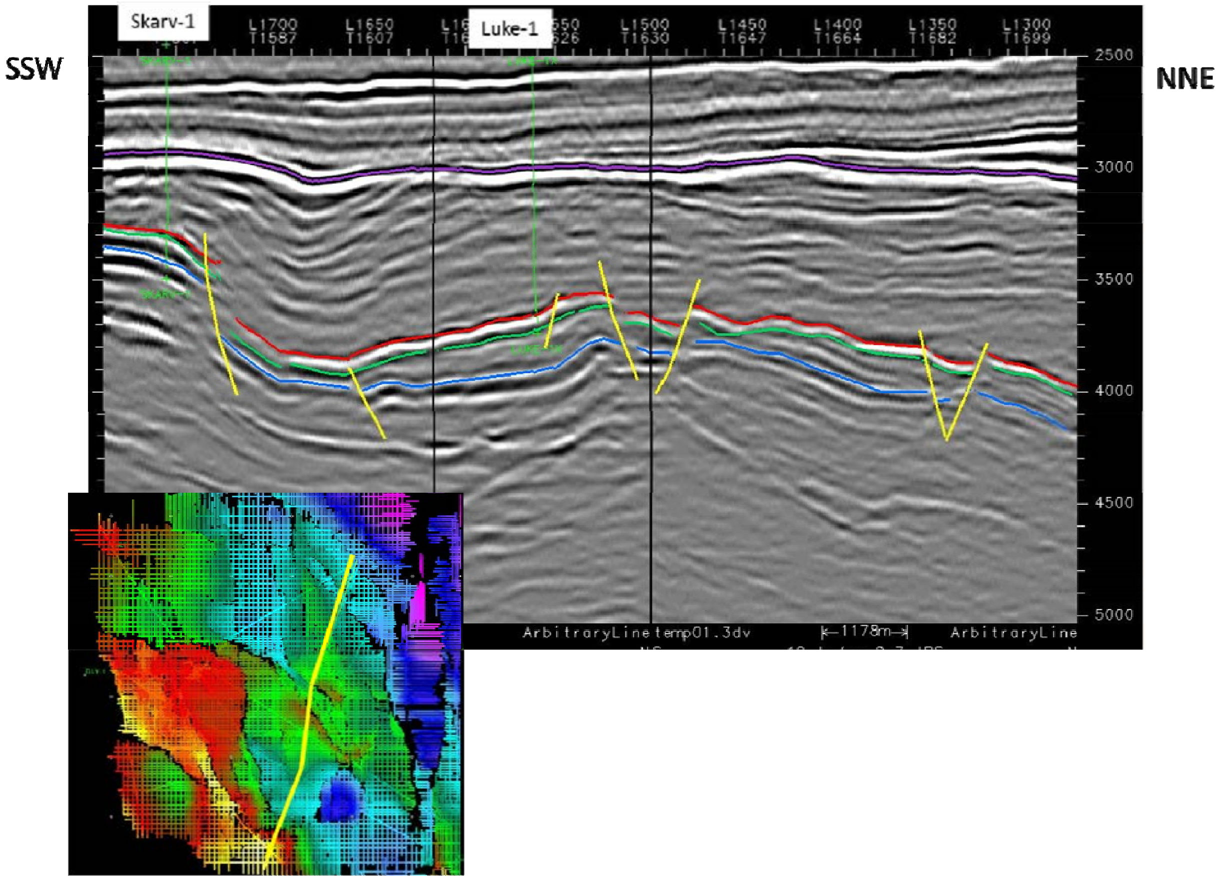


Appendix 1d


Profile No 4
Elly-3
SW
NNW
2500
3000
3500
4000
4500
5000
ArbitraryLine temp01.3dv
1177m
ArbitraryLine
IPS
NE SW
19 tr/cm 2.7 IPS
NE

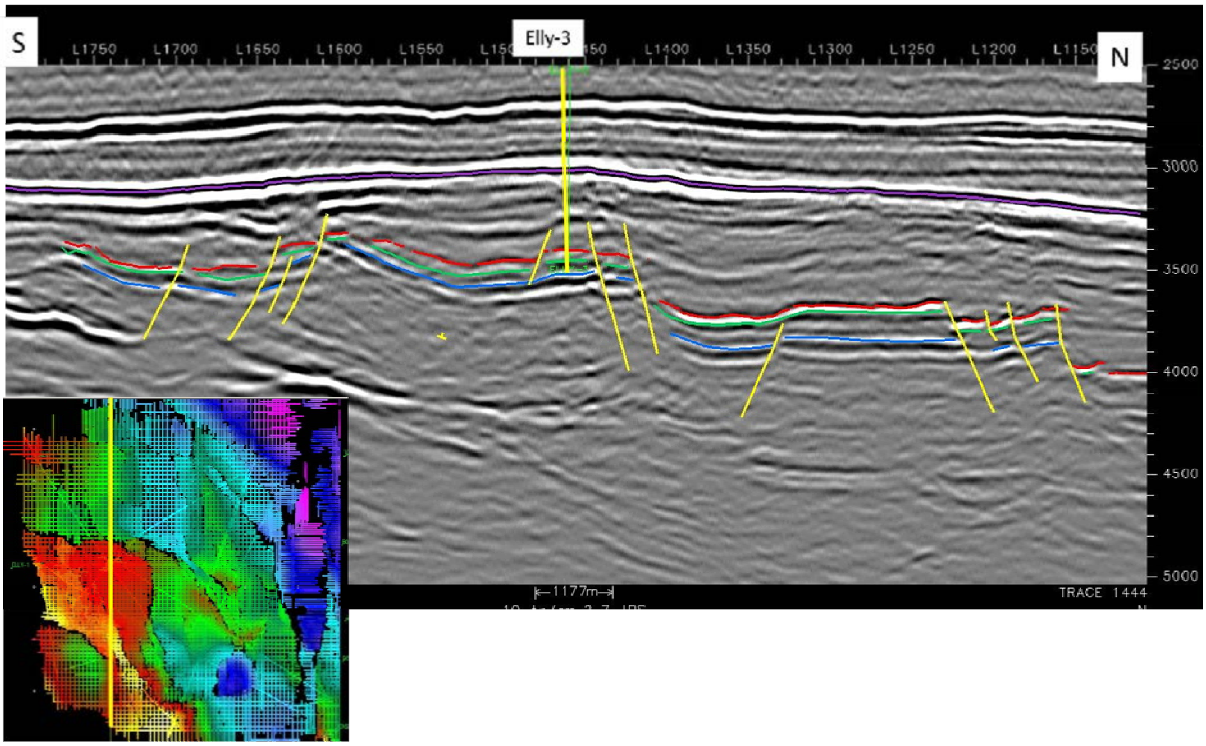
Appendix 1e

Profile No 5



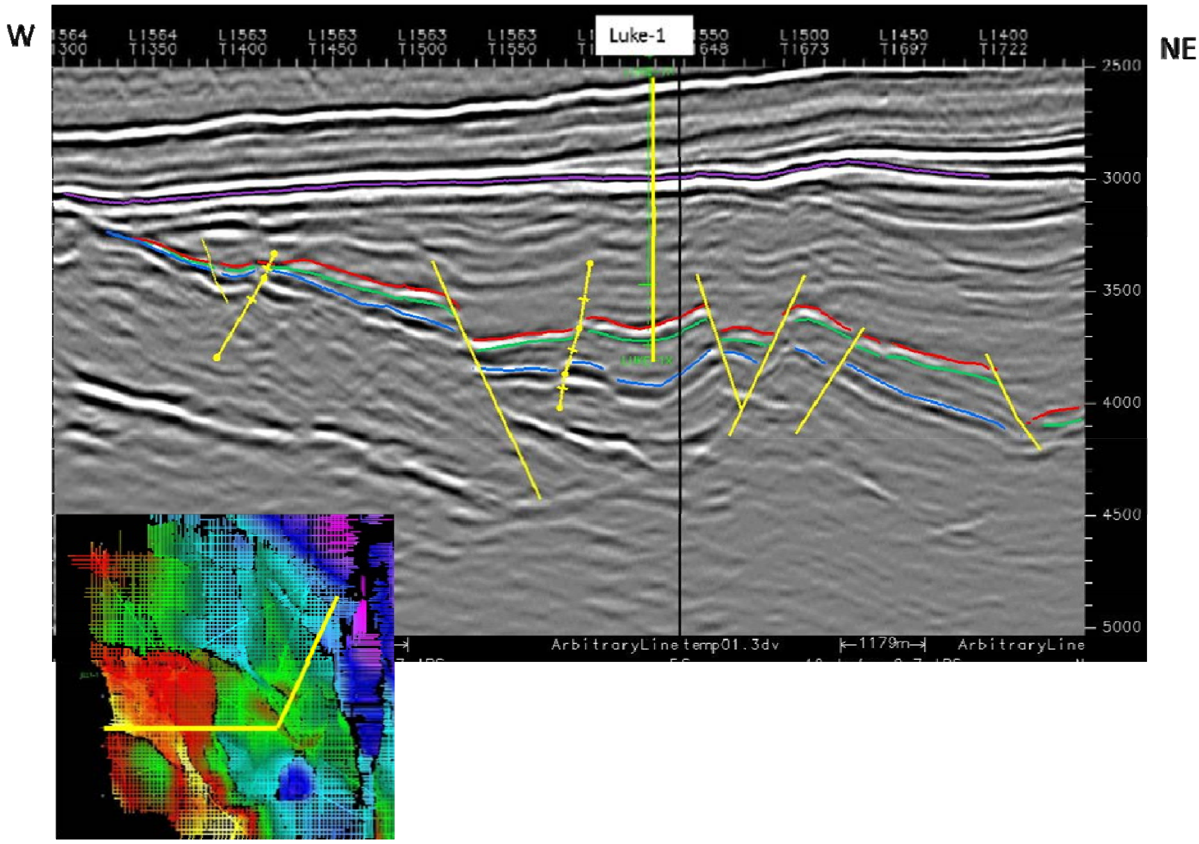
Appendix 1f

Profile No 6



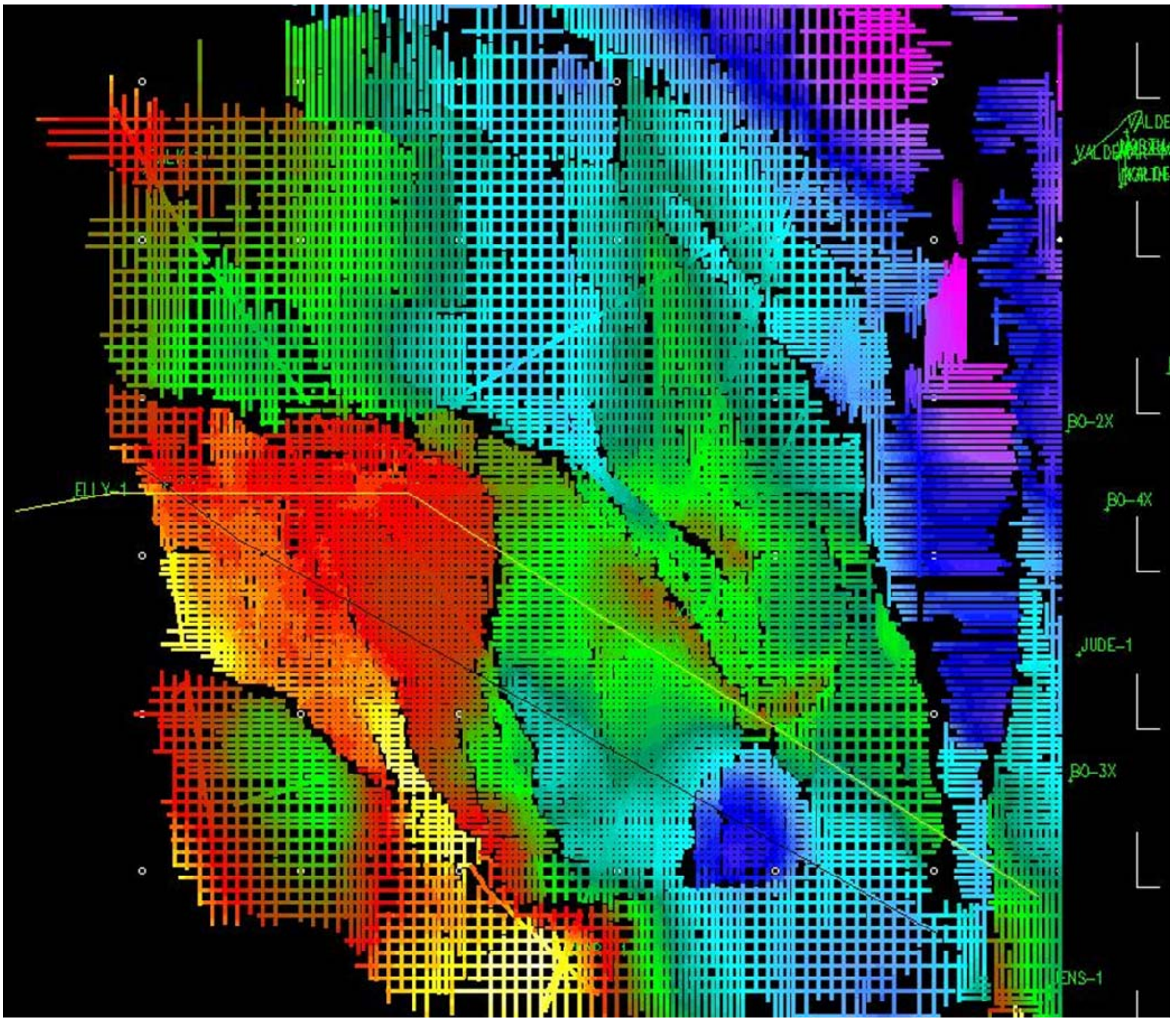
Appendix 1g

Profile No 7



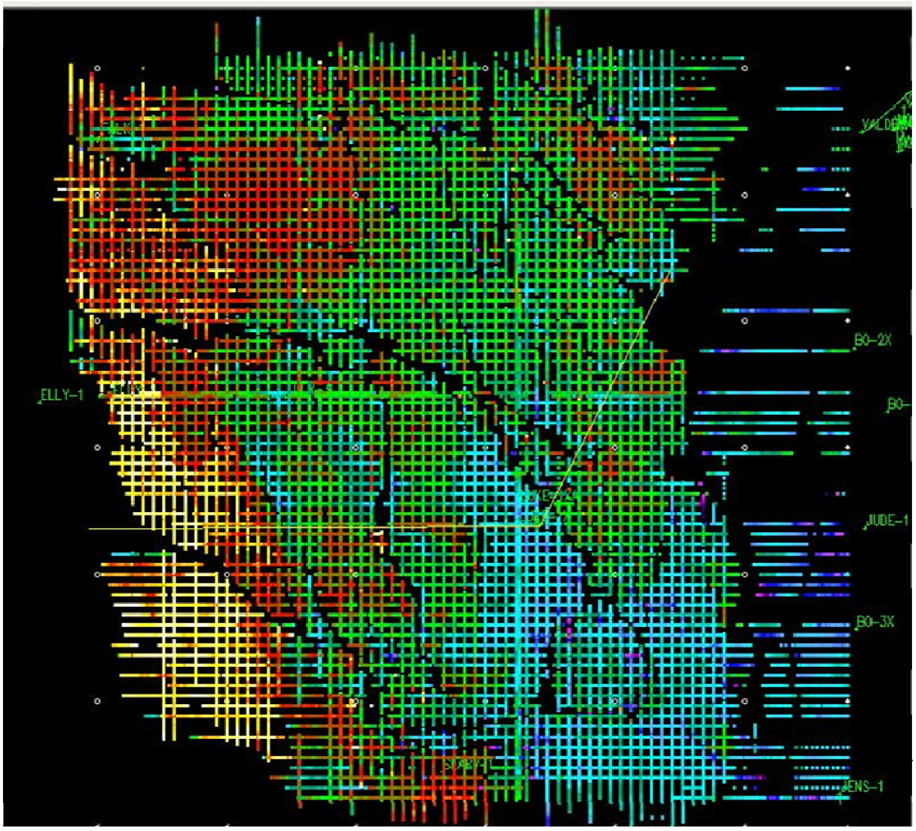
Appendix 1h

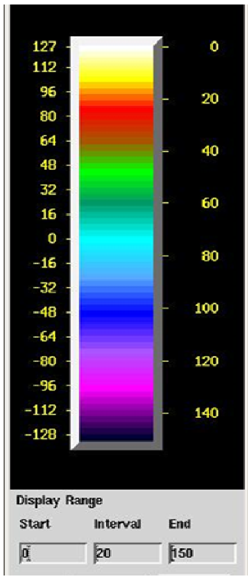
Time structure: Top Bryne Fm (T_Bryne_Time_2016)



Appendix 1i

Time isochore: Bryne Fm

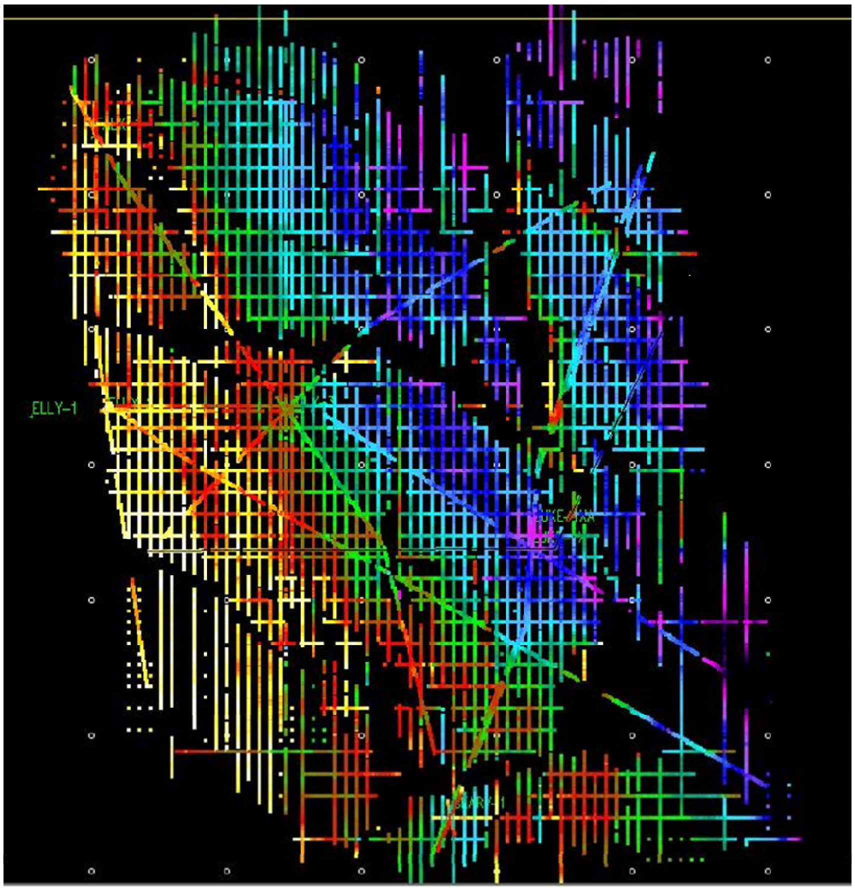


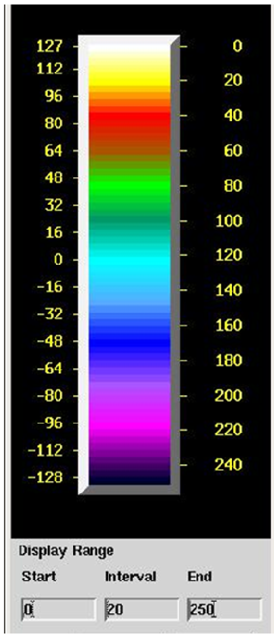


SeisWorks/map view

Appendix 1j

Time isochore: Lower Jurassic

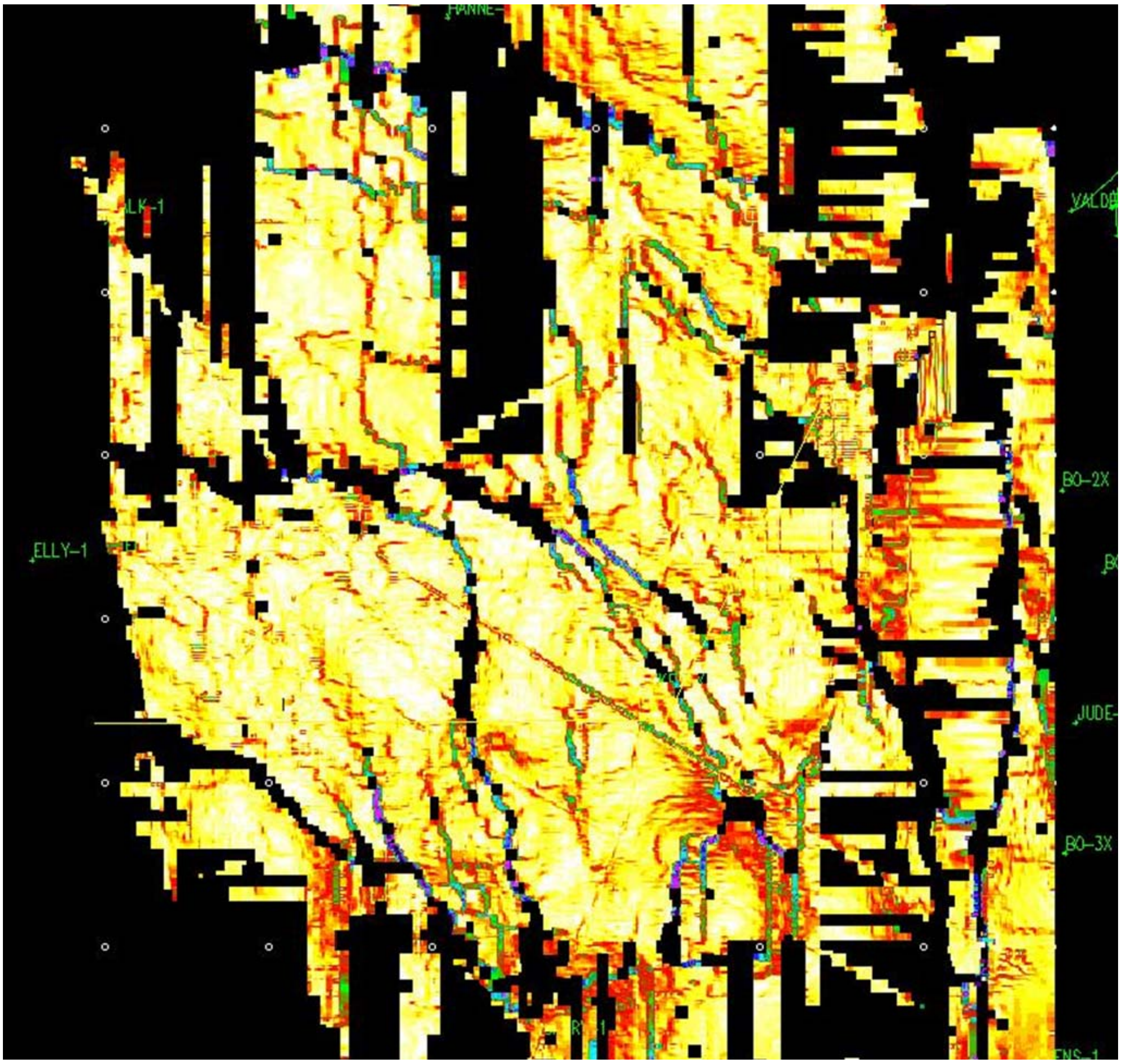




SeisWorks/map view

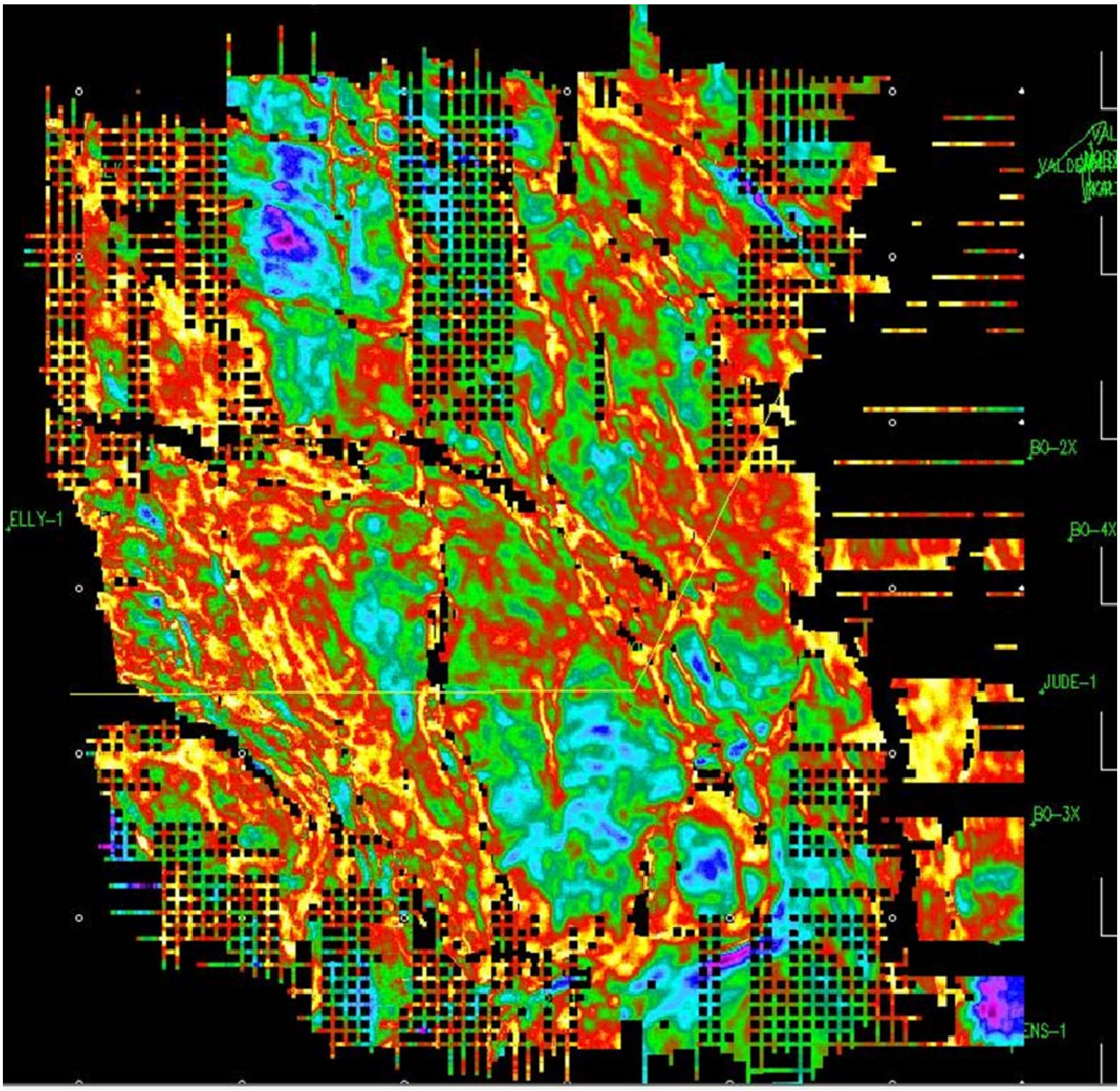
Appendix 1k

Top Bryne Fm edge detection



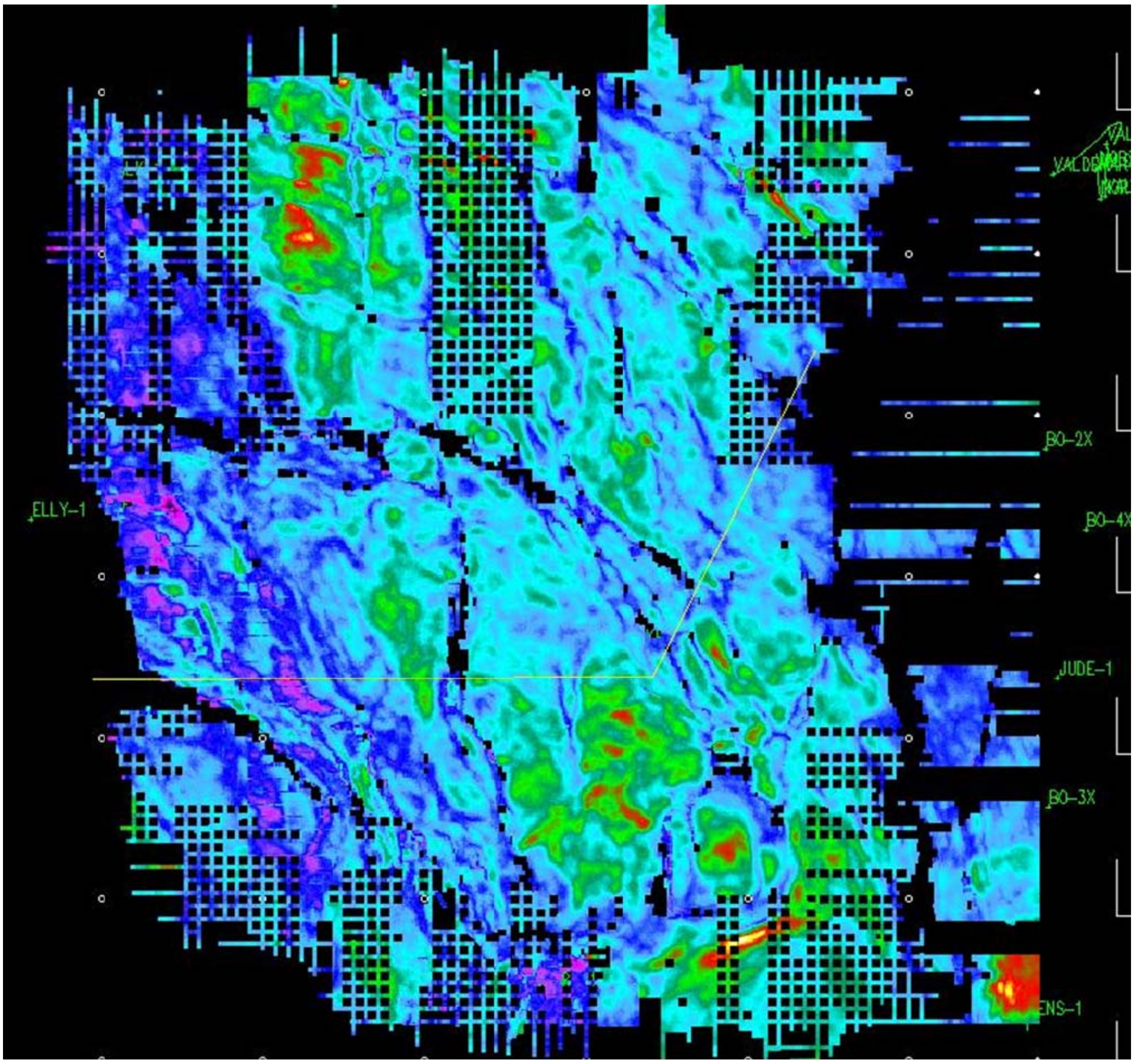
Appendix 1l

Bryne Fm RMS amplitudes



Appendix 1m

Bryne Fm max negative amplitudes



Appendix 2: List of coordinates for arbitrary seismic lines

		x	y	
Profile 1	start (W)	580276	6183147	
	kink 1	581828	6183445	
	kink 2	586472	6183445	
	end (SE)	596417	6177056	
Profile 2	start (NW)	582179	6183896	
	kink 1	583771	6182701	
	end (SE)	594864	6176453	
Profile 3	start (NW)	581828	6189554	
	kink 1	582824	6187762	
	kink 2	587679	6180952	
	end (SSE)	599035	6175496	
Profile 4	start (SW)	582638	6180099	
	Kink 1	587386	6184997	
	end (NE)	591932	6187695	
Profile 5	start (SW)	588588	6175233	
	kink 1	590281	6179466	
	kink 2	590540	6182481	
	end (NNW)	592485	6188078	
Profile 6	start (S)	585884	6174758	trace 1444
	end (N)	585884	6192232	
Profile 7	start (W)	582129	6180841	
	kink 1	590816	6180891	
	end (NE)	593334	6185926	

11 Enclosures

1 Stratigraphic Summary chart, Edna-1

2 Stratigraphic Summary chart, Elly-1

3 Stratigraphic Summary chart, Elly-2

4 Stratigraphic Summary chart, Elly-3

5 Stratigraphic Summary chart, Falk-1

6 Stratigraphic Summary chart, Jens-1

7 Stratigraphic Summary chart, Luke-1X

8 Stratigraphic Summary chart, Skarv-1

9 Log correlation panel 1 based on PetSys; Fig. 5.1 in text

10 Log correlation panel 2 based on PetSys; Fig. 5.2 in text

11 Tables with depths to all surfaces

11 A) Table with depths to all surfaces, interpretations from GEUS´ PetSys study.

11 B) Table with depths to all surfaces with the surfaces following the "layer cake model" highlighted in red.

11 C) Table with depths to all surfaces with the surfaces following the "incised valley model" highlighted in red.

12 Ichron Sedimentological core log, Falk-1

13 Ichron Sedimentological core log, Luke-1X

14 Preliminary GEUS Sedimentological core log, Elly-3;
a: lower part, b: upper part.

15 Layer cake model

Well log panel (Elly-1, Elly-2, Elly-3, Luke-1X, Luke-1XA, Jens-1) with interpreted depositional environments and three local sequences here termed A, B and C; the regional significance of these three sequences is uncertain. The panel is flattened on the base Lola Formation surface marking the top of the interval of interest.

16 Layer cake model

Well log panel (Falk-1, Elly-3, Luke-1X, Luke-1XA, Skarv-1, Edna-1) with interpreted depositional environments and three local sequences here termed A, B and C; the regional significance of these three sequences is uncertain. The panel is flattened on the base Lola Formation surface marking the top of the interval of interest.

17 Incised valley model

Well log panel including the wells Elly-1, Falk-1, Elly-2, Elly-3, Luke-1X, Luke-1XA and Jens-1 illustrating the incised valley model. The panel is flattened on the base Lola Formation surface marking the top of the interval of interest. Schematic outline of the model is shown in inset.

18 Incised valley model

Well log panel including the wells Elly-2, Elly-3, Luke-1X, Luke-1XA, Skarv-1 and Edna-1 illustrating the incised valley model. The panel is flattened on the base Lola Formation surface marking the top of the interval of interest. Schematic outline of the model is shown in inset.

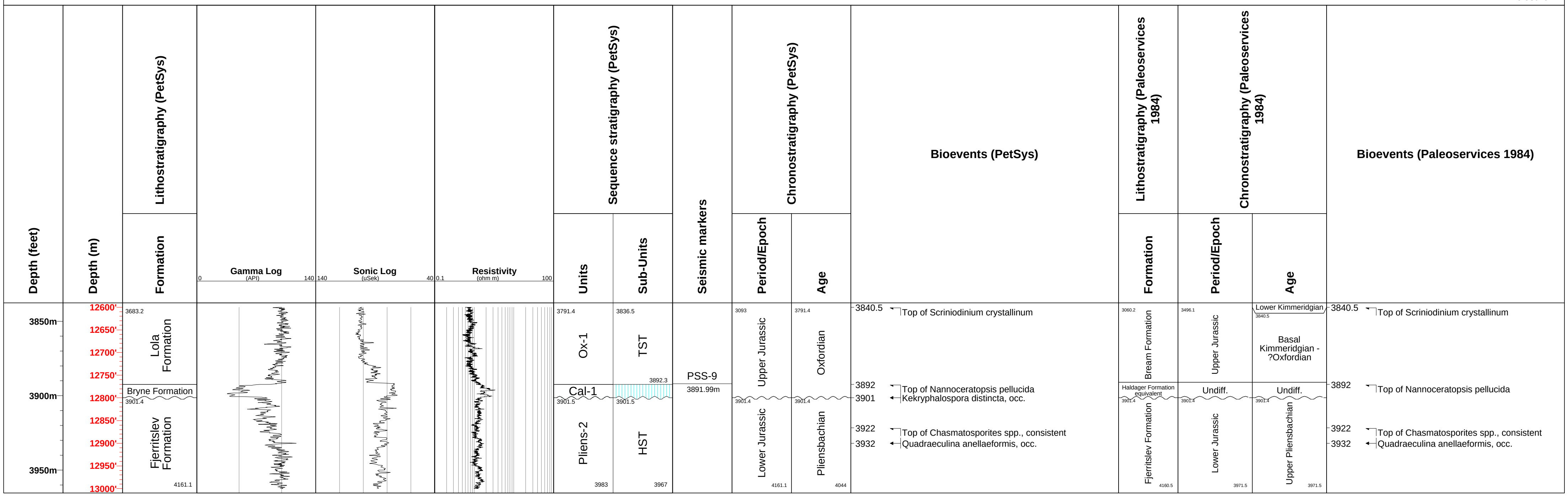
19 Palaeogeographic maps illustrating the incised valley model

Well Name : Edna-1

Interval Various
Scale : 1:2000
Chart date: 13 December 2016

GEUS

Enclosure 1

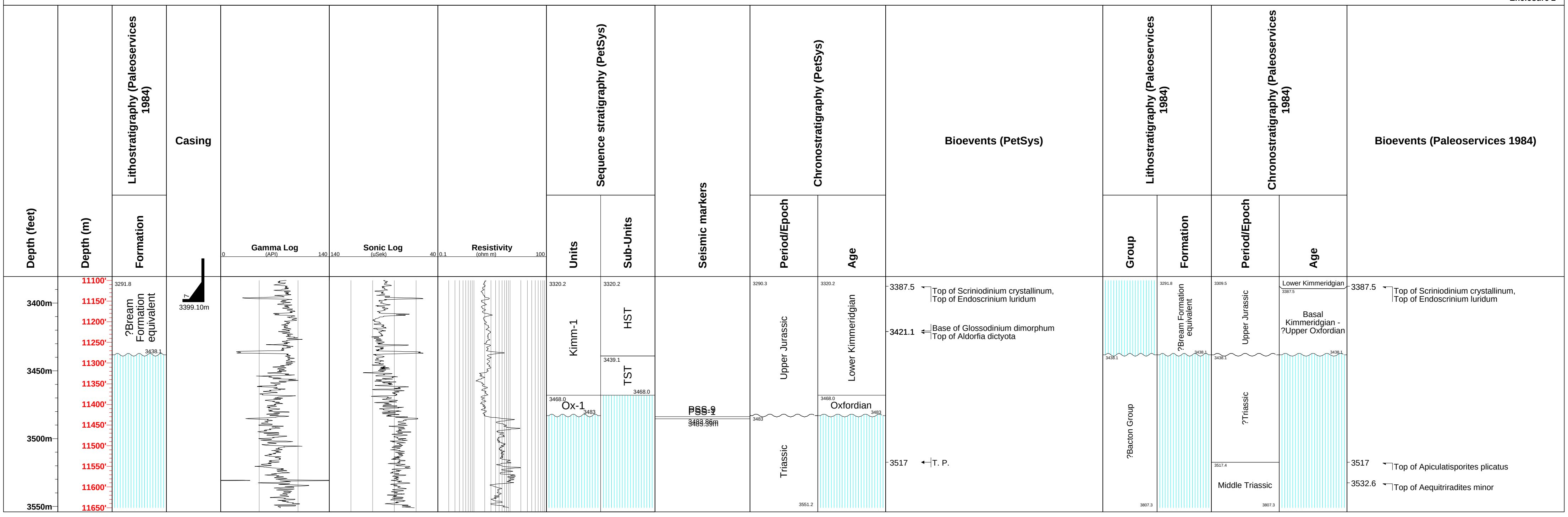


Well Name : Elly-1

Interval Various
Scale : 1:2000
Chart date: 13 December 2016

GEUS

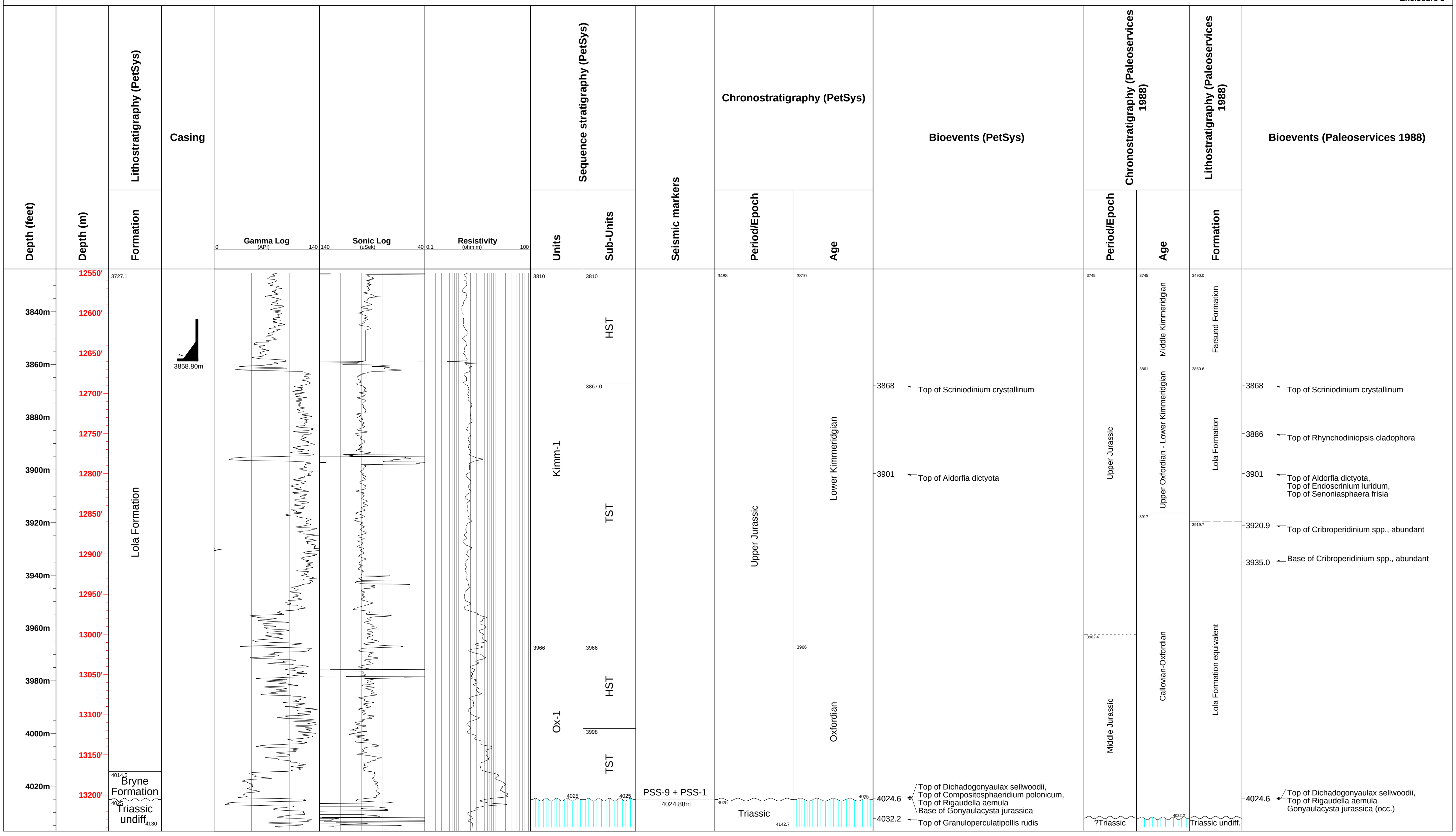
Enclosure 2



Well Name : Elly-2

Interval Various
Scale : 1:1000
Chart date: 13 December 2016

Enclosure 3



Well Name : Elly-3

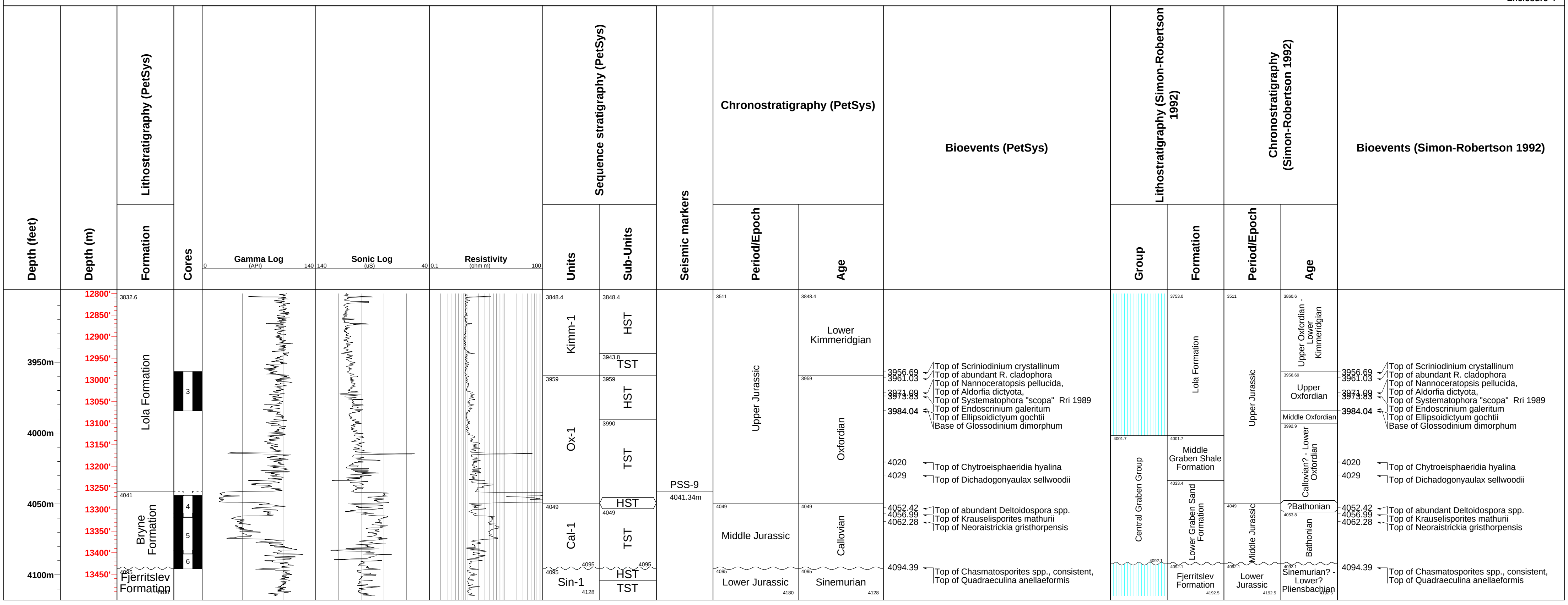
Interval Various

Scale : 1:2000

Chart date: 13 December 2016

GEUS

Enclosure-4

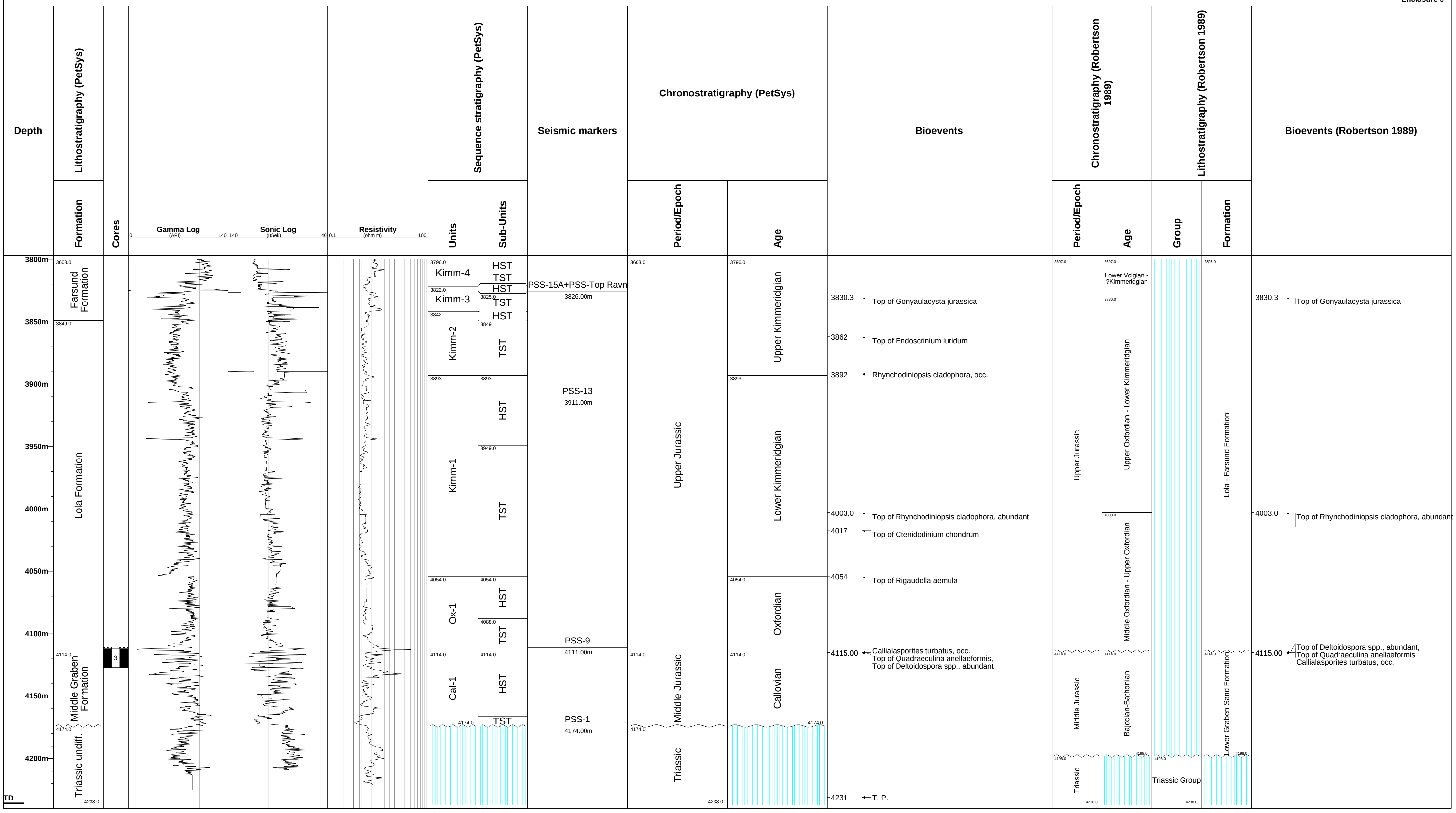


Well Name : Falk-1

Interval : 3800m - 4237m
Scale : 1:2000
Chart date: 13 December 2016

GEUS

Enclosure 5

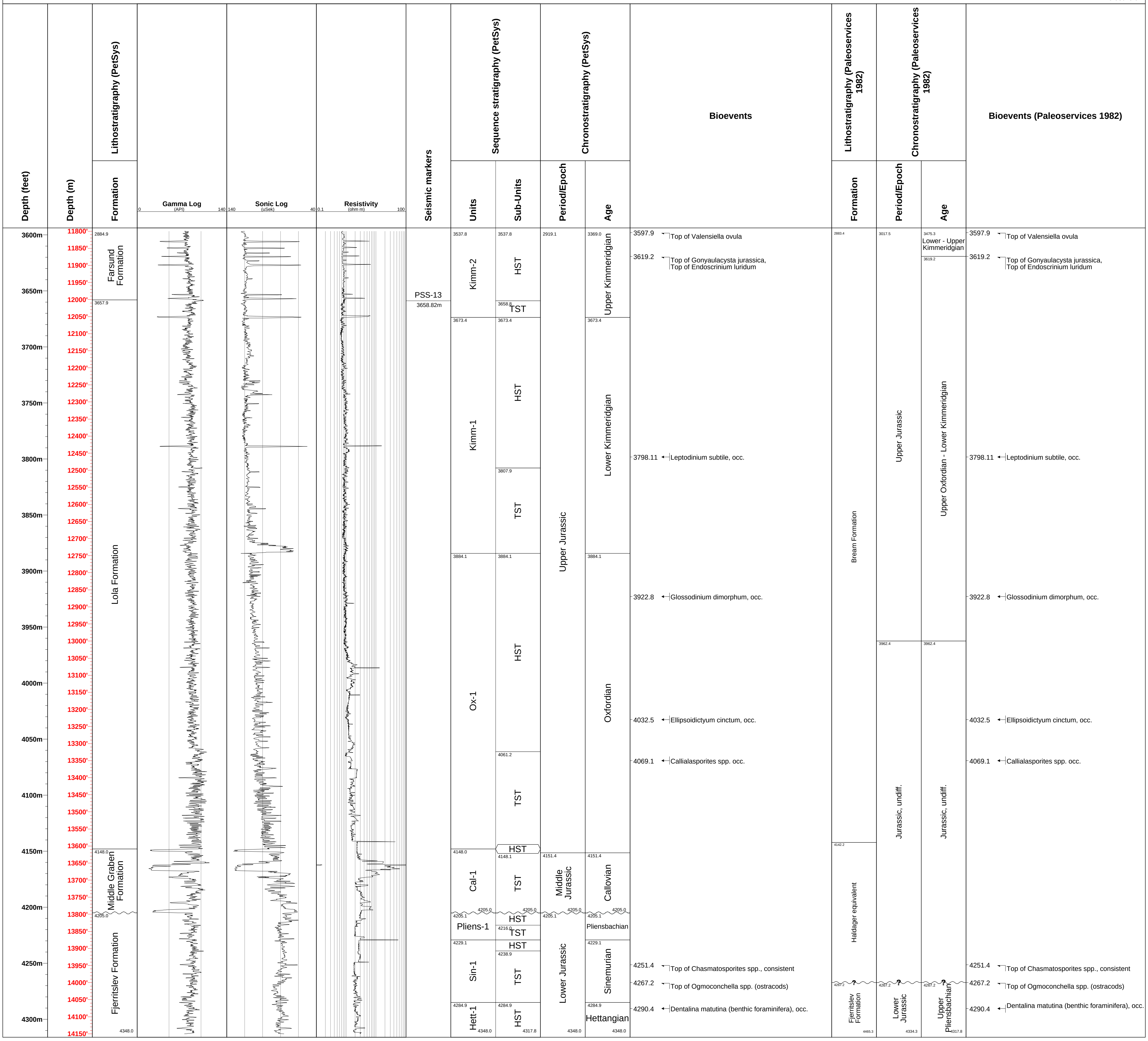


Well Name : Jens-1

Interval Various
Scale : 1:2000
Chart date: 13 December 2016

GEUS

Enclosure 6



Well Name : Luke-1X

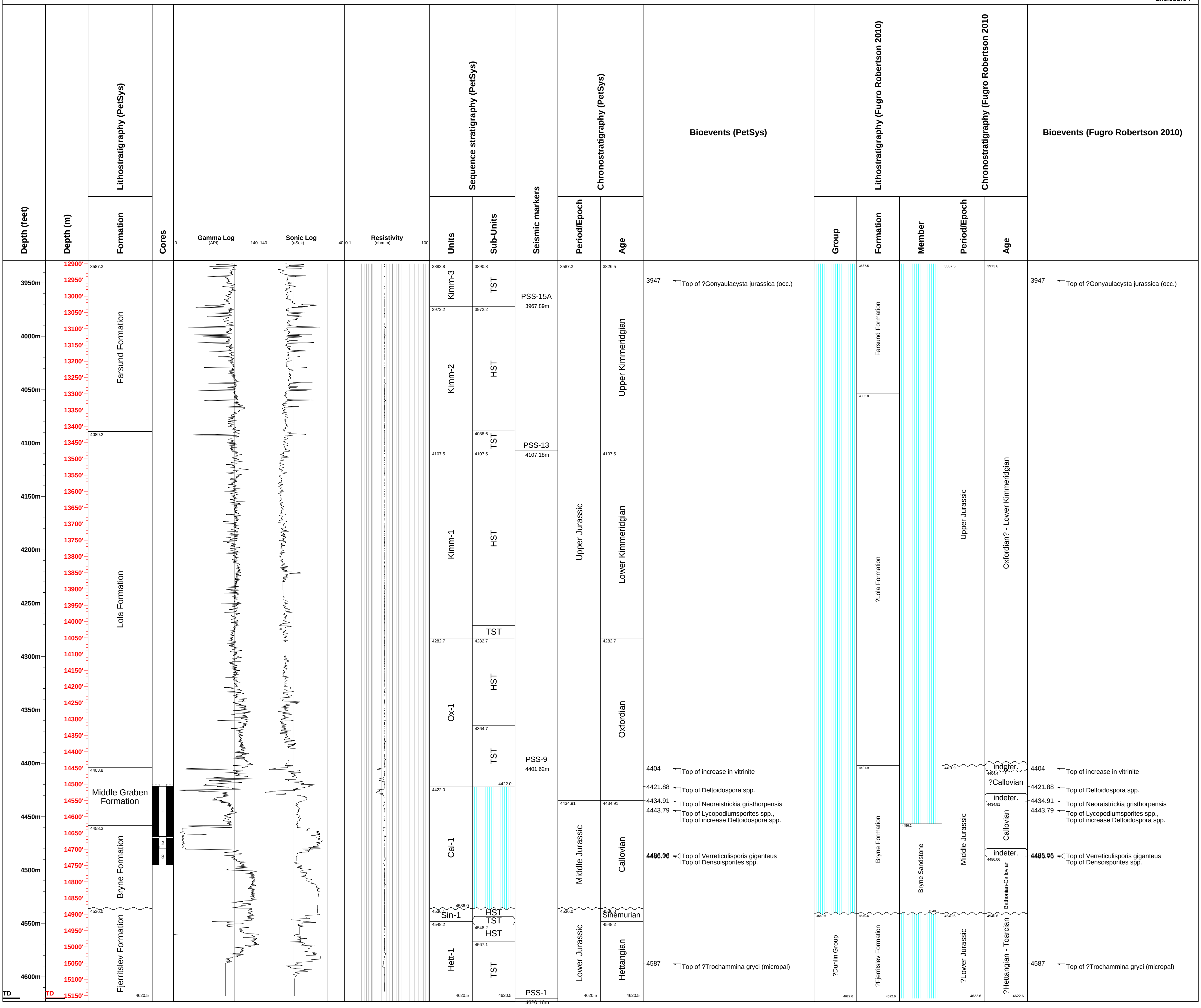
Interval Various

Scale : 1:2000

Chart date: 13 December 2016

GEUS

Enclosure 7



Well Name : Skarv-1

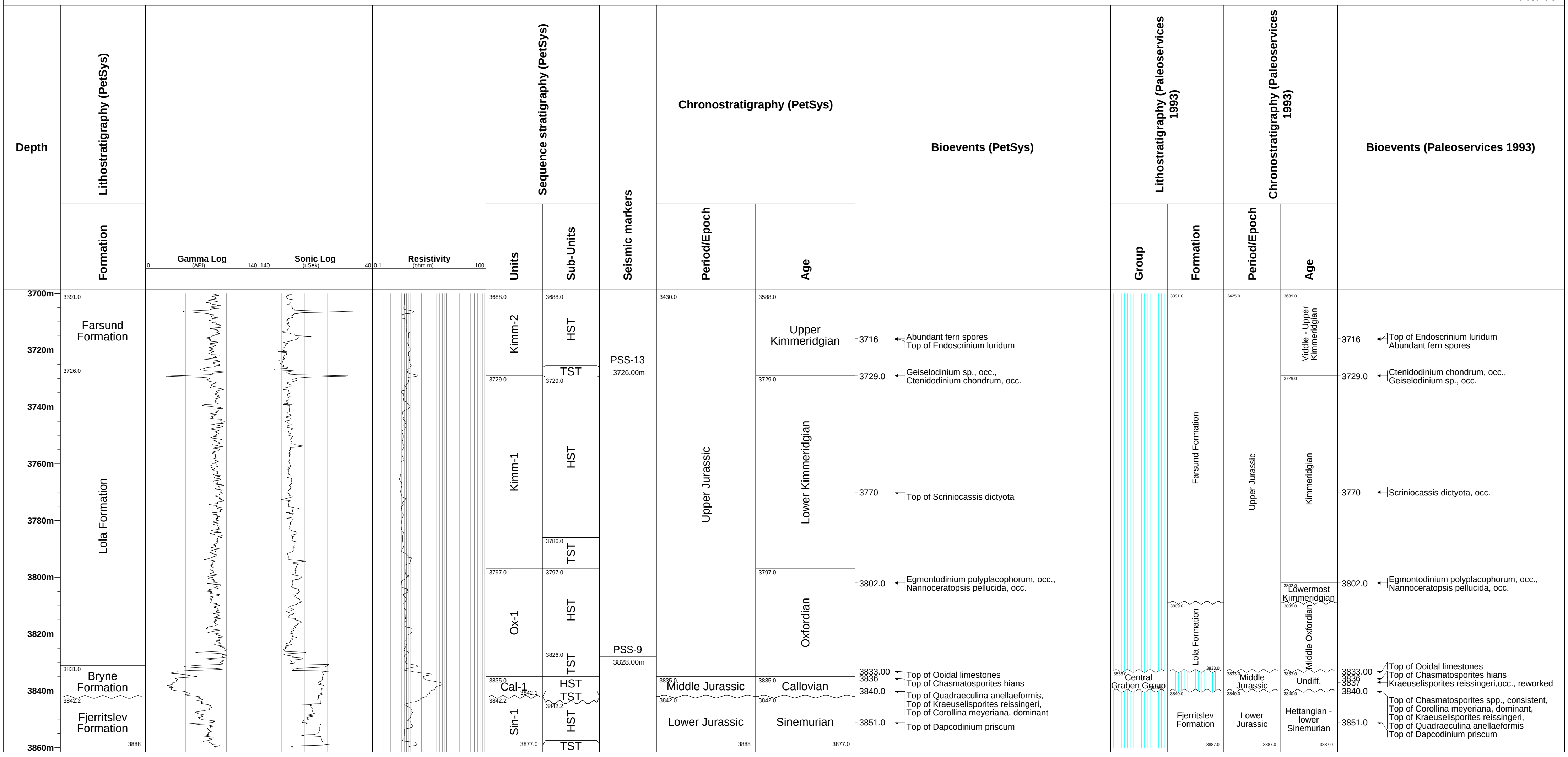
Interval : 3700m - 3860m

Scale : 1:1000

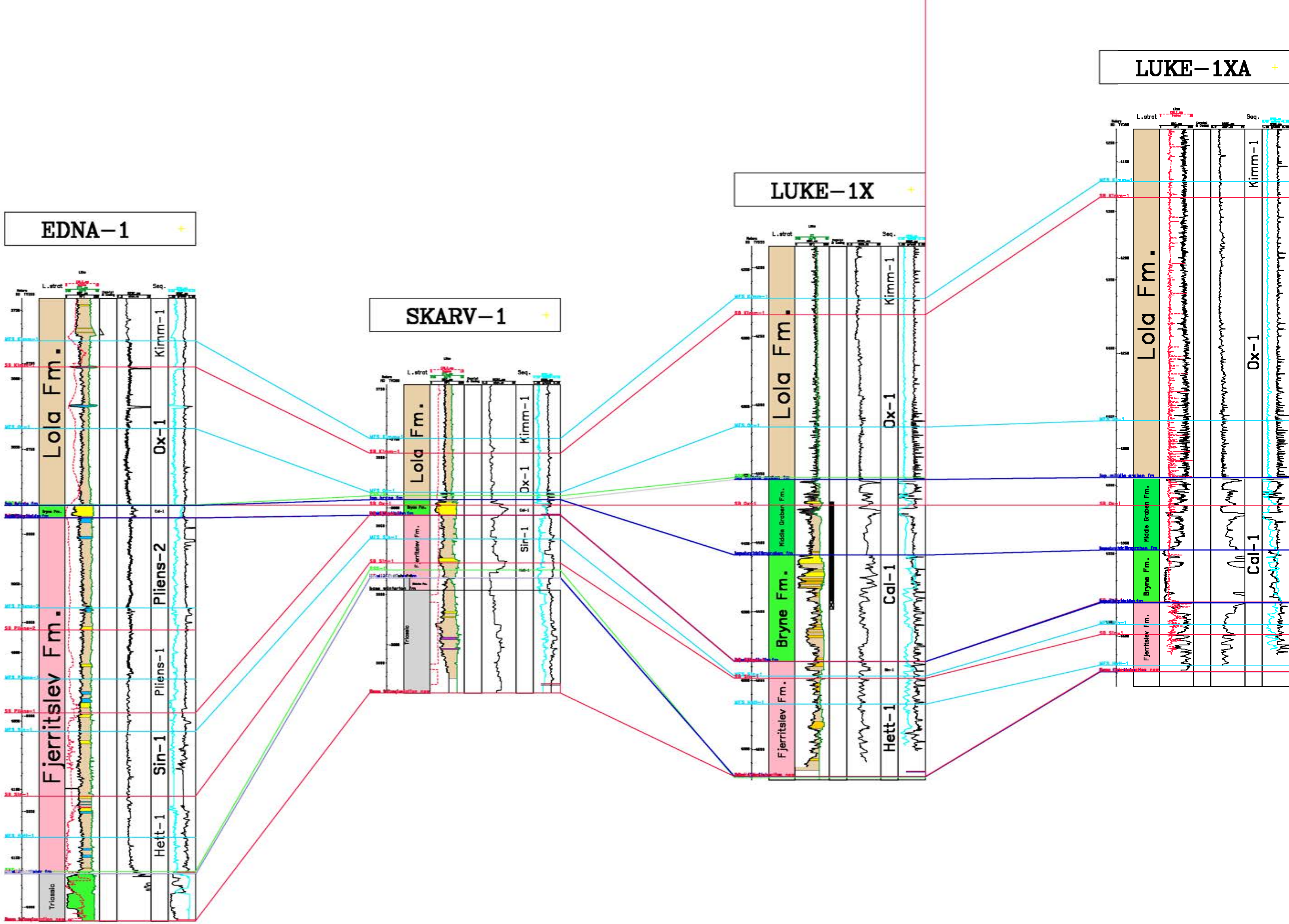
Chart date: 13 December 2016

GEUS

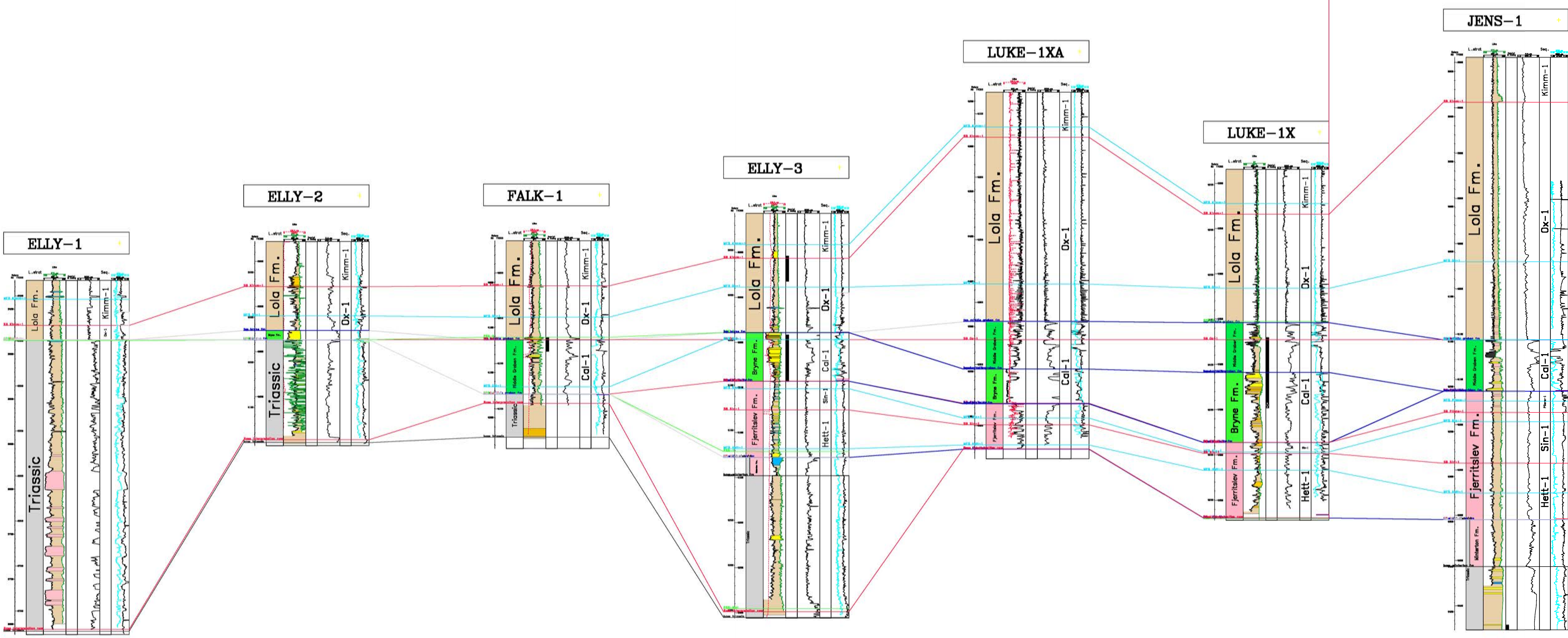
Enclosure 8



Enclosure 9


EDNA-1
SKARV-1
LUKE-1X
LUKE-1XA
L.strat
Seq.
Lola Fm.
Fjerritslev Fm.
Bryne Fm.
Middle Graben Fm.
Triassic
Kimm-1
Ox-1
Cal-1
Pliens-2
Pliens-1
Sin-1
Hett-1

Enclosure 10



Enclosure 11a: PetSys-model

Well name	Pick name	MD (m)	MD (ft)
EDNA-1	base lola fm	3892,5	12770,3
EDNA-1	top bryne fm	3892,5	12770,5
EDNA-1	base bryne fm	3901,5	12800,2
EDNA-1	top fjerritslev fm	3901,5	12800,1
EDNA-1	SB Ox-1	3892,4	12770,3
EDNA-1	SB Cal-1	3901,5	12800,0
ELLY-1	base lola fm	3484,0	11430,3
ELLY-1	top triassic	3484,0	11430,3
ELLY-1	SB Ox-1	3484,0	11430,3
ELLY-2	base lola fm	4014,5	13170,6
ELLY-2	top bryne fm	4014,5	13170,6
ELLY-2	base bryne fm	4024,8	13204,6
ELLY-2	top triassic	4024,8	13204,6
ELLY-2	SB Ox-1	4024,8	13204,6
ELLY-3	base lola fm	4041,6	13259,6
ELLY-3	top bryne fm	4041,6	13259,6
ELLY-3	base bryne fm	4095,4	13436,1
ELLY-3	top fjerritslev fm	4095,4	13436,2
ELLY-3	SB Ox-1	4049,4	13285,4
ELLY-3	SB Cal-1	4095,4	13436,1
FALK-1	base lola fm	4113,5	13495,6
FALK-1	top middle graben fm	4113,5	13495,6
FALK-1	base middle graben fm	4173,9	13693,7
FALK-1	top triassic	4173,9	13693,7
FALK-1	SB Ox-1	4113,5	13495,6
FALK-1	SB Cal-1	4173,9	13693,7
JENS-1	base lola fm	4147,8	13608,2
JENS-1	top middle graben fm	4147,8	13608,2
JENS-1	base middle graben fm	4205,0	13795,8
JENS-1	top fjerritslev fm	4205,0	13795,8
JENS-1	SB Ox-1	4147,8	13608,2
JENS-1	SB Cal-1	4205,0	13795,8
LUKE-1X	base lola fm	4403,0	14445,4
LUKE-1X	top middle graben fm	4403,0	14445,4
LUKE-1X	base middle graben fm	4458,2	14626,6
LUKE-1X	top bryne fm	4458,2	14626,6
LUKE-1X	base bryne fm	4536,1	14882,0
LUKE-1X	top fjerritslev fm	4536,1	14882,0
LUKE-1X	SB Ox-1	4422,0	14507,8
LUKE-1X	SB Cal-1	4536,1	14882,0

Enclosure 11a: PetSys-model

Well name	Pick name	MD (m)	MD (ft)
LUKE-1XA	base lola fm	4494,6	14746,0
LUKE-1XA	top middle graben fm	4494,6	14745,9
LUKE-1XA	base middle graben fm	4547,2	14918,6
LUKE-1XA	top bryne fm	4547,2	14918,6
LUKE-1XA	base bryne fm	4585,7	15044,9
LUKE-1XA	top fjerritslev fm	4585,7	15044,8
LUKE-1XA	SB Ox-1	4514,7	14811,8
LUKE-1XA	SB Cal-1	4585,2	15043,2
SKARV-1	base lola fm	3830,6	12567,4
SKARV-1	top bryne fm	3830,6	12567,4
SKARV-1	base bryne fm	3842,0	12604,9
SKARV-1	top fjerritslev fm	3842,0	12604,9
SKARV-1	SB Ox-1	3834,9	12581,5
SKARV-1	SB Cal-1	3842,0	12604,9

Enclosure 11b: Layercake model

Note: Picks marked by red have been changed in relation to PetSys

Well name	Pick name	MD (m)	MD (ft)
EDNA-1	top bryne fm	3892,4	12770
EDNA-1	base lola fm	3892,4	12770
EDNA-1	base bryne fm	3901,5	12800
EDNA-1	top fjerritslev fm	3901,5	12800
EDNA-1	SB Ox-1	3901.5	12800
ELLY-1	base lola fm	3484,0	11430
ELLY-1	top triassic	3484,0	11430
ELLY-1	SB Ox-1	3484,0	11430
ELLY-2	base lola fm	4003,7	13135
ELLY-2	top middle graben fm	4003,7	13135
ELLY-2	base middle graben fm	4014,5	13171
ELLY-2	top bryne fm	4014,5	13171
ELLY-2	base bryne fm	4027,6	13214
ELLY-2	top triassic	4027,6	13214
ELLY-2	SB Ox-1	4024,8	13205
ELLY-3	base lola fm	4012,3	13164
ELLY-3	top middle graben fm	4012,3	13164
ELLY-3	base middle graben fm	4041,6	13260
ELLY-3	top bryne fm	4041,6	13260
ELLY-3	base bryne fm	4095,4	13436
ELLY-3	top fjerritslev fm	4095,4	13436
ELLY-3	SB Ox-1	4049,4	13285
ELLY-3	SB Cal-1	4074,2	13367
ELLY-3	SB Bat-1	4095.3	13436
FALK-1	base lola fm	4113,5	13496
FALK-1	top middle graben fm	4113,5	13496
FALK-1	base middle graben fm	4173,9	13694
FALK-1	top triassic	4173,9	13694
FALK-1	SB Ox-1	4173,9	13694
FALK-1	SB Cal-1	4173,9	13694
FALK-1	SB Bat-1	4173,9	13694
JENS-1	base lola fm	4147,8	13608
JENS-1	top middle graben fm	4147,8	13608
JENS-1	base middle graben fm	4194,3	13761
JENS-1	top bryne fm	4194,3	13761
JENS-1	base bryne fm	4205,0	13796
JENS-1	top fjerritslev fm	4205,0	13796
JENS-1	SB Ox-1	4196,1	13767
JENS-1	SB Cal-1	4205,0	13796

Enclosure 11b: Layercake model

Note: Picks marked by red have been changed in relation to PetSys

Well name	Pick name	MD (m)	MD (ft)
LUKE-1X	base lola fm	4403,0	14445
LUKE-1X	top middle graben fm	4403,0	14445
LUKE-1X	base middle graben fm	4458,2	14627
LUKE-1X	top bryne fm	4458,2	14627
LUKE-1X	base bryne fm	4536,1	14882
LUKE-1X	top fjerritslev fm	4536,1	14882
LUKE-1X	SB Ox-1	4467,8	14658
LUKE-1X	SB Cal-1	4482,8	14707
LUKE-1X	SB Bat-1	4536,1	14882
LUKE-1XA	base lola fm	4494,6	14746
LUKE-1XA	top middle graben fm	4494,6	14746
LUKE-1XA	base middle graben fm	4547,2	14919
LUKE-1XA	top bryne fm	4547,2	14919
LUKE-1XA	base bryne fm	4585,7	15045
LUKE-1XA	top fjerritslev fm	4585,7	15045
LUKE-1XA	SB Ox-1	4514,7	14812
LUKE-1XA	SB Cal-1	4585,2	15043
SKARV-1	base lola fm	3830,6	12567
SKARV-1	top bryne fm	3830,6	12567
SKARV-1	base bryne fm	3842,0	12605
SKARV-1	top fjerritslev fm	3842,0	12605
SKARV-1	SB Ox-1	3842,0	12605

Enclosure 11c: Incised valley model

Note: Picks marked by red have been changed in relation to PetSys

Well name	Surface name	MD (m)	MD (ft)
EDNA-1	base lola fm	3892,5	12770
EDNA-1	top bryne fm	3892,5	12771
EDNA-1	base bryne fm	3901,5	12800
EDNA-1	top fjerritslev fm	3901,5	12800
EDNA-1	SB Cal-1	3901,5	12800
ELLY-1	base lola fm	3484,0	11430
ELLY-1	top triassic	3484,0	11430
ELLY-1	SB Ox-1	3484,0	11430
ELLY-2	base lola fm	4003,7	13135
ELLY-2	top middle graben fm	4003,7	13135
ELLY-2	base middle graben fm	4014,5	13171
ELLY-2	top bryne fm	4014,5	13171
ELLY-2	base bryne fm	4027,6	13214
ELLY-2	top triassic	4027,6	13214
ELLY-2	SB Cal-1	4024,7	13204
ELLY-2	SB Bat-1	4027,6	13214
ELLY-3	base lola fm	4012,3	13163
ELLY-3	top middle graben fm	4012,3	13163
ELLY-3	base middle graben fm	4041,6	13260
ELLY-3	top bryne fm	4041,6	13260
ELLY-3	base bryne fm	4095,4	13436
ELLY-3	top fjerritslev fm	4095,4	13436
ELLY-3	SB Cal-1	4048,6	13283
ELLY-3	SB Bat-1	4095,4	13436
FALK-1	base lola fm	4110,7	13486
FALK-1	top middle graben fm	4110,7	13486
FALK-1	base middle graben fm	4173,9	13694
FALK-1	top triassic	4173,9	13694
FALK-1	SB Cal-1	4113,5	13496
FALK-1	SB Bat-1	4173,9	13694
JENS-1	base lola fm	4147,8	13608
JENS-1	top middle graben fm	4147,8	13608
JENS-1	base middle graben fm	4194,3	13760
JENS-1	top bryne fm	4194,3	13760
JENS-1	base bryne fm	4204,8	13795
JENS-1	top fjerritslev fm	4205,0	13796
JENS-1	SB Cal-1	4205,0	13796
LUKE-1X	base lola fm	4403,0	14445
LUKE-1X	top middle graben fm	4403,0	14445
LUKE-1X	base middle graben fm	4458,2	14627

Enclosure 11c: Incised valley model

Note: Picks marked by red have been changed in relation to PetSys

Well name	Surface name	MD (m)	MD (ft)
LUKE-1X	top bryne fm	4458,2	14627
LUKE-1X	base bryne fm	4536,1	14882
LUKE-1X	top fjerritslev fm	4536,1	14882
LUKE-1X	SB Cal-1	4482,8	14707
LUKE-1X	SB Bat-1	4536,1	14882
LUKE-1XA	base lola fm	4494,6	14746
LUKE-1XA	top middle graben fm	4494,6	14746
LUKE-1XA	base middle graben fm	4547,2	14919
LUKE-1XA	top bryne fm	4547,2	14919
LUKE-1XA	base bryne fm	4645,3	15240
LUKE-1XA	top fjerritslev fm	4645,3	15240
LUKE-1XA	SB Cal-1	4585,2	15043
LUKE-1XA	SB Bat-1	4645,3	15240
SKARV-1	base lola fm	3830,6	12567
SKARV-1	top bryne fm	3830,6	12567
SKARV-1	base bryne fm	3842,0	12605
SKARV-1	top fjerritslev fm	3842,0	12605
SKARV-1	SB Cal-1	3842,0	12605

Enclosure 12

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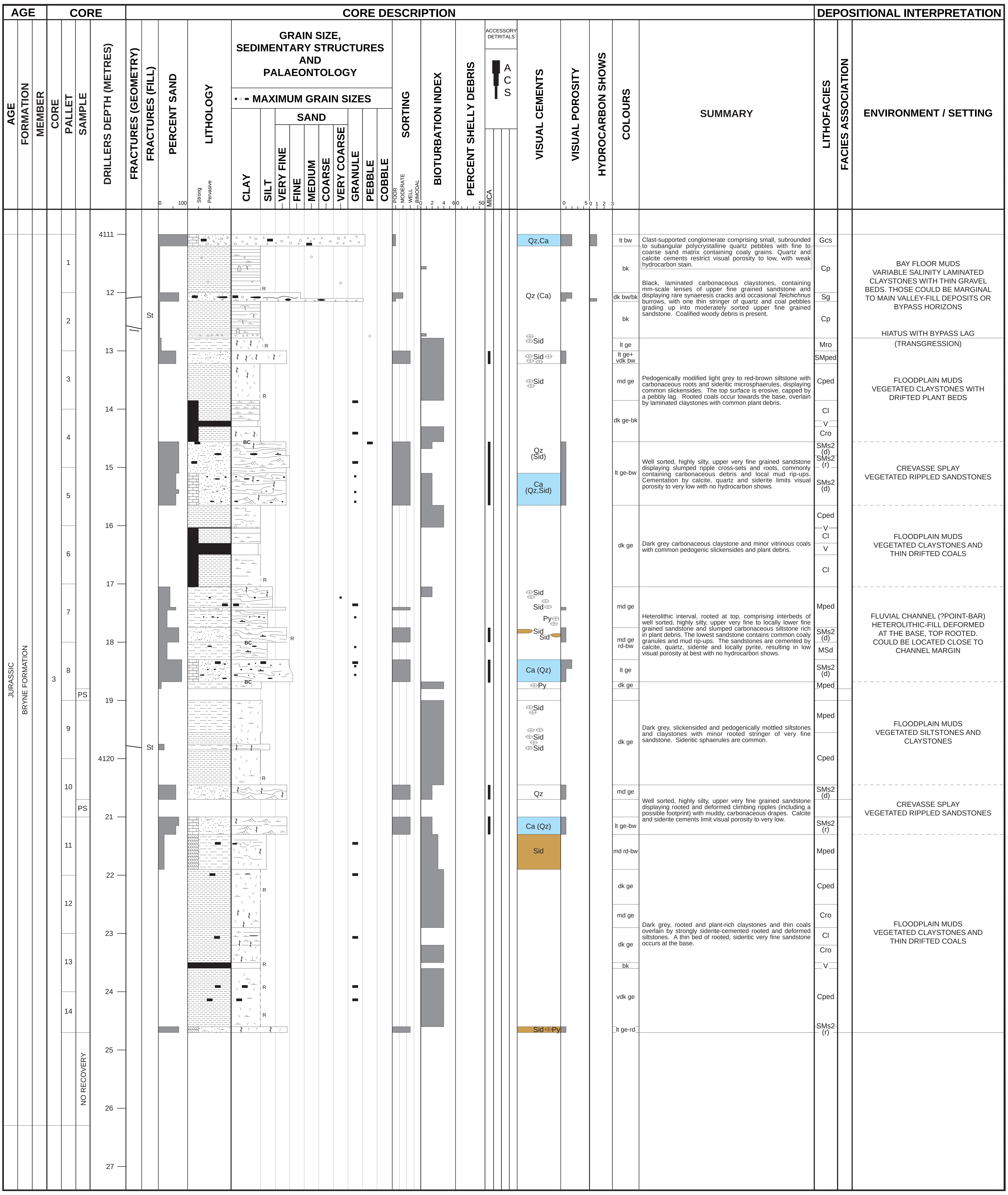
FALK-1

WELL : FALK-1
LOG TYPE : CORE DESCRIPTION CHART
SCALE : 1:50
DATE : March 2010
LOGGED BY : A. TAYLOR

MAERSK



LEGENDS & ICONS

LITHOLOGY
Conglomerate; Sandstone; Silty sandstone; Sandy siltstone; Siltstone; Claystone; Limestone; Dolostone; Anhydrite; Coal; Volcaniclastics

QUALIFIERS
Calcitic; Dolomitic; Anhydritic; Sideritic; Quartz; Pyritic; g Glauconitic; m Micaceous

BEDDING CONTACTS
S Sharp; E Erosive; G Gradational; F Fractured; BC Broken Core

LITHOCLASTS
Pebbles; Coarse sand/granules; Sandstone; Mudstone; Ooliths; Grapestone; Oolitic lithoclast; Oncoid; Peloid; Coal fragments

SEDIMENTARY STRUCTURES
Horizontal stratification; Low-angle cross-strat.; Tabular cross-strat.; Trough cross-strat.; Herring-bone cross-strat.; Hummocky cross-strat.; Slumped beds; Pinstripe bedding; Lenticular bedding; Wavy bedding; Flaser bedding; Ripple cross-lamination; Current ripples; Wave ripples; Bidirectional ripples; Synaeresis cracks; Consolidation laminae; Dish structures; Load structures; Dewatering; Flute casts; Geopetal

TRACE FOSSILS
Arenicolites; *Arenicolites carbonarius*; *Asterosoma*; Bivalve burrows; Bivalve burrow (laminated fill); *Chondrites*; *Conichnus*; *Cruziana*; *Cylindrichnus*; *Diplocraterion coloradoensis*; *Diplocraterion parallelum*; Escape (general); Excavation trace (deep); Excavation trace (shallow); Faecal pellets; Footprints; *Gastrochaenolites*; General burrow mottling; *Gordia*; *Gyrochorte*; *Gyrolithites*; *Lockeia*; *Helminthoidea*; *Helminthopsis*; *Isopodichnus*; J-shaped burrows; *Lingulichnus*; *Macaronichnus*; Meniscate burrows; *Nereites*; *Ophiomorpha irregulaire*; *Ophiomorpha nodosa*; *Palaeophycus*; *Palaeophycus heberti*; *Palaeodictyon*; Pedogenic; *Phoebichnus*; *Phycodes*; *Phycosiphon*; *Planolites* isp.; *Planolites montanus*; *Polykladichnus*; *Psilonichnus*; Resting/dwelling (general); *Rhizocorallium irregulare*; *Rhizocorallium jenense*; Roots; *Rosselia*; *Sabularia*; *Scolicia*; *Schaubcylindrichnus*; *Siphonichnus*; *Skolithos*; *Spirophyton*; *Spongeliomorpha*; Spreiten Burrow; *Taenidium*; *Teichichnus* isp.; *Teichichnus rectus*; *Teichichnus zigzag*; *Teichichnus zigzag* (diffuse); *Teredolites*; *Thalassinoides*; *Tigillites*; *Trichichnus*; *Trypanites*; *Zoophycos*

BODY FOSSILS
Ammonites; Articulated valves; Belemnites; Bivalves; Bivalve shells; Brachiopods; Bryozoans; Calcareous algae; Colonial coral; Crinoids; Echinoids; Echinoid spine; Fish remains; Forams (large); Forams (small); Gastropods; Graptolites; Orthocone; Ostracods; Plant debris (fine); Plant debris (coarse); Serpulids; Sponge spicules; Vertebrate remains; Worm tubes

BIVALVE LIFE MODE
Autochthonous / Allochthonous examples
Free-swimming; Epifaunal; Semi infaunal; Infaunal; Boring (endolithic)

SEQUENCE STRATIGRAPHY
Stratal Surfaces
Fs Marine flooding surface; MFS Maximum flooding surface; TS Transgressive surface; RS Regressive surface; SB Sequence boundary
Systems Tracts
LST Lowstand (brown); TST Transgressive (yellow); HST Highstand (blue); FRST Forced Regressive (green)
Hiatal Colonisation
Omission (red); Overprint (orange); Salinity change (blue); Subaerial exposure (green); Fish Scale

VISUAL POROSITY
0 Negligible; 1 Very low; 2 Low; 3 Moderate; 4 High; 5 Very high

HYDROCARBON SHOWS
0 None; 1 Weak; 2 Moderate; 3 Strong

HYDROCARBONS
Mobile oil; Tarry residual oil

DIAGENESIS
Nodules; Micronodules; Open fracture; Filled fracture; Stylolite; Ap Apatite; Ba Barite; Bs Brecciated sed't; Ca Calcite; Ch Chert; Cl Clay; Dm Dolomite; Ka Kaolinite; Ph Phosphate; Py Pyrite; Qz Quartz; Ro Residual oil; Sd Sand; Si Silica; Sid Siderite; Sp Sphalerite; St Silt

COLOUR
Lt Light; Md Mid; Dk Dark; Vdk Very dark; Bf Buff; Bk Black; Bw Brown; Ge Grey; Gn Green; Or Orange; Pp Purple; Rd Red; Wh White; Ye Yellow

Well defined Cements
e.g. Ca (Qz) / Ca, Qz — Calcite cement with subordinate quartz cements / Subequal calcite & quartz cements
'Possible' Cements
e.g. (?Qz) (?Dm) — No clear confirmation but suspected

strong; pervasive

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MAERSK

LUKE-1X

WELL : LUKE-1X
LOG TYPE : CORE DESCRIPTION CHART
SCALE : 1:50
DATE : January 2010
LOGGED BY : A. TAYLOR

LEGENDS & ICONS

LITHOLOGY
- Conglomerate
- Sandstone
- Silty sandstone
- Sandy siltstone
- Siltstone
- Claystone
- Limestone
- Dolostone
- Anhydrite
- Coal
- Volcaniclastics

QUALIFIERS
- Calcitic
- Dolomitic
- Anhydritic
- Sideritic
- g Glauconitic
- m Micaceous

BEDDING CONTACTS
- S Sharp
- E Erosive
- G Gradational
- F Fractured
- BC Broken Core

LITHOCLASTS
- Pebbles
- Coarse sand/granules
- Sandstone
- Mudstone
- Ooliths
- Grapestone
- Oolitic lithoclast
- Oncoid
- Peloid
- Coal fragments

SEDIMENTARY STRUCTURES
- Horizontal stratification
- Low-angle cross-strat.
- Tabular cross-strat.
- Trough cross-strat.
- Herring-bone cross-strat.
- Hummocky cross-strat.
- Slumped beds
- Pinstripe bedding
- Lenticular bedding
- Wavy bedding
- Flaser bedding
- Ripple cross-lamination
- Current ripples
- Wave ripples
- Bidirectional ripples
- Synaeresis cracks
- Consolidation laminae
- Dish structures
- Load structures
- Dewatering
- Flute casts
- Geopetal

TRACE FOSSILS
- *Arenicolites*
- *Arenicolites carbonarius*
- *Asterosoma*
- Bivalve burrows
- Bivalve burrow (laminated fill)
- *Chondrites*
- *Conichnus*
- *Cruziana*
- *Cylindrichnus*
- *Diplocraterion coloradoensis*
- *Diplocraterion parallelum*
- Escape (general)
- Excavation trace (deep)
- Excavation trace (shallow)
- Faecal pellets
- Footprints
- *Gastrochaenolites*
- General burrow mottling
- *Gordia*
- *Gyrochorte*
- *Gyrolithites*
- *Lockeia*
- *Helminthoidea*
- *Helminthopsis*
- *Isopodichnus*
- J-shaped burrows
- *Lingulichnus*
- *Macaronichnus*
- Meniscate burrows
- *Nereites*
- *Ophiomorpha irregulaire*
- *Ophiomorpha nodosa*
- *Palaeophycus*
- *Palaeophycus heberti*
- *Palaeodictyon*
- *Phoebichnus*
- *Phycodes*
- *Phycosiphon*
- *Planolites isp.*
- *Planolites montanus*
- *Polykladichnus*
- *Psilonichnus*
- Resting/dwelling (general)
- *Rhizocorallium irregulare*
- *Rhizocorallium jenense*
- Roots
- *Rosselia*
- *Sabularia*
- *Scolicia*
- *Schaubcylindrichnus*
- *Siphonichnus*
- *Skolithos*
- *Spiroraphe*
- *Spongeliomorpha*
- Spreiten Burrow
- *Taenidium*
- *Teichichnus isp.*
- *Teichichnus rectus*
- *Teichichnus zigzag*
- *Teichichnus zigzag* (diffuse)
- *Teredolites*
- *Thalassinoides*
- *Tigillites*
- *Trichichnus*
- *Trypanites*
- *Zoophycos*

BODY FOSSILS
- Ammonites
- Articulated valves
- Belemnites
- Bivalves
- Bivalve shells
- Brachiopods
- Bryozoans
- Calcareous algae
- Colonial coral
- Crinoids
- Echinoids
- Echinoid spine
- Fish remains
- Forams (large)
- Forams (small)
- Gastropods
- Graptolites
- Orthocone
- Ostracods
- Plant debris (fine)
- Plant debris (coarse)
- Serpulids
- Sponge spicules
- Vertebrate remains
- Worm tubes

BIVALVE LIFE MODE
Autochthonous / Allochthonous examples
- Free-swimming
- Epifaunal
- Semi infaunal
- Infaunal
- Boring (endolithic)

SEQUENCE STRATIGRAPHY

Stratal Surfaces
- Fs Marine flooding surface
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Systems Tracts
- LST Lowstand (brown)
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Hiatal Colonisation
- Omission (red)
- Overprint (orange)
- Salinity change (blue)
- Subaerial exposure (green)
- Fish Scale

VISUAL POROSITY
- 0 Negligible
- 1 Very low
- 2 Low
- 3 Moderate
- 4 High
- 5 Very high

HYDROCARBON SHOWS
- 0 None
- 1 Weak
- 2 Moderate
- 3 Strong

HYDROCARBONS
- Mobile oil
- Tarry residual oil

DIAGENESIS
- Nodules
- Micronodules
- Open fracture
- Filled fracture
- Stylolite
- Ap Apatite
- Ba Barite
- Bs Brecciated sed't
- Ca Calcite
- Ch Chert
- Cl Clay
- Dm Dolomite
- Ka Kaolinite
- Ph Phosphate
- Py Pyrite
- Qz Quartz
- Ro Residual oil
- Sd Sand
- Si Silica
- Sid Siderite
- Sp Sphalerite
- St Silt

COLOUR
- Lt Light
- Md Mid
- Dk Dark
- Vdk Very dark
- Bf Buff
- Bk Black
- Bw Brown
- Ge Grey
- Gn Green
- Or Orange
- Pp Purple
- Rd Red
- Wh White
- Ye Yellow

Well defined Cements
- e.g. Ca (Qz) Calcite cement with subordinate quartz cements
- Ca, Qz Subequal calcite & quartz cements

'Possible' Cements
- e.g. (?Qz) (?Dm) No clear confirmation but suspected

strong pervasive

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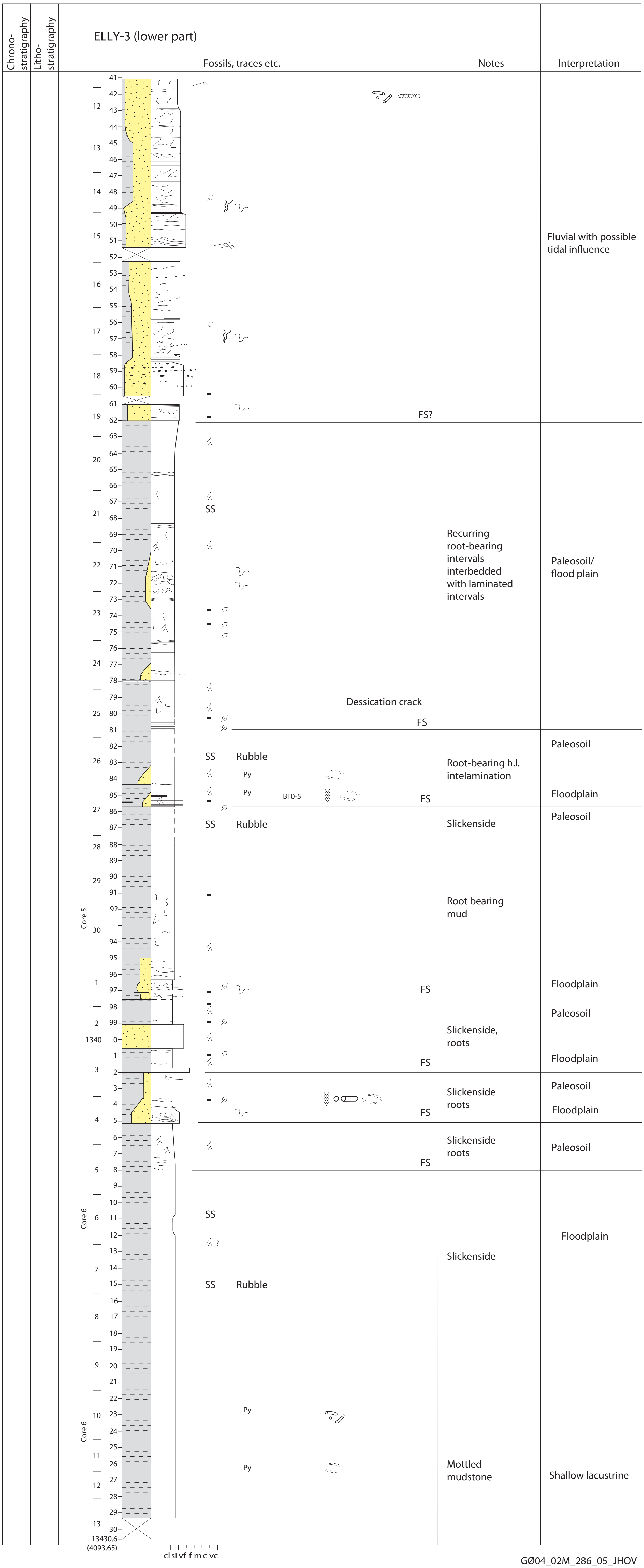
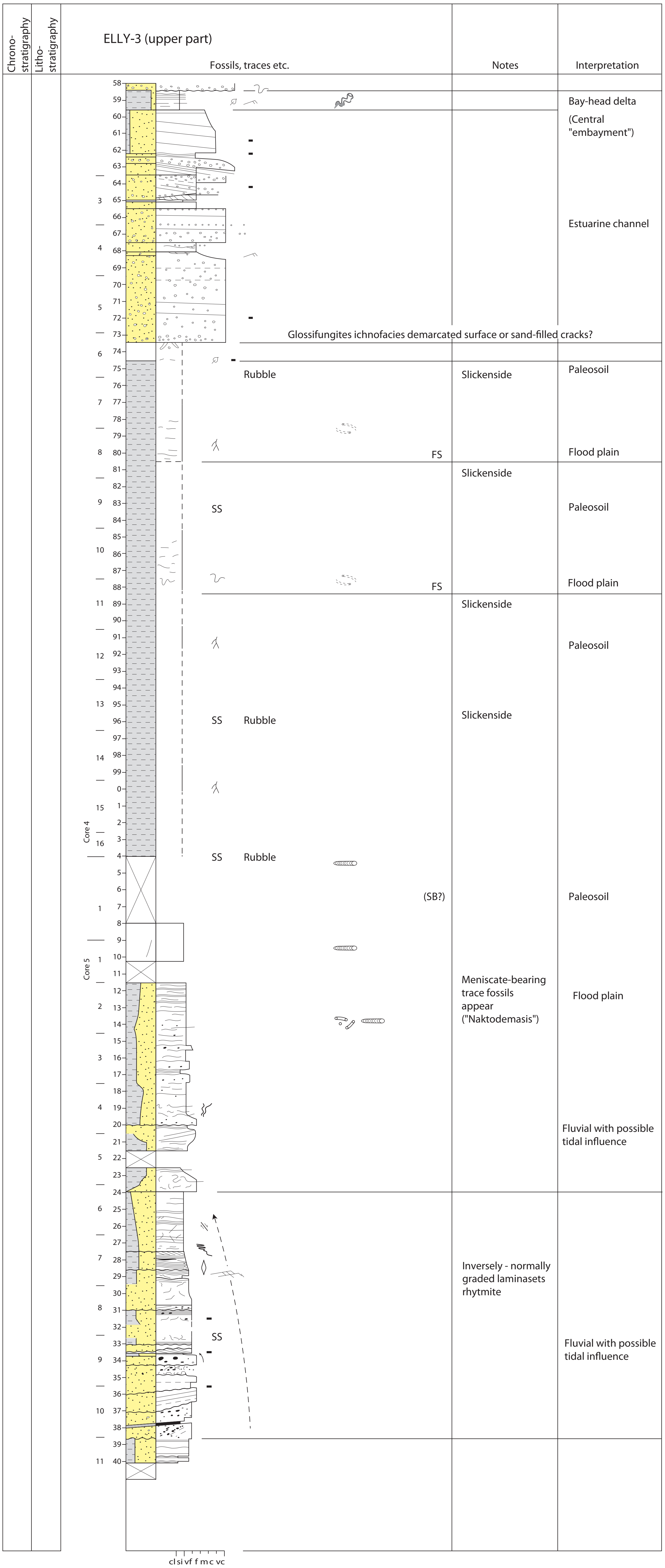
Enclosure 14a





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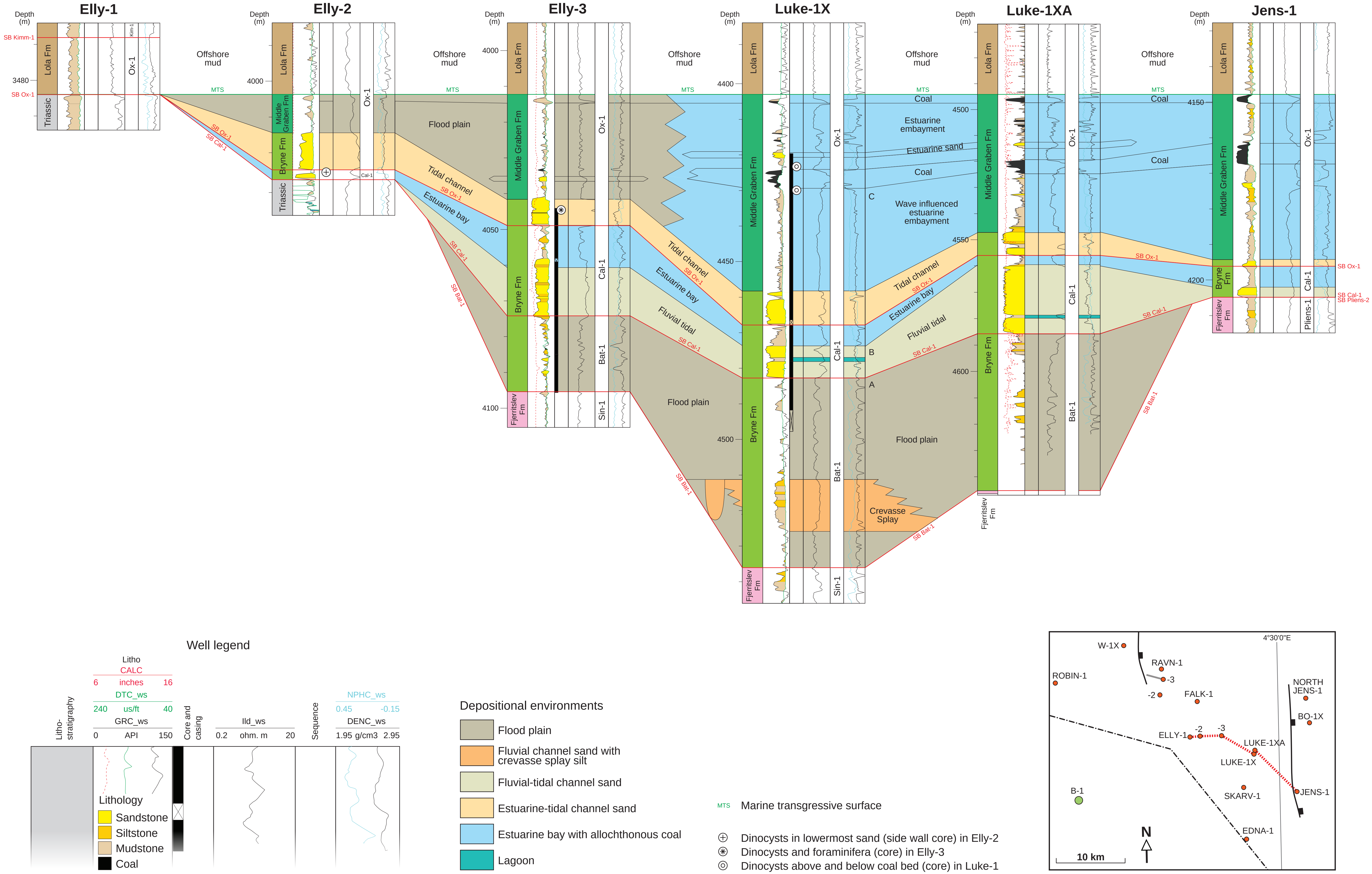
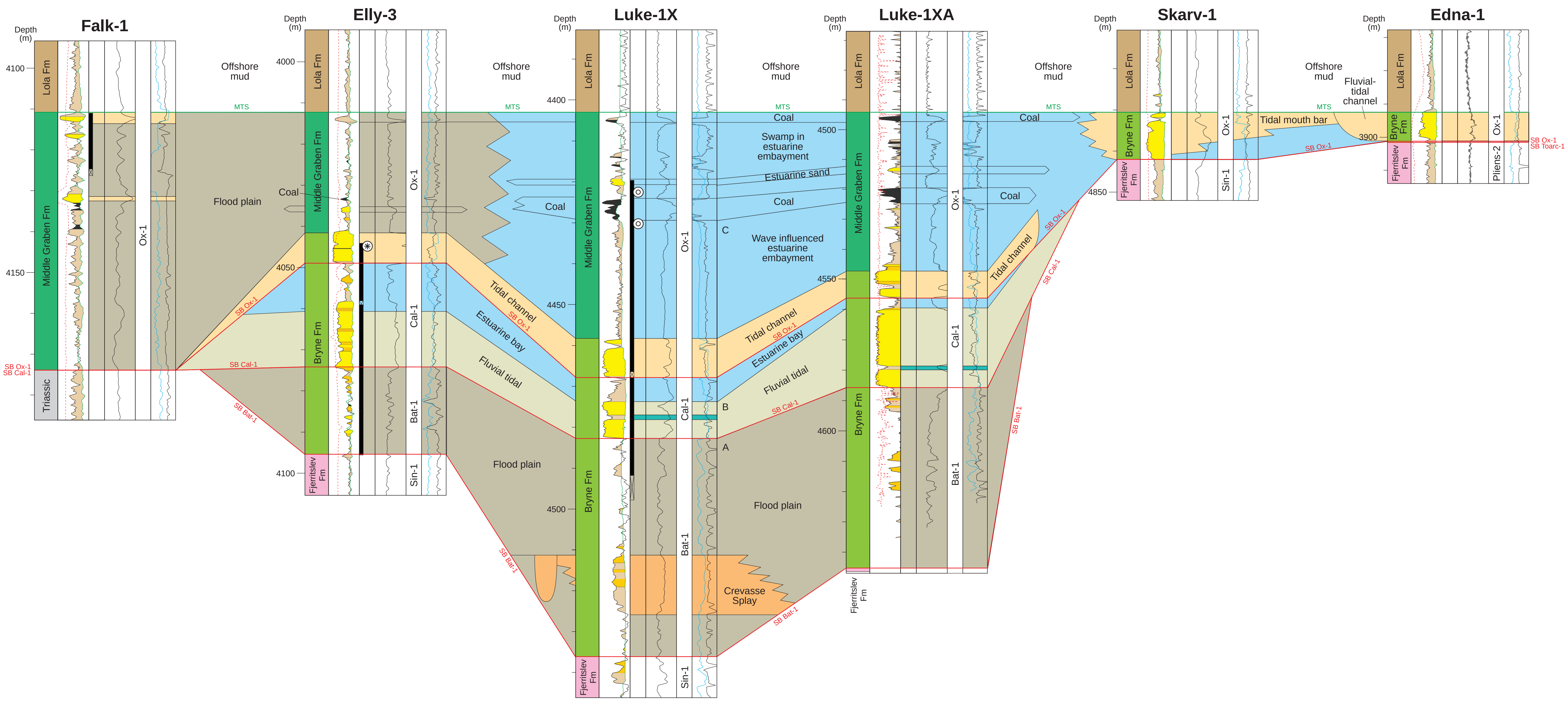
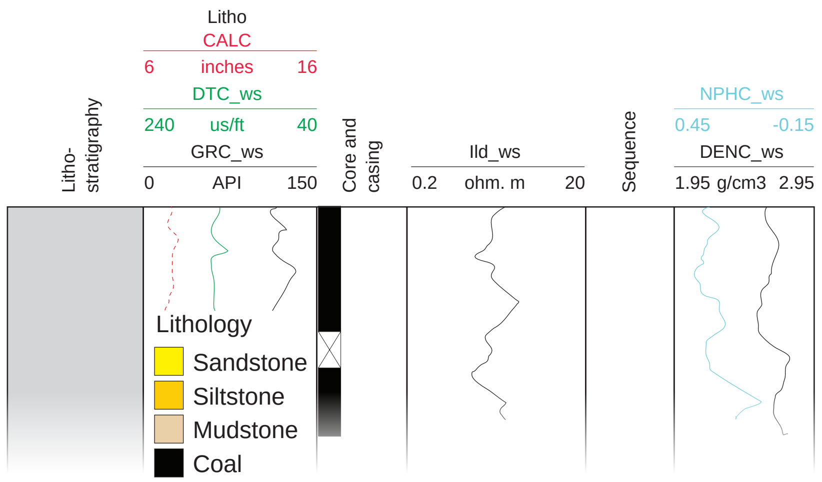

Elly-1
Elly-2
Elly-3
Luke-1X
Luke-1XA
Jens-1
Depth (m)
SB Kimm-1
SB Ox-1
SB Cal-1
SB Bat-1
SB Pliens-2
MTS
Lola Fm
Middle Graben Fm
Bryne Fm
Fjerritslev Fm
Triassic
Ox-1
Cal-1
Bat-1
Sin-1
Pliens-1
Kim-1
Offshore mud
Flood plain
Tidal channel
Estuarine bay
Fluvial tidal
Coal
Estuarine embayment
Estuarine sand
Wave influenced estuarine embayment
Crevasse Splay
A
B
C
3480
4000
4050
4100
4400
4450
4500
4550
4600
4150
4200
Well legend
Litho-stratigraphy
Litho
CALC
6 inches 16
DTC_ws
240 us/ft 40
GRC_ws
0 API 150
Core and casing
Ild_ws
0.2 ohm. m 20
Sequence
NPHC_ws
0.45 -0.15
DENC_ws
1.95 g/cm3 2.95
Lithology
Sandstone
Siltstone
Mudstone
Coal
Depositional environments
Flood plain
Fluvial channel sand with crevasse splay silt
Fluvial-tidal channel sand
Estuarine-tidal channel sand
Estuarine bay with allochthonous coal
Lagoon
MTS Marine transgressive surface
Dinocysts in lowermost sand (side wall core) in Elly-2
Dinocysts and foraminifera (core) in Elly-3
Dinocysts above and below coal bed (core) in Luke-1
4°30'0"E
W-1X
RAVN-1
-3
-2
ROBIN-1
FALK-1
NORTH JENS-1
BO-1X
ELLY-1
LUKE-1XA
LUKE-1X
JENS-1
SKARV-1
B-1
EDNA-1
N
10 km



Well legend



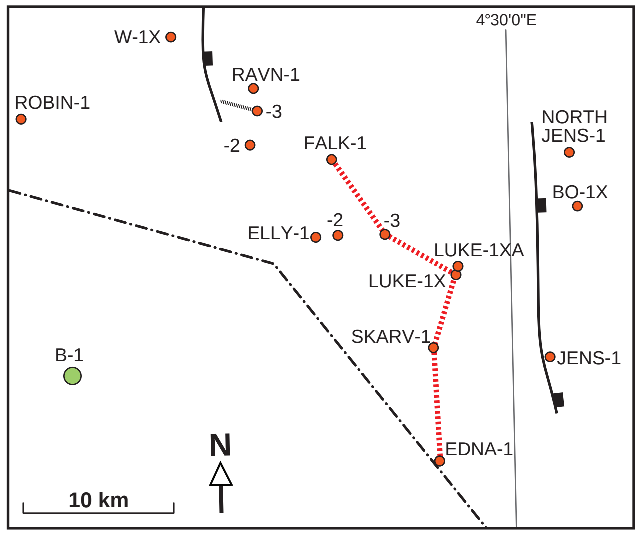
Depositional environments

- Flood plain
- Fluvial channel sand with crevasse splay silt
- Fluvial-tidal channel sand
- Estuarine-tidal channel sand
- Estuarine bay with allochthonous coal
- Lagoon

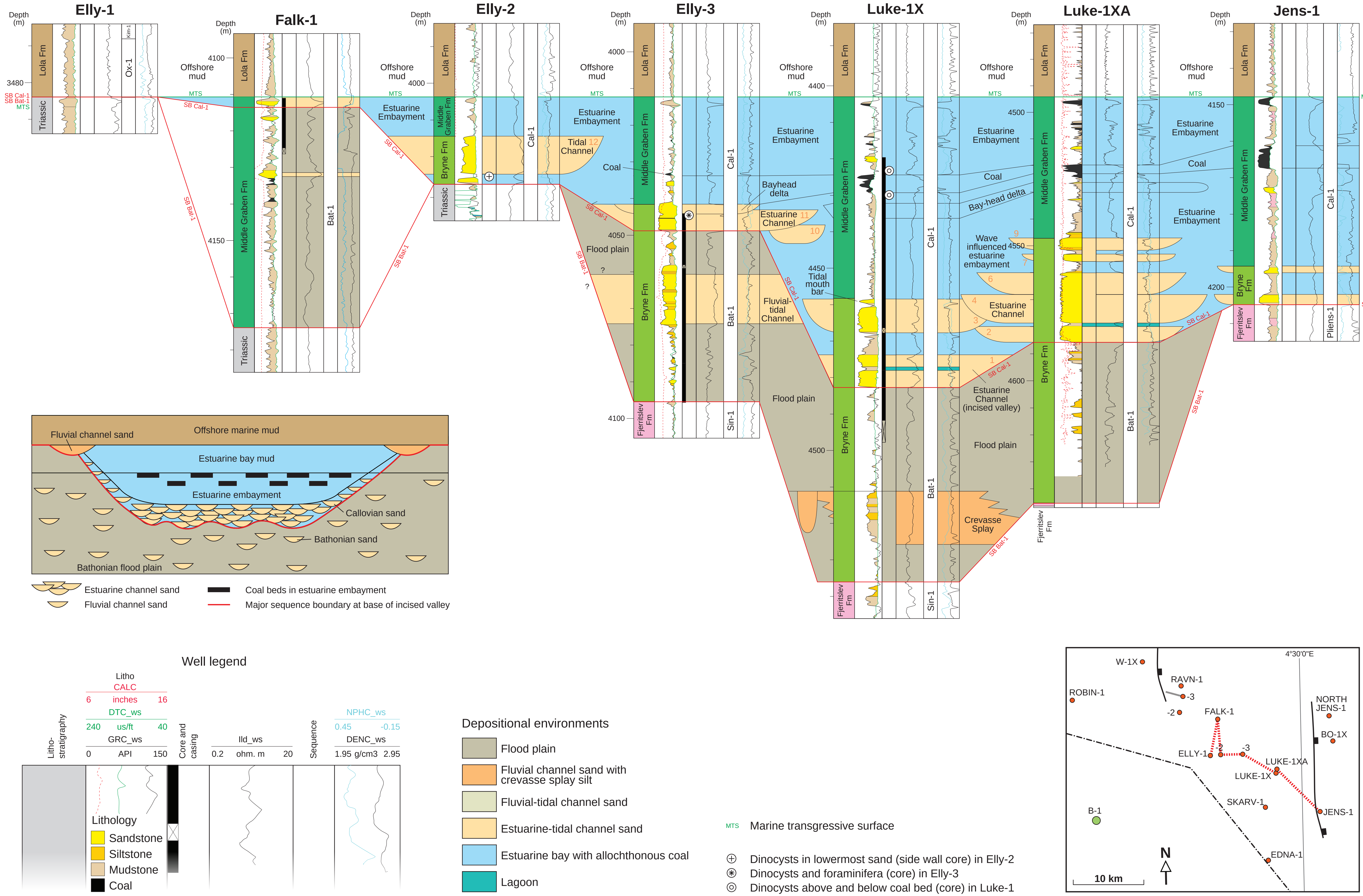
MTS Marine transgressive surface

⊛ Dinocysts and foraminifera (core) in Elly-3

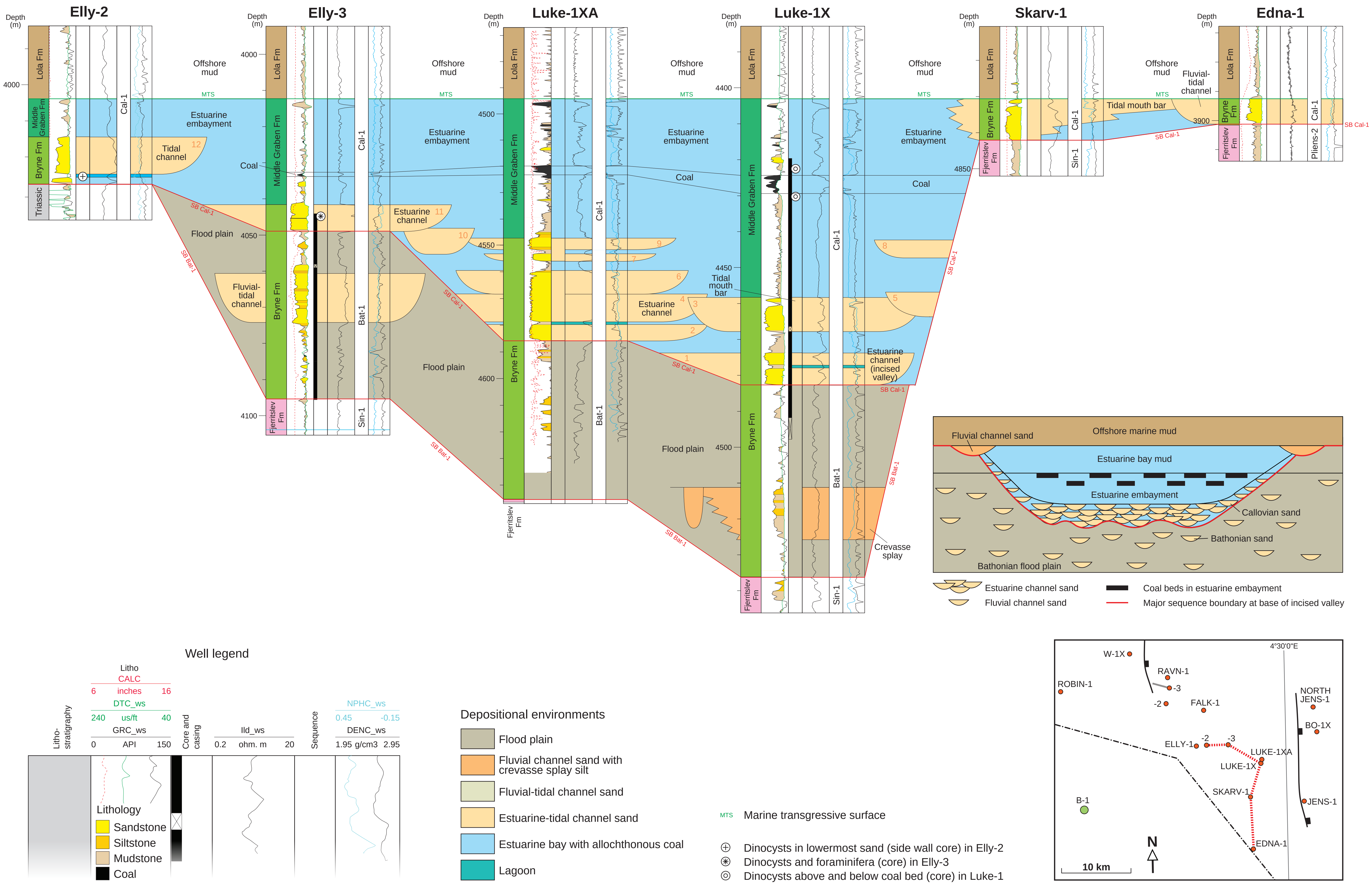
◎ Dinocysts above and below coal bed (core) in Luke-1

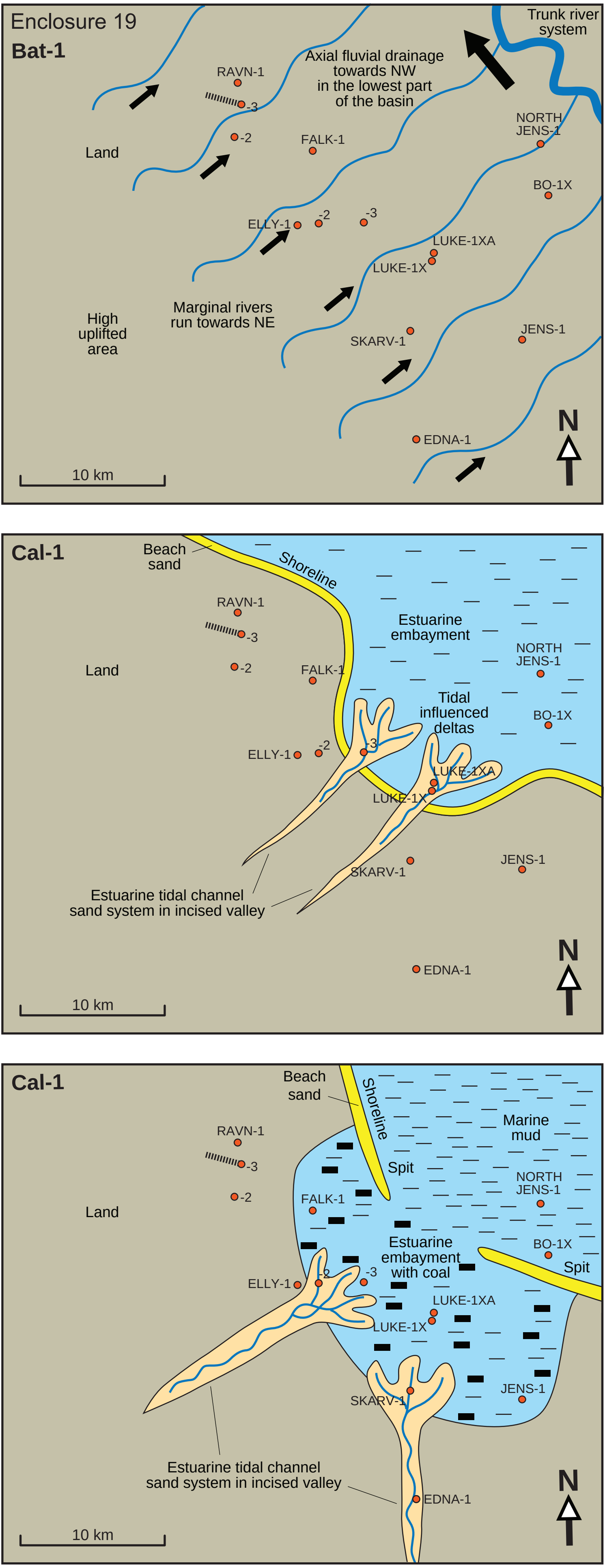


Enclosure 17



Enclosure 18




Enclosure 19
Bat-1
Trunk river system
Axial fluvial drainage towards NW in the lowest part of the basin
RAVN-1
-3
-2
FALK-1
NORTH JENS-1
BO-1X
Land
ELLY-1
-2
-3
LUKE-1XA
LUKE-1X
Marginal rivers run towards NE
High uplifted area
SKARV-1
JENS-1
EDNA-1
N
10 km
Cal-1
Beach sand
Shoreline
Estuarine embayment
RAVN-1
-3
-2
FALK-1
NORTH JENS-1
Land
Tidal influenced deltas
BO-1X
ELLY-1
-2
-3
LUKE-1XA
LUKE-1X
JENS-1
SKARV-1
Estuarine tidal channel sand system in incised valley
EDNA-1
N
10 km
Cal-1
Beach sand
Shoreline
Marine mud
RAVN-1
-3
Spit
-2
NORTH JENS-1
Land
FALK-1
Estuarine embayment with coal
BO-1X
Spit
ELLY-1
-2
-3
LUKE-1XA
LUKE-1X
SKARV-1
JENS-1
Estuarine tidal channel sand system in incised valley
EDNA-1
N
10 km