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**TNO report**

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# Sedimentary facies analysis of sequence 2 of the Upper Jurassic in the Terschelling Basin and the southern Dutch Central Graben

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# Contents

# 1 Introduction

The Central Graben in the northern Dutch offshore is an important area of interest for offshore gas and oil production. TNO is requested by the Ministry of Economic affairs (MEA) to improve access to information of the offshore as a part of MEA's effort to stimulate oil- and gas exploration on the Dutch offshore. Therefore a detailed study has commenced in the southern Dutch Central Graben and the Terschelling Basin. The study in this report is a small component of the detailed study of this region. In this report a facies study has been executed of sequence 2 of the Upper Jurassic in the Terschelling Basin and southern Dutch Central Graben (research area NCP-2A) on the Dutch offshore.

During the Jurassic the sealevel change was overall trangressive (Hallam, 1987; Hallam, 2001; Vail et al., 1991). However, in the North-West European offshore the relative sealevel was highly affected by local tectonics (Hallam, 2001; Cloetingh et al., 1987; Herngreen & Wong, 1989; Vail et al., 1991), including faulting and halokinesis. Though sealevel was affected by tectonics, the overall transgression can still be observed. In the "Late" Jurassic this transgression has been divided into three different sequences by Abbink et al. (2006). The division is visualized in figure 1. The different sequences are in fact three tectonostratigraphic units representing three different events: (1) the initial opening of the Dutch Central Graben, (2) the initiation of the Terschelling Basin and (3) flooding of the whole Dutch offshore by the overall regional transgression. In this study a facies-interpretation is made of sequence 2 of the Upper Jurassic in the Terschelling Basin and the southern most part of the Dutch Central Graben on the Dutch offshore. The main objective is to obtain insights in the evolution of the paleogeography and to describe the different depositional environments. To achieve this objective a series of activities has to be accomplished. First of all it is essential to observe the lithology and sedimentological structures in the cored intervals that are present in the sequence. These observations from cores can than be interpreted towards depositional environments. Subsequently these depositional environments are extrapolated to the non-cored part of the sequence. Displaying all data on correlation panels, combined with parallel seismic sections, the depositional environments can be mapped. Interpolation of these data points, using a conceptual model, results in a paleogeographic map of sequence 2 of the study area.

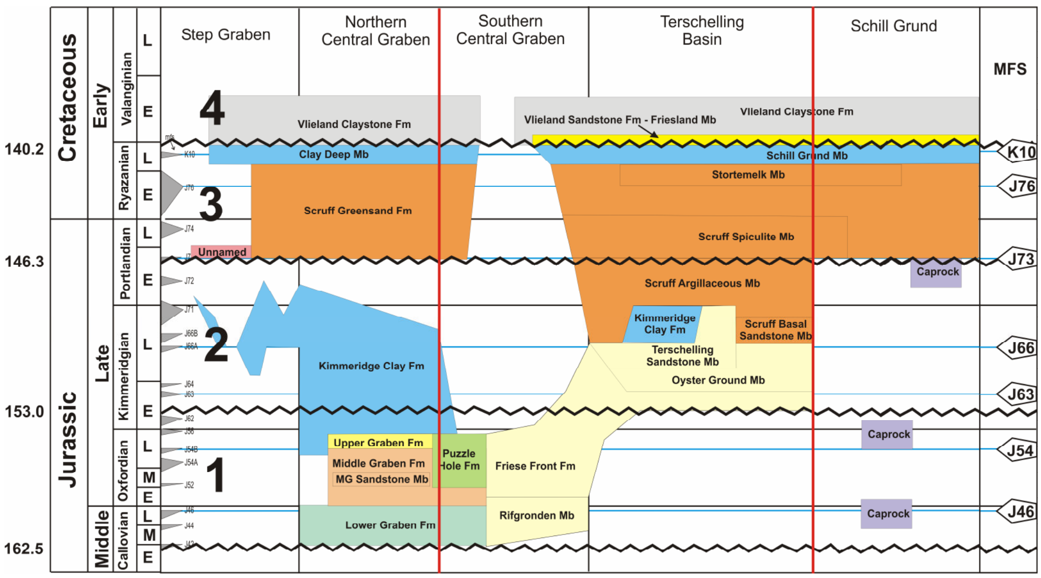


Figure 1: Schematic diagram of the different sequences. On the left the different ages of the boundaries of the three sequences are given (Modified after Abbink et al., 2006). The different epochs are subdivided according to the British Boreal classification (See Gradstein et al., 2004).

# 2 Methods

## 2.1 Study area

The studied area comprises the Terschelling Basin and the southernmost extension of the Central Graben on the northern Dutch offshore. These basins are incorporated in the research area NCP-2A, which has been defined by TNO. The dimensions of the basins are approximately 80 x 50 km's. In the north it is bordered by the Dutch Central Graben itself and the Schill Grund High. To the west and east lie respectively the Cleaver Bank High and the Ameland Block. In the south the basins are bordered by the Central Offshore Platform, the Friesland Platform and the Lauwerszee Trough (Fig. 1).

## 2.2 Database

In the study area only twelve wells contain cored intervals of sequence 2. These wells comprise nine exploration wells of the NAM, two of Mobile and one of AGI. The wells are mostly situated in the southern most part of the Dutch Central Graben and the Terschelling Basin. Only one well is located on the Schill Grund High. Additionally, biostratigraphical data was obtained from TNO's biostratigraphical dataset and from Abbink et al. (2006). The biostratigraphical dataset comprises the studied wells that contain cored intervals and a number of offset wells. See table 1 for exact information.

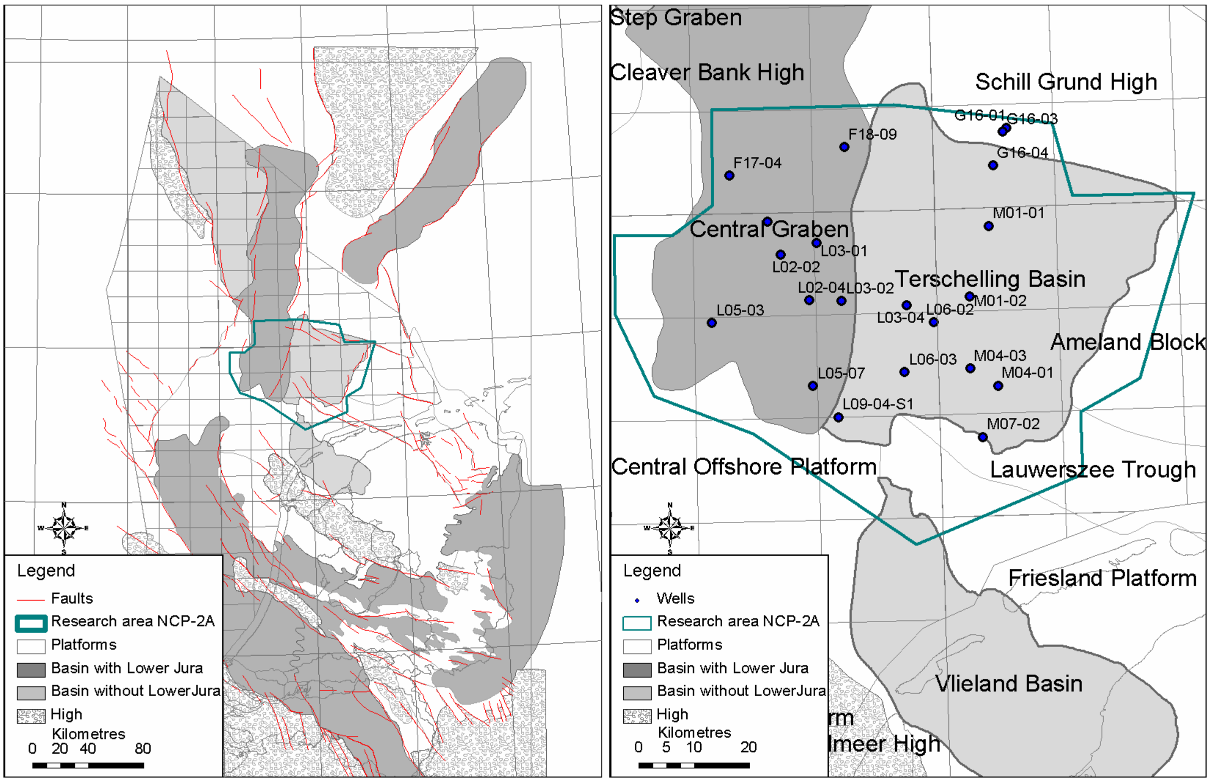


Figure 1. Left: General overview of the study area and tectonic units in the onshore and offshore of the Netherlands. Right: Detailed location map and general overview of the tectonic elements in the study area.

| | Macroscopical described | Biostratigraphical data | Basin |
|---|---|---|---|
| F17_04 | x | x | CG |
| F18_05 | x | | CG |
| F18_09 | x | | CG |
| G16_01 | | x | SH |
| G16_03 | x | | SH |
| G16_04 | | x | TB |
| L02_02 | | x | CG |
| L02_04 | x | x | CG |
| L03_01 | x | x | CG |
| L03_02 | | x | CG |
| L03_03 | x | | TB |
| L05_01 | | x | CG |
| L05_03 | x | x | CG |
| L05_04 | | x | CG |
| L05_07 | x | | CG |
| L06_02 | x | x | TB |
| L06_03 | x | x | TB |
| L09_04 | | x | TB |
| M01_01 | x | x | TB |
| M01_02 | | x | TB |
| M04_01 | | x | TB |
| M04_03 | | x | TB |
| M07_02 | | x | TB |

Table 1. Additional data of the wells.
CG = Dutch Central Graben, TB = Terschelling Basin,
SH = Schill Grund High.

## 2.3 Methods

The working method of the whole study can be subdivided in four major parts:
1) Describing the cores, 2) Correlation of the cores to the well logs, 3) Studying of the seismic sections and 4) Production of the paleogeographic maps.

The study of the cores has been done at three locations: TNO Built Environment and Geosciences in Utrecht, TNO Central Core Storehouse in Zeist and NAM Core Storehouse in Assen. The cores were described by using a core description software package called CoreCAD. As the objective of the study was to obtain insights of the depositional environments, specific interest has been laid on the lithology and sedimentological structures as they contain the most information on the depositional environment of the sediments. Additionally the grain size, colour, ichnofossils, bioturbation, diagenetic components and fractures were described. The cores have been visually described on a macroscopic level.

The next step was to correlate the interpreted depositional environments of the studied cores to the interval of the well that contained sequence 2. First of all the studied cores had to be added to the well logs. Subsequently vertical extrapolation of the depositional environments was done per well. To make a good correlation, the following information was needed:

1) Biostratigraphical data; which was provided through earlier biostratigraphic studies at TNO.
2) Electrologs; including gamma ray logs, sonic logs, bulk density logs and neutron-porosity logs, if they were available.
3) Cuttings descriptions; information about the cuttings that have been described during the drilling of the well.

The biostratigraphical data contained additional information about the depositional environments, obtained from the presence of specific dinoflaggelates and pollen. Samples were obtained from cores, side wall cores and cuttings. Furthermore the biostratigraphic data also defined the boundaries of the sequences of the boundaries in the wells. The different electrologs represent different characteristics. The gamma ray log (GR) represents the natural gamma-ray radiation given off by rocks. As shales normally release a lot of natural gamma-rays, they are normally represented by high values in the gamma ray log. Low values are commonly related to sandstones and limestones. The sonic log (DT) is an acoustic log. It represents the travel time of a compression wave along a unit distance. The sonic log is often used to determine the porosity of sediments.The bulk density log (Rhob) tool consists of a highly radioactive gamma-ray source that is beamed into the rocks. Heavy and dense rocks reflect few gamma-rays. Light and porous rocks, like sandstones and porous limestones, reflect a lot of gamma rays. The neutron-porosity log (Nphi) is a type of porosity log that measures the presence of hydrogen in a formation. Very high porosities are related to shale formations, as shale contains a lot of water. The cuttings descriptions are the analysis of the fragments of rocks, obtained from the cutting action during the drilling process.

After the vertical correlation was done, correlation could be done in the remaining wells. This correlation was done with the use of correlation panels. Four correlation sections were chosen to represent the structure in the basins. The sections were selected on the basis of the distribution of the studied wells. The correlation panels were made by using the visualization software package Petrel.

After correlation of the cores, seismic sections parallel to the correlation sections were studied. The main aim of the seismic sections was whether it was possible at all to correlate the wells to each other.

Additionally the stratigraphic architecture in the basin was studied, like onlap, offlap or wedge geometry.

Finally the maps were compiled using GIS-software. Three time frames were chosen to be able to illustrate the evolution of the paleogeography. The three maps present the distribution of the different depositional environments in the study area during the start of sequence 2, the situation in the middle of sequence 2 and the final stage of sequence 2. The time frames are based on biostratigraphical data.

# 3 Geological setting and previous work

The general pattern of sea-level change during the late Jurassic was dominantly transgressive, with several time intervals of stillstand (Hallam, 2001). In the northern North Sea it was characterized by a transgressive supercycle, which has been subdivided by twelve smaller cycles (Vail & Todd, 1981). Though the research of Vail & Todd (1981) was specific to the northern North Sea, it still represented to a larger extent the behaviour of sea-level fluctuation in this region. Though the global sea level rose during this age, the relative sea-level was likely a function of both local tectonism and eustatic processes (Hallam, 1987). Where both processes were active during the same time span, it becomes considerably more difficult to distinguish the different processes in the general sea-level curve.

The high frequency occurrence of short-period fluctuations towards the end of the Jurassic can be related with a simultaneously pronounced increase in fault-controlled tectonic activity, in the form of rifting episodes and compressional pulses to the more regional stress state (Hallam, 1987; Cloetingh et al, 1987). Hallam recognized a number of significant regressive events that appeared to be caused by regional tectonics rather than 'global' fall in sea-level, as Vail et al. suggested (Cloetingh et al, 1987). These regional tectonics can also be referred to as the Cimmerian movements (Ziegler, 1982). They lasted from early Jurassic to early Cretaceous. During this time the central Atlantic started opening and spreading. During the Middle Jurassic the North Sea was affected by a rift doming event, which was concentrated on the northern Central Graben. When doming diminished, crustal extension gradually increased along the rift system of the Northern and Central North Sea (Ziegler, 1982). The beginning of the increase in crustal extension was marked by the 'Mid-Cimmerian' tectonic pulse, which affected much of Northwest Europe. It caused a period of increased tectonic instability on the Dutch onshore and offshore, which terminated only at the end of the Early Cretaceous. During and after the mid-Jurassic faulting episode the high blocks adjacent to the Central Graben were exposed to erosion which partially affected their morphology. The eroded material started to fill the lows and grabens (Ziegler, 1982). Subsequently, marine transgressions, originating in the Central Graben, initially inundated the basinal areas and only later covered their flanking highs (van Wijhe, 1981). The initial inundation of the basinal areas corresponds to the second sequence of the Jurassic, where initial deposition in the Terschelling Basin occurred.

Herngreen & Wong (1989) gave a revised stratigraphical classification of the Dutch Central Graben of the "Late" Jurassic. This classification included the non-marine Central Graben Group and the distinct marine Scruff Group. The latter has been interpreted once again in the stratigraphic nomenclature of the Netherlands (Van Adrichem Boogaert & Kouwe, 1993). New insights and data have lead to a new sequence stratigraphic insight in the rock stratigraphy of the Terschelling basin and the southern Dutch Central Graben. The new sequence classification comprises three sequences in the "Late" Jurassic. These three sequences represent three tectono-stratigraphic intervals, representing the filling of the Central Graben, the inundation of the Terschelling Basin and the flooding of the adjacent highs. In the second sequence, Abbink et al. (2006) showed that two MFS's are present. The first MFS is of Early Kimmeridgian age and forms the first marine transgression in the Terschelling Basin. The second MFS is of Late Kimmeridgian age.

# 4 Core descriptions

## 4.1 Core descriptions

The core descriptions summarize the observations of the cored intervals of the different wells. Features that have been incorporated in the descriptions are: grain size, sedimentary structures, lithology, colour, ichnofossils, bioturbation, diagenetic components and fractures. If the cores contained interesting structures or needed extra explanation, they were added in the remarks column.

The cores that were described using CoreCAD, are summarized below. One has to keep in mind that the description of the cores has been done with the objective to obtain insights of the depositional environments. Therefore emphasis was set on the lithology and the sedimentological structures. The described cores all enclose sediments of sequence 2, though a few cores contain material of sequence 1 or 3.
A summary of each described core is presented in this chapter, which complements the core description log presented within the appendices.[1] Subsequently a short interpretation of the depositional environments is given.

### *4.1.1 Well F17_04*

#### *4.1.1.1 Core 1 (2453-2471 m)*

This core is composed of dark claystones and light brown bioturbated silts, which divide the core in two. The claystones are horizontally laminated and are very platy. No shells are present. Intervals of siderite are common. On top of these claystones interbedded siltstones and clayey layers are present. The siltstones are crossbedded, whereas the claystones are commonly horizontally layered. Synaeresis cracks were observed. The silt- and claystones are commonly bioturbated, with the presence of ichnofossils Diplocraterion, Teichichnus and Arenicolites. From 2455.34 no shaly layers are present anymore and crossbedding becomes the dominant structure, some high angle cross stratification is present. Only ichnofossils Teichichnus and Arenicolites are present in this siltstone. At the top of the core 40 cm of very fine sandstone has been observed, which has the same sedimentological structures as the underlying silts.

#### *4.1.1.2 Core 2 (2538-2556.5 m)*

The second core in this well looks rather the same as the first core, with the exception that beneath the dark claystones, more silty layers is present. Bioturbation in this silty material is common, though this can also be seen in the claystones. In the siltstone burrows of Diplocraterion are present. The burrowing has made original structures difficult to see in both the silt- and claystones, although some horizontal lamination is still visible. The dark claystone contains small intervals with siderite and some pyrite. On top of the claystone at 2541.63 lightbrown siltstone is present. It is mainly composed of a coarsening up sequence of several meters. At its base the siltstone shows Diplocraterion and Teichichnus burrows. On top of this bioturbated zone crossbedding is visible, which includes a high amount of pyrite cementation and concretions.

[1] See Appendix H for the original core descriptions.

#### 4.1.2 *F18_09 (2625-2626.5, 2653.68-2657.21, 2662-2693)*

Most of the core was not slabbed and is still stored as whole cores in their boxes. However, these intervals were studied anyway by using the photographs and some in situ checks. Quick scans of these core boxes revealed that these core intervals contained predominantly rubbled claystone. The slabbed intervals of the cores comprise the relative coarse clastic intervals, which range from silts to conglomerates.

The basal core encloses a large amount of soil fractures and soft sediment deformation in the siltstones and sandstones. Where these structures are not present, conglomerates and structureless or mottled silts to very fine sands are present. The conglomerates are matrix supported and contain subrounded pebbles that are smaller than 2 cm. The pebbles are mainly composed of brown structureless material, which is thought to be siderite.

The third cored interval consists of fine silty clayish material. It contains soil fractures, soft sediment deformation and root remains. The second segment has not been slabbed. The available photographs only show that fine dark material is present. The upper core is very similar to the third one, as it is also comprised of silty clayish material. This interval contains iron staining and remarkable dots of pure clayish material of unknown origin.

#### 4.1.3 *G16_03 (2709.96-2710.86, 2722-2723.8, 2731.45-2733.25)*

Large intervals of this core are regrettably missing and only few metres in three short intervals are left. The basal interval comprises 1 meter of conglomerate, which contains clasts from 0.4 – 2 cm. The larger clasts are commonly claystone intraclasts. The overlying sandstone is composed of fine sands that form non-parallel wavy lamination. The middle interval is less than 1 meter thick, and is composed of very fine bioturbated sandstone. Though the sand is bioturbated, lamination is still visible. The upper interval is once again constructed of conglomerates and conglomeratic sandstone and contains organic material. Convolute bedding is present in the conglomeratic sandstone. Furthermore it contains white clasts up to 2 mm. The conglomerate itself supports white moderately rounded clasts up to 6 mm.

#### 4.1.4 *Well L02_04*

##### 4.1.4.1 *Core 1 (2085-2116.35 m)*

The upper core of this well can be separated in three parts. The basal part contains green clayish silts and very fine sandstones. Red stains, as a result of oxidation processes, are commonly visibly. Rootlet traces of rootlets are present, though they can be difficult to recognize. Apart from the rootlets, some lamination is visible. On top of these deposits a short interval of several meters of heavily bioturbated sand- and siltstone is present. Individual burrows are not recognizable, with the exception of one relative large burrowing trace on dm-scale. On top of these bioturbated sandstones interbedded fine siltstones and shaly claystones are present, with bedding thicknesses of up to several dm's. The whole interval contains shells.

##### 4.1.4.2 *Core 2 (2205-2214.5 m)*

The interval is being characterized by fine sandstones and siltstones. At the base small current ripples are present. It is followed by a claystone interval of 1.5 m. In this interval small mm-sized calcite nodules are observed. Red stains as a result of oxidation processes are commonly present. Furthermore the claystone contains a thin red layer that is interpreted as a paleosoil. On top of the claystone, sandstones and siltstones are present. In the sandstones layers and pockets of conglomerate are observed. The conglomerates are matrix-supported and consist of subrounded pebbles of 0.5 – 1.0 cm. The sand- and siltstones contain a lot of organic material and a lot of soft sediment deformation structures, though some lamination is still recognizable despite the contortion. Rootlets and soil fractures are moderately present. At the top of the core deformation is absent and parallel wavy bedding and low angle lamination is present.

#### *4.1.5 L03_01 (2547-2555.55, 2556.7-2558.9 m)*

Core L03_01 is divided in two segments. The lower segment contains green mottled silts, alternated with dark clay with "soil fractures". The upper segment is composed of coarse to very fine light brown sands. In this part one major fining upward sequence and two minor ones are present. The major sequence contains medium grained sandstone at the bottom and a 5 cm thin layer of clay at the top. In this sequence tangential crossbedding is succeeded by consecutively: horizontal lamination, low angle cross-stratification and crossbedding. It must be noted that the structures are difficult to see, as the sand is extremely clean. The silt at the top of this fining upward sequence is slightly bioturbated. On top of this sequence, a considerable amount of organic material is present, followed by two smaller fining upwards sequences.

#### *4.1.6 L03_03 (2408-2425.83 m)*

This core is largely composed of grayish black claystones, with a small light olive gray silt layer on top of it. The claystone is horizontally laminated and contains a variable amount of shells. The shells are of 1 species and are thin, white and slightly curved. Siderite cementation is rarely present. The siltstone is thoroughly bioturbated and as a consequence no original sedimentary structures are visible.

#### *4.1.7 L05_03 (2611.1-2650.95 m)*

Core L05_03 was not described due to lack of time, though it has been scanned quickly. The core displays a high variability of sedimentary structures. Soil fracturing and soft sediment deformation are the most common. The sediments have a high organic matter content. Keeping the other cores in mind, the deposits in this core have probably been deposited in a lower delta plain.

#### *4.1.8 L05-07 (3148-3165.46 m)*

This core consists of very fine to medium green sands. It is divided in 2 parts. The lower part consists of very fine sands and is completely bioturbated. The bioturbation is commonly represented by cm-width vertical burrows. The burrows have thin walls of dark material and also have 'compartiments'. Glauconite is common, resulting in a greenish colour of the sediments. The upper part is a pebbly sandstone. The sandstone is very porous and grains are subangular and moderately sorted. The pebbles float in the sediment. The available organic fragments are subangular. One conglomeratic interval of 10 cm is intercalated. Though the amount of pebbles is higher in comparison with the surrounding material, the subangular pebbles still float in the sandstone and are of the same black and brown material as in the sandstone. Above the conglomeratic part, an interval of greenish black pebbly sandstone is present. This interval contains red streaks up to several cm's. The red colour is likely a result of ironoxidation. In the whole core distinct white grains can be observed of unknown origin, though in this interval the amount is exceptional. The top of the core is moderately bioturbated.

#### *4.1.9 L06_02 (2510-2464.5 m)*

Core L06_02 comprises very fine to medium-grained sandstone with intervals of clays/silts, underlain by anoxic dark claystone with many shells.

The claystones have a very dark grey to black colour. Thick layers (dm-scale) of siderite cementation can be observed. At the top of the claystone many white thin shells up to 2 cm are present parallel to the bedding. On top of the clays, medium to very fine-grained sandstones are present. These sandstones are characterized by horizontal lamination, low to high angle cross-stratification and intervals of bioturbation. The observed burrows have been interpreted as Ophiomorpha, Thalasinoide and Planolites. Organic material is present. An interval of bioturbated silt is intercalated, with Teichichnus-shaped burrows.

#### *4.1.10 Well L06_03*

##### *4.1.10.1 Core 1 (2027-2045.22)*

The upper core in well L06_03 consists of very fine-grained dark green bioturbated argillaceous sands. The abundance of glauconite causes the green colour of the sediements. The core is divided in two parts. The lower part is a bit darker due to a higher content of clay. It is characterized by bioturbation on mm-scale, like Terebellina. At 2039.65 the material becomes a bit lighter and cm-scale bioturbation like Cylindrichnus takes over. Furthermore an increase in shells and shell fragments is observed in comparison with the lower part.

##### *4.1.10.2 Core 2 (2095-2110.86)*

This core consists of fine light grey sands. It can be divided in two parts. The lower part is very light grey and is largely horizontally laminated. It also contains a considerable amount of shells. In the upper part, the sand is thoroughly bioturbated. The burrows are interpreted as Ophiomorpha.

##### *4.1.10.3 Core 3 (2254.7-2270.03 m)*

This core consists of silts to very fine sands, which predominantly show features of soil forming processes, such as rootlets and ‘soil fractures’. The core can be divided into three segments. The lowest one includes very fine sands that have a reddish colour. They contain parallel wavy lamination and smallscale cross-stratification or ripples. Traces of rootlets are present. Burrows of the Scoyenia species can be observed. The middle segment comprises siltstones, which are interpreted as an immature paleosoil (laterite). However, at the base a fully developed purplish gray paleosoil is present. Furthermore roots and soft sediment deformation structures are observed in this segment. The upper segment contains light olive gray to dark gray silts and very fine sands. Main structures are soft sediment deformation structures, rootlets and soil fractures. The sediments have a high content of organic material.

##### *4.1.10.4 Core 4 (2304-2322.96)*

This core contains a high variety of sediments: from silts, to very fine sands to conglomerates. Like core 3 a lot of organic material is present. The core can be separated in three parts. The lowest part consists of light grey sands and silts. Almost the whole segment has endured soft sediment deformation and contains a lot of organic material. At some levels horizontal lamination can be seen. The middle segment is an alternation of bluish to olive gray conglomerates and greenish gray sands. The conglomerates are poorly sorted. The pebbles are well rounded and are mainly claystone and quartz extraclasts, though at the top clay intraclasts are also present. Pyrite concretions are common. The sands differ in grain size from silty towards medium grained sands. Wavy parallel lamination is present. The upper segment is made of olive gray silts. In the silts a lot of soft sediment deformation and soil fractures are present. The silts also contain a considerable amount of pyrite concretions. At the top several levels with intraclasts are present.

#### *4.1.11 M01_01 (2288-2308.64 m)*

Core M01_01 can be divided into two segments. The lower segment consists of very dark claystones. In several intervals white thin shells up to 1.5 cm are present. Superposed on these claystones siltstones are deposited. At the transition of the claystone to the siltstone, an exceptional amount of glauconite grains are present. These grains are situated in highly bioturbated glauconitic sandstone. The siltstones contain an alternation of laminated and bioturbated silts. Lamination differs between horizontal lamination and low angle cross stratification. Furthermore a repeated pattern can be observed:
1) Intervals of shells,
2) Parallel laminated siltstone,
3) Low angle laminated siltstone,
4) Bioturbated muddy siltstone.
Bioturbation varies between vertical and horizontal burrows and includes Ophiomorpha-shaped burrows. The bioturbated intervals commonly possess a higher percentage of clay, as a result of mixed silt and clay layers during the burrowing process.

## 4.2 Depositional environments

Five different depositional environments can be interpreted from the cores. Consequently the different interpreted depositional environments from the continent towards the marine realm are:

1) Lower delta plain
2) Restricted lagoon
3) Open lagoon
4) Barrier system
5) Shallow marine

The different depositional environments are all positioned in figure 2, except for the lower delta plain. As can already be seen from the diagram, the barriers play a significant role in the system. First they protect the coastline and secondly they determine the conditions of water circulation in the lagoon environment.

Below the descriptions of every depositional environment and their characteristics as described in the cores are given.

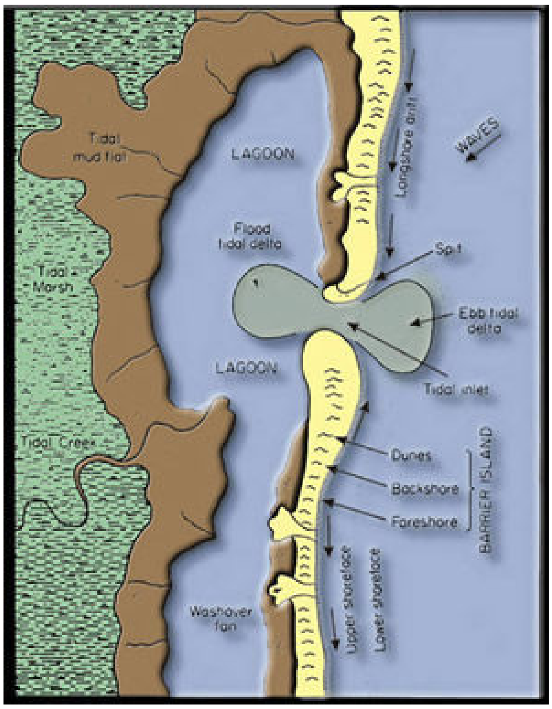


Figure 2: Diagram showing the environments of a barrier island system. (from Blatt et al., 1980, Origin of Sedimentary Rocks, *http://www.csc.noaa.gov/beachnourishment/html/geo/barrier.htm*)

### *4.2.1 Lower delta plain*

The lower delta plain is interpreted as an area with swamps, lakes and river patterns. Typical structures that can be seen are crevasse splays and paleosoils.

In the cores this depositional environment is represented by a high variety of clastic sediments with many different colours, including grey, red, green, purple, orange and brown. The difference between coarse and fine material can be related to the proximity to a river. The coarser sediments like conglomerates and sandstones can be interpreted as point bars and crevasse splays (especially the sands). The crevasse splays often display nice current ripples and/or internally rippled cross-stratification. Finer materials are interpreted to be lower energy environments like muddy lake margins.

Structures like soft sediment deformation and ‘soil fractures’ are predominantly observed in the fine sandstones and siltstones. Soft sediment deformation is often present in the shape of convolutions. ‘Soil fractures’ are the result of fluctuation in the groundwater level. The alternation of dry and wet conditions causes the soil to swell and shrink. This occurs along fractures, of which the fracture planes are very smooth. In the core this structure can be recognized as typical angular cm-sized polygons. The continental origin of this environment is also verified by the presence of paleosoils, laterites, rootlets and organic material. Pyrite concretions can also be found, though this mineral isn’t typical for this environment only.

It is very rare to observe the remains of animal trails like burrows. However, in the third core of L06_03, Scoyenia-shaped burrows can be found. These burrows are the result of arthropods (possibly a larval beetle) and are typically associated with non-marine environments, originally formed in moist soils (Werver, 1996).

Wells that contain lower delta plain deposits in their described cores are: F18_09, G16_03, L02_04, L05_03 and cores 3 and 4 of well L06_03.

### *4.2.2 Restricted lagoon*

The restricted lagoon is situated between the coast and a barrier system. It is protected from the influence of the sea by the barriers. In the lagoon itself water circulation is reduced towards a minimum. As a result anaerobic circumstances occur, causing a stressed system for the present animal life.

In the cores this environment is represented by dark grey to black claystones. The stressed conditions in this environment can be interpreted from the presence of a monoculture of thin white bivalves. Apparently, only these specific bivalves can thrive in these difficult circumstances. Note however, that bivalves don’t have to be present. In intervals without shells, the mineral siderite may be observed.[1] It is mostly present as cementation.

Wells that contain restricted lagoon deposits in their described cores are: F17_04, L02_04, L03_03, L06_02 and M01_01.

### *4.2.3 Open lagoon*

The open lagoon depositional environment is situated between the coast and a barrier system, just like the restricted lagoon environment. It is more located towards the inlets between barriers and thereby experiences more water circulation. The increase in circulation results into an increase in energy, so coarser material like siltstones are

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[1] See Appendix B for explanation of the origin of siderite and pyrite.

deposited. The higher energy circulation is also supported by the presence of small channels, for which evidence can be found in the cores.

In the cores this environment is represented by thoroughly bioturbated gray siltstones. The abundant bioturbation demonstrates that bottom life is more present than the restricted lagoon environment. Typical burrows that can be observed are those of Teichichnus. In M01_01 the channels are present in the shape of fining up sequences. The interpreted channels are probably small tidal channels in the lagoon, which slowly clog up until the channel is filled and alters its course.

The proximity to the continent is argumentated by the rare presence of organic material. Nearness to freshwater can be deduced from the presence of synaeresis cracks, which can be observed in the core 1 of well F17_04. These cracks are caused by salinity fluctuation and form in thin layers of shale as a result of subaqueous shrinkage.

It's very rare to observe glauconite in this depositional environment. In well M01_01 it can be found at the transition between claystones of a restricted lagoon environment and the siltstones of the open lagoon environment. The extreme 'glauconisation' is likely an indirect result of bioturbation. During a temporary period of non-deposition the deposited sediments were completely burrowed. The amount of faeces of the burrowing creatures could slowly increase as deposition didn't take place. Afterwards the high amounts of faeces were transformed to glauconite grains.

Wells that contain open lagoon deposits in their described cores are: F17_04, L02_04, L03_01, M01_01 and limited in the cores of L06_02 and L03_03.

### 4.2.4 *Barrier system*

In the coastal system, barriers can be present to protect the coastline. These barrier islands lie in front of the coast and contain high energy deposits, as they are directly affected by the effect of waves. When the barrier islands are close to each other, the tidal inlets between the islands become smaller. As a result circulation diminishes in the lagoon behind it and so becomes more restricted. With more space between the barriers, a more open lagoon environment will likely arise. The location of the barrier islands and tidal inlets in this system varies quite often, which can also be seen in the well logs.

In the cores the barrier system environment is characterized by light brown medium grained laminated and crossbedded sandstones. Horizontal lamination is typical for the foreshore or beach line (fig. 3); whereas low to high angle laminated sands are interpreted to tidal gullies. In the horizontal laminated sands shell lags are often present. Fine grained sandstones are frequently bioturbated and are related to the upper

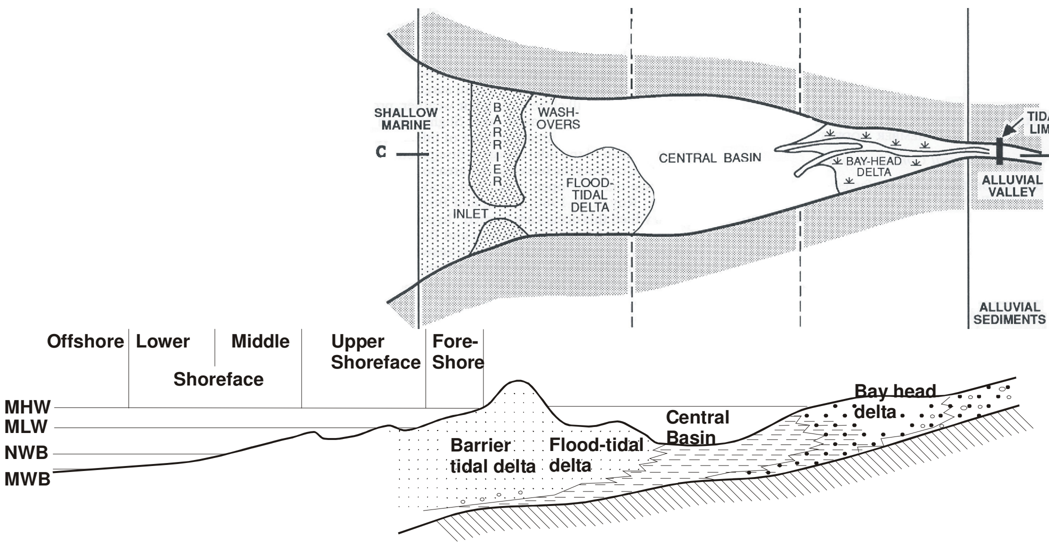



Figure 3: Idealized map and cross-section through the shoreface and adjacent barrier environments (modified after Werver, 1996 and Dalrymple, 1992). MHW: Mean high water, MLW: Mean low water, NWB: Normal wave base, MWB: Minimum wave base.

shoreface. Typical burrows are those of Ophiomorpha. Pyrite concretions and cementation can also be found, though they're not necessary argument for this environment. Nearness to the continent is again supported by the rare presence of organic material. As mentioned before, this environment can migrate laterally relatively quickly. At the base of the barrier sandstones in the core of L06_02, a few metres of siltstones can be found that represent open lagoon conditions. These siltstones are situated in between barrier sandstones. The variation of the barriers can also be found in the alternation of open and restricted lagoon deposits, as can be seen in the cores of well F17_04.

Wells that contain barrier deposits in their described cores are: L06_02 and core 2 of L06_03.

#### *4.2.5 Shallow marine*

The shallow marine depositional environment is specified from the upper offshore to the lower shoreface. It is still marginally affected by the wave base, though much less influenced by it in comparison with the barrier system.

In the cores this environment is characterized by very fine bioturbated dark sandstones. The dark colour is partly a result of the abundant presence of glauconite, which is a typical mineral for shallow marine conditions. The presence of the pervasive bioturbation specifies the environment towards the upper offshore and lower shoreface (fig. 3). As the material is heavily bioturbated, individual burrows are barely preserved. Those that have been observed appear to be of the Terebellina and Cylindrichnus ichnofacies.

In L05_07 a difference in bioturbation within the core can be observed. Where the upper part contains burrows on cm-scale, the lower part contains mm-scale burrows. This difference can probably be related to the amount of clay in the lower part. Apparently different ichnofacies depend heavily on grainsize and clay percentage. Wells that contain shallow marine deposits in their described cores are: L05_07 and core 1 of L06_03.

#### *4.2.6 Additional environment*

In the electronic logs it appears that an additional depositional environment is present. In the various logs the different characteristic output is mostly directly overlying the barrier sands. As this interval has not been cored in any of the wells, it has not been observed and described. Biostratigraphic data and lithological logs indicate that this environment is a marginal marine environment. It is predominantly represented by claystones that have been deposited in these marginal marine conditions.

The marginal marine depositional environment can be placed in front of the barrier systems, but is not as distal as the shallow marine deposits. It inhibits very low energy, as it is largely composed of clays. However, deposits range from very light grey sandstones to medium grey siltstones to light and dark claystones.

In this depositional environment a prominent trend is observed. In well L06_02 this environment is interpreted from 2464 to the top of sequence 2. Above the barrier sands the different gamma ray logs show clayey/silty sediments, which slowly become coarser. At a certain point in time this process is reversed and the material becomes finer again. This turning point is situated at 2415 m. It can also be seen in other wells:

Well L03_02 - 2725 m
Well L03_04 - 2620 m

| | | |
|---|---|---|
| Well M01_01 | - | 2212 m |
| Well M01_02 | - | 2980 m |
| Well L02_04 | - | 2078 m |
| Well G16_04 | - | 3340 m |

This turning point can likely be explained by the ending of a minor regression in the Upper Jurassic supercycle transgression. As the value decreases towards the turning point it is assumed that coarser sediments were deposited, thereby suggesting that regression took place. The increasing value of the gamma ray log above the turning point indicates that transgression took over again. Further evidence for this hypothesis cannot be given in this study.

# 5 Correlation panels

## 5.1 Correlation panels

Four correlation sections have been drawn on basis of the locations of the wells that contained described core intervals and those that supported biostratigraphic data (fig. 4). Interpreting was done per well, using the information from the cored intervals as the basis for extrapolation.[1]

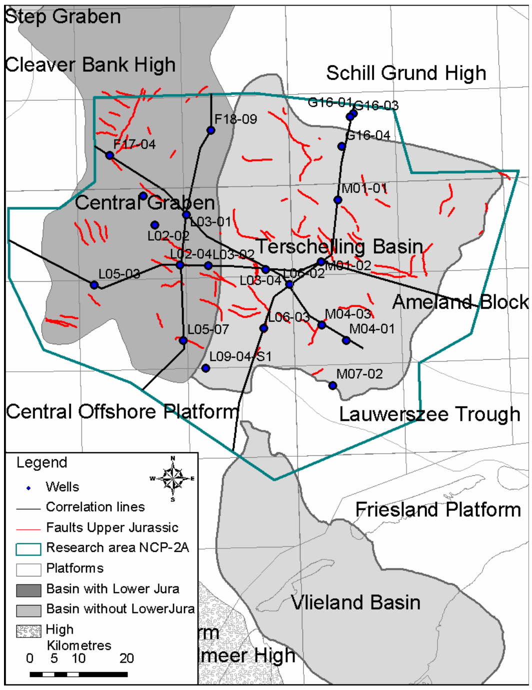



Figure 4: Overview of the the study area. The correlation sections are represented by the black lines.

In the correlation panels the different wells are positioned next to each other, according to the chosen section lines. In each well 4 different logs are placed, if they were available: gamma ray, sonic, density and neutron logs. Subsequently the different depositional environments interpreted from the cores are posted on the position of the cored interval and then extrapolated to the rest of the sequence 2 interval penetrated in the well. The boundaries of the different sequences are also placed in the correlation panels. These are based on biostratigraphic data. Seismic sections parallel to the correlation lines were used to check the well correlations.

Extrapolation and interpretation of the depositional environments in the different wells lead to the following mean values of the electrologs:

Shallow marine: typical in core 1 of L06_03, L05_07.
- Gamma ray: 30-60 (API) — Sonic: 70-100 (µs/ft)
- Density: 2,20-2,70 (g/cm$^3$) — Neutron: -

Marginal marine: typical at the tops of L06_03, M01_01 and L02_04.
- Gamma ray: 70-120 (API) — Sonic: 70-105 (µs/ft)
- Density: 2,35-2,6 (g/cm$^3$) — Neutron: 0,17-0,32

Remarks: The logs appear relatively calm.

Barrier: typical in core 2 of L06_03, L06_02.
- Gamma ray: 15-45 (API) — Sonic: 60-100 (µs/ft)
- Density: 2,05-2,65 (g/cm$^3$) — Neutron: 0,07-0,36

Open lagoon: typical in first core of M01_01.
- Gamma ray: 35-110 (API) — Sonic: 65-110 (µs/ft)
- Density: 2,40-2,65 (g/cm$^3$) — Neutron: 0,18-0,36

[1] See Appendix I for complete correlation panels.

Restricted lagoon: typical in L06_02 and the lower cores of M01_01.

| | | |
|---|---|---|
| Gamma ray: | 60-140 (API) | Sonic: 75-110 (µs/ft) |
| Density: | 2,20-2,65 (g/cm$^3$) | Neutron: 0,20-0,42 |

Remarks: In the logs the environment has a typical spiky appearance.

Lower delta plain: typical in cores 3 & 4 of L06_03, L05_03, F18_09 and L02_04.

| | | |
|---|---|---|
| Gamma ray: | 15-120 (API) | Sonic: 70-110 (µs/ft) |
| Density: | 2,10-2,65 (g/cm$^3$) | Neutron: 0,20-0,44 |

Remarks: Though the delta plain can have the same appearance as the restricted lagoon, it is a bit calmer. Furthermore the values of the gamma ray output normally have a higher range, as the deposits also possess sandy and conglomeratic intervals. Fact remains that these two environments can be very difficult to distinguish.

At F18_09 the base of the shallow marine interval shows a different log output. This interval should not be interpreted as a specific interval, as it is likely to be an error in the output as the result of changing equipment during the actual drilling activities.

L03_01 has a specific sandy interval. In the electronic logs peaks of low value in the gamma ray log are present. Low values commonly represent sand in the sequence 2 sediments. However, these peaks are not as coherent as the normal barrier sands do. An open lagoon system is also not very convincing as the logs look far too sandy. Furthermore the studied core doesn’t offer other convincing evidence, as the visible structures can be illustrated as barrier deposits as well as open lagoon deposits. It is likely that the well was located on the boundary between a barrier system and an open lagoon environment, so that the deposited sediments alternated between these two environments

## 5.2 Correlation panels vs. seismic sections

### *5.2.1 Introduction*

The seismic sections lie parallel to the correlation lines. In the seismic sections the base of sequence 1 and 3 are interpreted. As the base of sequence 2 is very difficult to observe, it has only been interpreted were it can clearly be distinguished. The different stratigraphic data from the correlation panels is than transferred to the intervals of the specific wells. The seismic sections have two important goals. The first one is to observe whether the depositional environments in the different wells can be correlated between the different wells. The second goal is to study the stratigraphic architecture in the basin, like onlap, offlap or wedge geometry.[1]

### *5.2.2 Seismic character of the deposits*

The seismic character alters within sequence 2 (fig. 5).[2] At the base clear continuous seismic reflectors are present, whereas the reflectors of the above lying layers are not very clear and discontinuous. The layers at the top have moderately clear reflectors. These three seismic facies appear to correlate with respectively lower delta plain and restricted lagoon deposits, barrier and open lagoon deposits and marine deposits. The

[1, 2] See appendix D for detailed seismic images of the seismic sections. Appendix J contains the original seismic sections.

barrier deposits are not always very clear in the seismic image. This is likely a result of the smaller thickness of this facies, which almost falls below the seismic resolution at some locations.

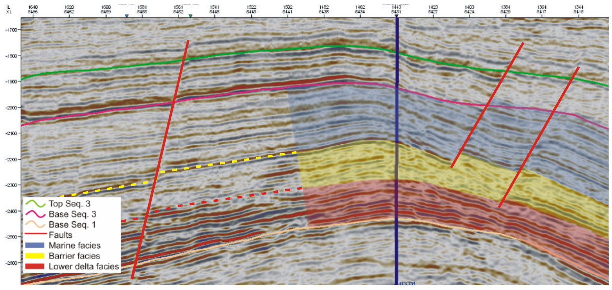



Figure 5: Three different seismic facies can clearly be distinguished.

The seismic facies of the lower delta plain deposits lies parallel to the base of the sequence. At a few locations onlap is visible, with a few exceptions: Between well L03_04 and M01_02 and between well M01_01 and M01_02. The onlap suggests that the topography was slightly higher here. Apart from the parallel characteristic, the delta plain deposits also slowly thin towards the edges of the basin. Taking these two observations into account, it appears that the study area was tectonically stable. However, internal onlap within sequence 2 is also visible in the seismic sections (appendix B, fig. B2). The uppermost lower delta plain seismic facies and the superposed barrier and marine seismic facies show onlap on the lower delta plain sediments. Two explanations for this onlap are possible. The first explanation involves a tectonic phase that occurred at the final deposition of the delta plain sediments. The onlap can also be explained by progradation of the sediments as a consequence of transgression. The onlap surface should then be a maximum flooding surface. However, in that case the upper layers should reveal progradation and aggradation. In figure 6[1] the normal geometry of these two processes are visualized in two diagrams. The seismic image near well F18_09 shows a high similarity to the second hypothesis. Further active tectonism is discussed in the next paragraph.

The seismic sections clearly show that several wells have been truncated at the top. All truncated wells are located in the southern Dutch Central Graben. In some cases, like well L02_03, only a minor part of sequence 2 has been eroded. In well L02_02 a large amount of sediment has been eroded and in well F17_04 even all sediments of sequence 2 were eroded. The wells that appear to have been truncated are mostly positioned near locations of salt domes. South of well L06_03 the layers of sequence 2 are lightly truncated towards the basins edge, though not necessarily as a result of halokinesis.

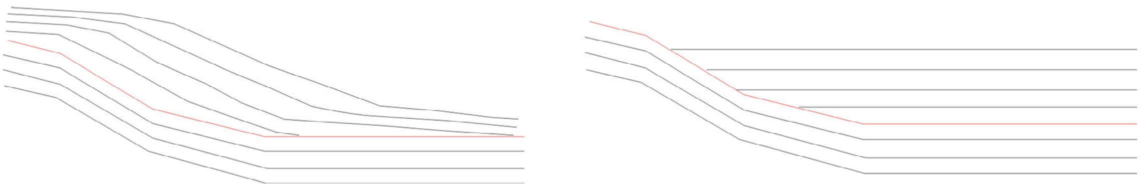
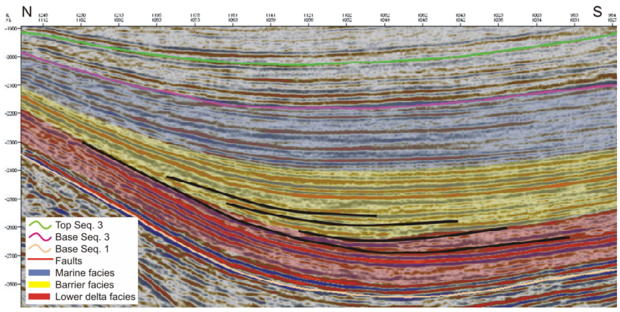


Figure 6. Left: a prograding and aggrading delta, with a maximum flooding surface. Right: Sedimentation after a tectonic event. Lower right: seismic image just south of well F18_09 (see figure B2, appendix B for an enlargement).




[1] See appendix D for detailed seismic images of the seismic sections. Appendix J contains the original seismic sections.

In the eastern N-S profile, the thickness of the deposits increases gradually towards the south of the Terschelling basin, where it abruptly thins out. A similar observation can be made in the western N-S profile. The thickness increases from well F18_09 towards well L03_01, with the thickest deposits just south of well F18_09. Between well L03_01 and well L02_04 the thickness decreases again, especially in the marine and barrier facies. Just south of well L02_04 the thickness quickly thins at a fault. This trend inclines to conclude that the faults on the southern side of the basin were active during sequence 2. This can be seen in figure B4 (appendix B). As the fault was active, accommodation space was created. However, this didn't lead to a swift existence of a shallow sea, as can be seen in the sediments. Instead a thick interval of stacked barrier sands and lagoonal sands can be seen (well L03_01, appendix H). This may lead to the conclusion that a lower delta plain was present in this area, which could deliver enough sediment to compensate the development of accommodation space.

### 5.2.3 *Active salt movement*

Active salt movement during sequence 2 can be deduced from the NW-SE profile. It shows rapid synsedimentary thinning from well L03_01 towards the northwest, from approximately 800 to 300 meters. This is the result of the salt dome near well F17_04. To the west of well L03_04 the salt dome also appears to have been active during sequence 2 in the late Jurassic.

In the eastern N-S-profile active salt doming was present near wells L06_02 and L06_03. The sediments in well L06_03 likely have directly been affected by the salt doming, as the well is located just south of the main salt structure. This could explain the thick barrier deposits in this well. If the area was pressed upwards by halokinesis and the resulting rising topography could keep up with the transgressive sea level, thicker barrier deposits could be the result. However, this is considerable speculative. A second explanation would be that the salt doming created a topographic ramp, against which the sea level collided. The transgression was then temporarily halted and the sea stopped moving landinwards. Locking the depositional environment distribution this way, the different environments could keep stacking, providing that accommodation space kept equal to sediment supply. The seismic image doesn't offer any additional help for these explanations, as the area at well L06_03 is very distorted and faulted (see figure B8, appendix B). The western N-S profile shows synsedimentary halokinesis at well F18_09, during deposition of the open lagoon sediments. The seismic image is not clear in the south, as the seismic profile is positioned parallel to a large fault system in the south.

In the W-E profile, the greatest thickness of sequence 2 is located near L03_04. In this profile salt structures don't appear to have influenced sedimentation processes in sequence 2, though salt movement does have been active during sequence 1.

### 5.2.4 *Conclusions of the seismic sections*

Several conclusions can be drawn from the four seismic sections:

I. Most wells can be correlated with each other
II. Three seismic facies can be distinguished.
III. Many salt structures have not been active during sequence 2, with the exception of the following ones:
  - Salt between wells L06_02 and L06_03
  - Salt beneath well F17_04
  - Salt northwest of well L03_04

- Salt beneath well F18_09

IV. Sequence 2 becomes thinner from the centre to the sides of the basin and pinches out at the edges of the basins. In the southwest of the study area, erosion causes thinning as well.

V. The latest deposited delta plain sediments, the barrier and open lagoon deposits show onlap on the basal delta plain sediments.

### 5.2.5 *Thickness map*

Two different maps are generated for the whole sequence: 1) Thickness map; representing the thickness of sequence 2 in the basins, 2) Pie-charts; showing the percentages of the different depositional environments per well. The thickness map indirectly also shows the outline of sequence 2 and thereby presents the position where deposits of sequence 2 can be found. The pie-chart map is discussed in chapter 6.

Firstly it must be noted that the thickness map is a combination of the thickness of sequence 1 and sequence 2. This is the consequence of the difficulty to distinguish the sequence boundary between these sequences in the seismic profiles. This doesn't cause a problem in the Terschelling basin itself, as sequence 1 was not deposited here.

The map shows a distinct deposition centre in the middle of the study area. The axis of this deposition area is aligned in a NW-SE direction, though it deviates slightly towards the east at its south-eastern segment. It appears that the larger part of the Terschelling basin in the northeast has been very flat, as the thickness contours lie far apart from each other. The deposition centre in the middle of the study area has a high gradient of the thickness contours at its southern and south-western edge. Apparently some kind of steep topography like cliffs was present here, halting the transgression further southwards during sequence 2.

The small circular deposition centres in the south and southwest are likely the result of salt depletion areas. Salt movements during sequence 2 caused the topography to drop and thereby created accommodation space. It's possible that the blank spaces in the map were locations where salt surfaced the topography, as no deposition could occur here. Though some indications of this fact are visible in the seismic sections, it is very difficult to verify this with the available data. Note however that not all blank spaces in the thickness map have to be the result of salt surfacing. Some areas have simply been eroded and consequently no deposits of sequence 1 and 2 are present anymore.[1]

As the south-western area contains only delta plain remains and the sediments in well L05_07 only contain marine sediments, these two areas are probably separated from each other. The western N-S profile shows that the location between these areas is very faulted. The thickness map also shows that no sequence 2 deposits have been found here. These arguments support that a fault(zone) was active just west of well L05_07 which strikes NNE-SSW.

In the seismic images it becomes clear that the fault just south of the deposition centre was active during sequence 2. This fault strikes WNW-ESE and is cut off by salt structures in the west and east at respectively wells L02_02 and L06_03. At well L02_02 the fault seems to be redirected to a more northern position.

[1] See Appendix D for thickness map.

# 6 Model

## 6.1 Global maps

With the available data it is possible to obtain 2 kinds of maps. Firstly pie-charts are presented. In these maps pie-tables are presented: they represent the percentages of the different depositional environments per well. This chart was used to gain a further understanding how the different depositional environments are distributed in the study area. Subsequently the paleogeographic interpretations of the study area are given.
To illustrate the evolution of the paleogeography in the basin during sequence 2, three maps have been created. They represent the initial situation, a stage in the middle of sequence 2 and the paleogeographic situation at the end of sequence 2.

### *6.1.1 Pie-chart*

The pie-chart is composed of the percentages of the different depositional environments in the wells that have been interpreted in the four correlation panels. Wells which do not contain deposits of sequence 2 are also included in the map as blank pie-tables. Beneath the wells the thickness map has been added. [1] Several things can be observed from the map.

1) The restricted lagoon environment is only present in the Terschelling basin, with the exception of well F18_09.
2) The marginal marine environment is mainly located in the centre of the Terschelling basin, whereas shallow marine deposits are mostly situated on the northern side of the study area.
3) In the southwest the pie-tables only contain 1 depositional environment. As the deposits of sequence 2 are very thin in this area, little data is present. Consequently only one depositional environment is interpreted in these sediments.
4) The southern wells in the Terschelling basin show that marine sediments have had little influence in this area. However, apart from well L05_07 these wells contain considerable amounts of marine sediments. The fact that the marine depositional environment didn't have as much influence here can be explained by low accommodation space relative to a large sediment supply. Evidently a river estuary has been located here, providing the sediments.

It is important that the pie-chart is related to the thickness map, since the different pie-tables represent the different depositional environments in percentages of the whole sequence 2 in the wells. Therefore the tables present a ratio, and the observer could obtain a distorted view and reach inaccurate conclusions. A good example can be seen in the wells in the southwest, where only 1 depositional environment is present in the well. However, the wells show that a very small amount of sediments of sequence 2 is present here.

### *6.1.2 Timeframes*

In sequence 2 three time frames have been chosen to present the evolution of the Terschelling basin in the Upper Jurassic. The first time frame (map A) shows the initial situation of the Terschelling basin at the beginning of sequence 2. It is based on the

[1] See Appendix E for pie-chart.

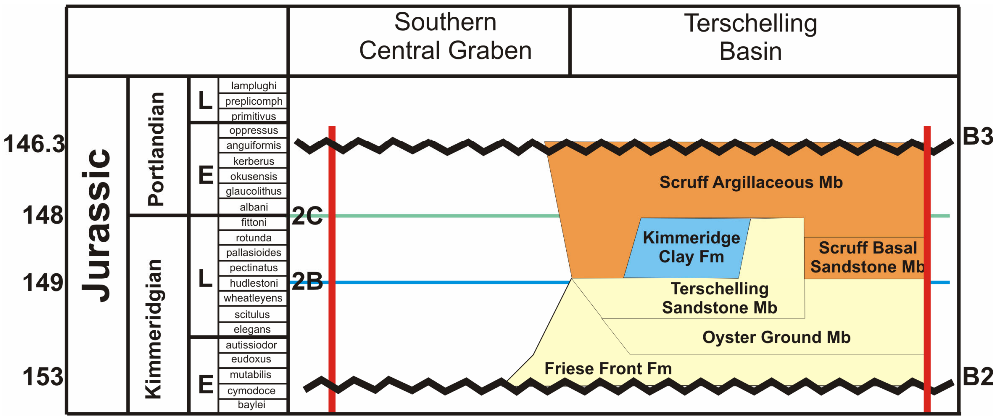



Figure 7. Schematic diagram of sequence 2. On the left the different ages of the boundaries (B2 and B3) and the timeframes (2B and 2C) are given (Modified after Abbink et al., 2006). The different epochs and ammonite zones are subdivided according to the British Boreal classification (See Gradstein et al., 2004).

boundary between sequence 1 and 2, which is biostratigraphically dated at approximately 153 Ma. The second time frame (map B) is placed in the middle of the sequence, representing the paleogeographic situation halfway through sequence 2. It is biostratigraphically dated at approximately 149 Ma and is based on a maximum flooding event (J66a). The final time frame (map C) presents the ending stage of sequence 2. It is based on the turning point of a regressional phase towards a transgressional one, which is biostratigraphically dated at the beginning of the Portlandian (148 Ma). Note that still some time remains in sequence 2, until sequence 3 commences. See figure 7 for a schematic diagram of sequence 2, including the position of the timelines. See the correlation panels for the position of the different timeframes in the wells.

### 6.1.2.1 *Map A: Initial situation*

The map shows a consistent view of continental delta plain deposits (Fig. 8). To add more information to the map, the percentage of sand in the delta plain deposits per well has been added in the figure. The sand percentage has been calculated by taking the mean value of the minimum and maximum of the gamma ray log per well. Absolute numbers could not be taken, as the gamma ray measurements are relative values in a well. Using this method a net-to-gross sand-clay distribution can be made. When more sand is present, it is assumed that the location was closer to the river itself. A general contour line has also been incorporated in the figure. It represents the areas with a higher sand percentage. The higher sand percentages are located in the west, the north-east and the south. Apparently the sediment influx doesn't originate from one specific

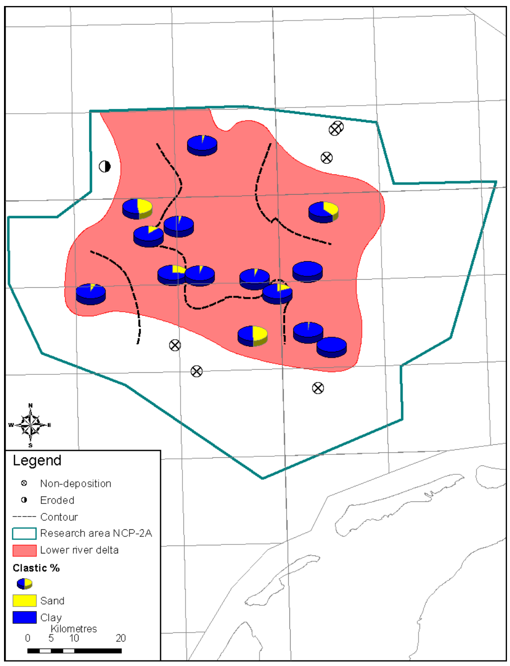



Figure 8: Map A, initial situation of sequence 2.

direction, but enters the basin from different sides: the south, the west and the northeast. Wells in the north, the south-east and the south-west show very small sand percentages. Faults aren't shown in Map A, as the seismic sections showed that faults became active after deposition of the delta plain sediments. [1]

At well G16_04 the delta plain sediments are cut off by erosion. It is difficult to say whether these sediments were ever present at all, though it appears that the boundary between deposition and non-deposition should be very near the current interpreted line.

Well L05_07 only contains marine deposits that are dated at the end of sequence 2. Apparently, non-deposition occurred in this initial stage. These deposits should show onlap in the seismic sections. However, as the sediments are relatively thin, it cannot be proven nor be denied by the seismic images.

### *6.1.2.2 Map B: Situation in sequence 2*

At this stage marine conditions had entered in the study area, as can be seen in figure 9. The coastal area typically encompasses lagoonal environments. Only in the west a lower delta plain is located behind the barriers. More to the southwest it is not very clear how the exact environment looked like. Deposits of sequence 2 are still present, but are limited to ten's of metres. As a result other data of this area is also very limited. In the seismic profiles the thin layers also become eroded locally. It appears that during this period a small delta plain area was present which, in some places endured subaerial conditions.

At the northern side of the study area it is also not quite clear what happens. The restricted lagoonal conditions are backed up by well data. Whether this environment continues towards the east is hard to say, though it is likely that lagoons were present. Biostratigraphical data also supports this hypothesis as the marginal marine deposits should be placed just in front of the barrier deposits, thus implying that the sea depth is very shallow.[1]

Well L02_03 displays the remains of a lower delta plain. It must be noted that the

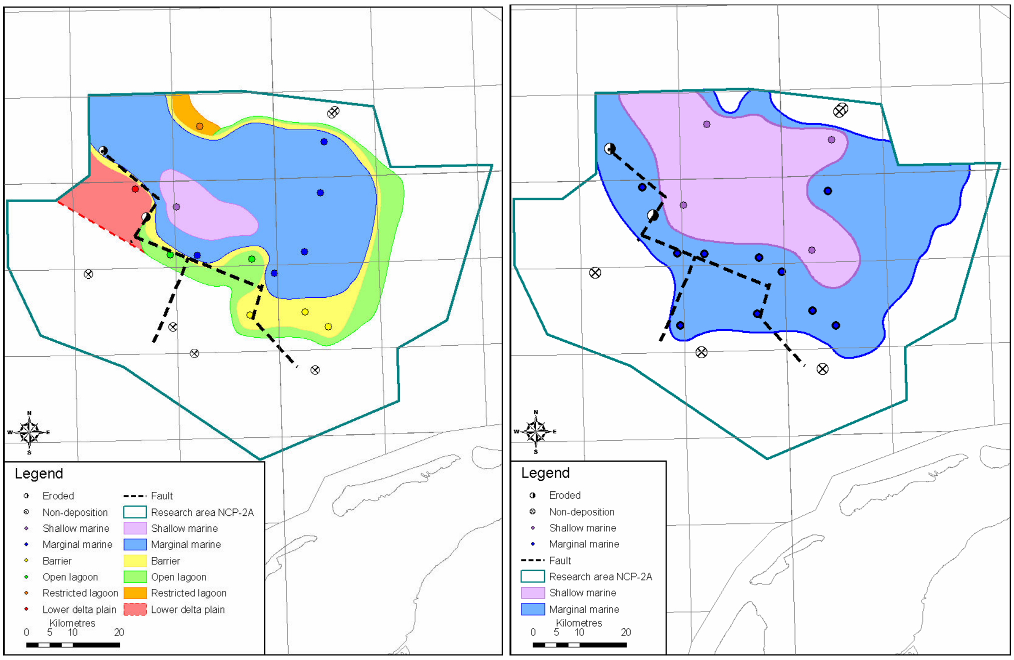



Figure 9. Left: Map B, situation in the middle of sequence 2. Right: Map C, final stage of sequence 2.

[1] See appendix F for an enlargement of Map A

seismic image shows a lot of faults at this location and some of them appear to cross the well. This could result in some hiatuses in the rock record of the well.

#### 6.1.2.3 *Map C: Final stage*

Figure 9 shows that almost the whole study area has been flooded by the rising sea level, except in the southwest where marine sediments are not present. The area was likely exposed to aerial conditions, though hard evidence is not available.

Though well L05_07 contains marine sediments, they are approximately dated at the last 100.000 years of sequence 2. As the timing at which this timeframe was chosen is older, this area was probably exposed to aerial conditions. However, in this figure the marine conditions of this well were added, to give a better impression of the situation of the study area during this period.

The boundaries of the marginal marine environment aren't positioned at the outmost edges of the basin. The reason is that the end of sequence 2 has not yet been reached. As already mentioned before, the thickness contours of the Terschelling basin lie relatively far from each other. This can only mean that the basin must have been relatively flat. Small differences in the sea level will therefore affect large areas in the Terschelling basin. After the timing of this time frame the sea level will likely slowly rise in the basin until the whole basin is flooded at the end of sequence 2, with the exception of the south-western region.

Evidence of large lagoonal areas during this period is absent. This is probably the result of the risen sea level, which rose high enough to drown the barriers. As lagoons are not or barely present the sea borders directly to the beach.[2]

## 6.2 Model and concept

Taken all data into account, the following sequence of events must have occurred:

1) A lower delta plain existed in the Terschelling basin and the southern Central Graben during the intial stages of sequence 2. The study area was tectonically stable and the sediments could slowly fill the topography of the basins.
2) During the final stages of deposition of the delta plain deposits it is likely that tectonism was active in the study area, in which the deposits were affected by salt movement and faulting.
3) Initial marine flooding in the study area. The marine influence protruded from the Central Graben towards the southern Central Graben and the Terschelling basin. The main location of deposition is positioned in the centre of the basins.
4) Marine flooding continues until the study area is almost completely flooded. Exception is the southwestern region in the study area.

The thickness map shows a thickening trend from the north towards the centre of the study area, up to the fault zone. This trend can be explained as a result of tectonic activity. Apparently the fault zone on the south of the Terschelling basin was active during sequence 2, thereby creating accommodation for sediments north of it.

Salt domes are also present in the study area. However, not all salt domes were active during sequence 2 of the upper Jurassic. The best way to check the timing of activation is by studying detailed seismic sections of the study area.

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[1] See appendix G for an enlargement of Map B
[2] See appendix H for enlargement of Map C

# 7 Conclusions

The studied cores and well logs show six different depositional environments in the studied area for sequence 2 of the Upper Jurassic.

1) Lower delta plain
2) Restricted lagoon
3) Open lagoon
4) Barriers
5) Marginal marine
6) Shallow marine

The sequence of events that has been proposed in chapter 6 clearly represents a transgressive sealevel during sequence 2 of the upper Jurassic. In this transgression the different depositional environments that were described in the studied cores, superposed each other. This is demonstrated in the correlation panels. Interfingering is also present and can clearly be seen in well L03_01, where barrier sands are alternated with fine lagoonal sands.

The rising sea level can also be seen on the produced paleogeographic maps. Whereas the initial setting of sequence 2 in map A is mainly continental, the sequence concludes with a general shallow marine setting.

As mentioned in chapter 4, a remarkable trend is visible in the sediments of the marginal marine environment. Apparently a small regression took place at the end of sequence 2. In the marine sediments this regression is stopped at a certain ‘turning’ point, after which transgression took place again. This trend can best be seen in the correlation panels. Hard evidence cannot be given in this study.

Though the seismic sections show that the wells can be correlated to each other, they presented more information. Apparently, tectonism has been active in different ways during sequence 2. This is in disagreement with the general idea that tectonic activity primarily took place at the sequence boundaries. The seismic images appear to show that an active tectonic phase took place at the final stages of deposition of the lower delta plain deposits. Furthermore, salt domes near wells F17_04, L06_03, L03_04 and F18_09 have been active. It also appears that salt surfaced during sequence 2. To draw definitive conclusions it is necessary to do a more detailed seismic study of the study area of sequence 2. This should probably reveal that more domes were active.

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# 9 Appendices

A. Siderite and pyrite formation
B. Seismic images
C. Thickness map
D. Pie-charts
E. Map A : Initial situation
F. Map B : Situation in sequence 2
G. Map C : Final stage

H. Core descriptions

I. Correlation panels

J. Seismic sections

# A Siderite and pyrite formation

The mineral siderite is not a very common mineral, as it is not very stable. For example one of the conditions for siderite formation is the absence of dissolved sulfate. Furthermore, siderite can only remain stable when the concentration of iron is 5 percent greater with respect to calcium. This can be seen in the following reaction:

$$FeCO_{3\ siderite} + Ca_{aq}^{++} \leftrightarrow CaCO_3 + Fe_{aq}^{++}$$

With $K = 0.05 = a_{Fe}^{++} / a_{Ca}^{++}$ (Berner, 1971)

The above mentioned conditions indicate that it is very unlikely for siderite to develop in a marine environment. This can be concluded due to the fact that seawater contains abundant dissolved sulfate. Furthermore the normal ratio of iron to calcium is normally only 0.1 percent in seawater. Therefore it is more logical to find siderite concretions in continental deposits. However, according to Haese et al. (1997) and Ellwood et al. (1988) siderite is closely interlinked with pyrite in environments such as salt marshes, where fluxes of fresh and salt water vary spatially and temporarily. The close relationship of the minerals lies in the fact that both minerals are dependant on the amount of dissolved iron and sulfate. When abundant sulfate is present pyrite is more likely to develop. Sulfate reduction logically dominates in sediments beneath oxygen-depleted coastal waters, providing better conditions for siderite formation.

Taken the studied cores into account, the boundary of fresh and salt water can be found at the estuary of the lower delta plain. Subsequently anaerobic conditions can be found in a restricted lagoonal setting. The relative high amount of siderite in the restricted lagoon deposits is therefore explicable. At the point that low values of sulfate enter the system, siderate formation ceases and conditions for pyrite formation arise.

# B Seismic images

In this section different seismic images are displayed that have been taken out of the seismic sections.[1] The different images show several features that are important for the understanding of the structural elements in the basin. Vertical lines represent wells along the seismic image. The beige line represents the base of sequence 1, the pink line the base of sequence 3 and the green line the base of Cretaceous sediments. These sequence boundary lines are taken from a regional seismic interpretation, which are put over these seismic sections. Therefore it is possible that the lines deviate from their supposed position. Where the regional interpreted lines aren't accurate, they have been reinterpreted. The base of sequence 2 has not been incorporated, as this boundary is very difficult to distinguish in the seismic sections. The contents of the different figures are summarized below:

Figure B1: Truncation near well F17_04.
Figure B2: Internal onlap in sequence 2 near well F18_09.
Figure B3: Internal truncation in sequence 2 near well G16_04.
Figure B4: Halfgraben structure at well L02_04.
Figure B5: The different seismic facies at well L03_01.
Figure B6: Synsedimentary salt doming at well L03_04.
Figure B7: Thin deposits near L05_07.
Figure B8: Disrupted sediments around well L06_03.
Figure B9: Postsedimentary salt doming at well M01_01.

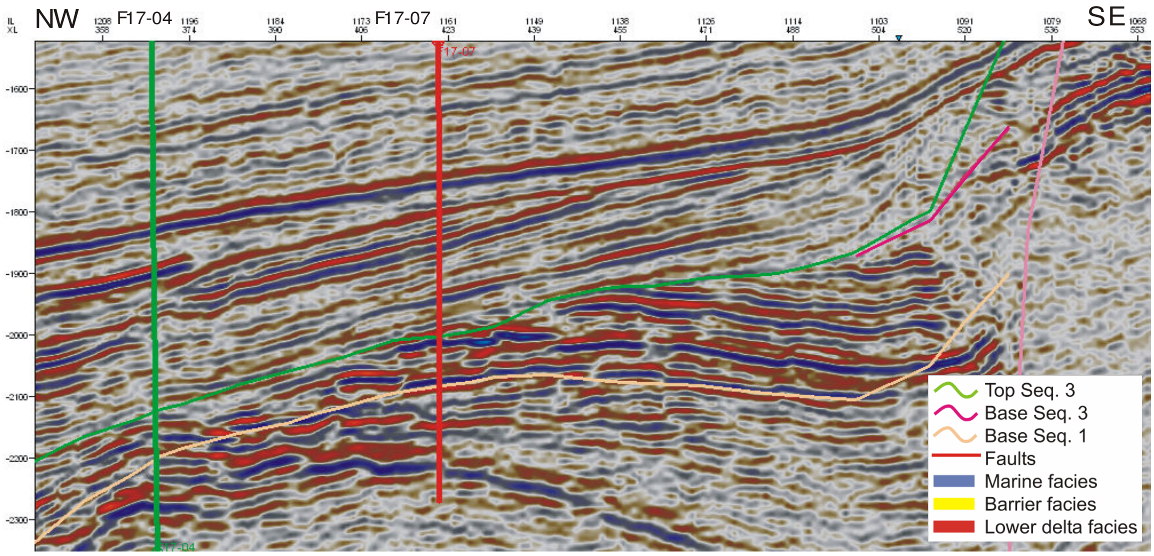



Figure B1: Truncation of sequence 2 at well F17_04, only the base of sequence 1 is still present.

[1] The complete seismic sections can be found in appendix J.

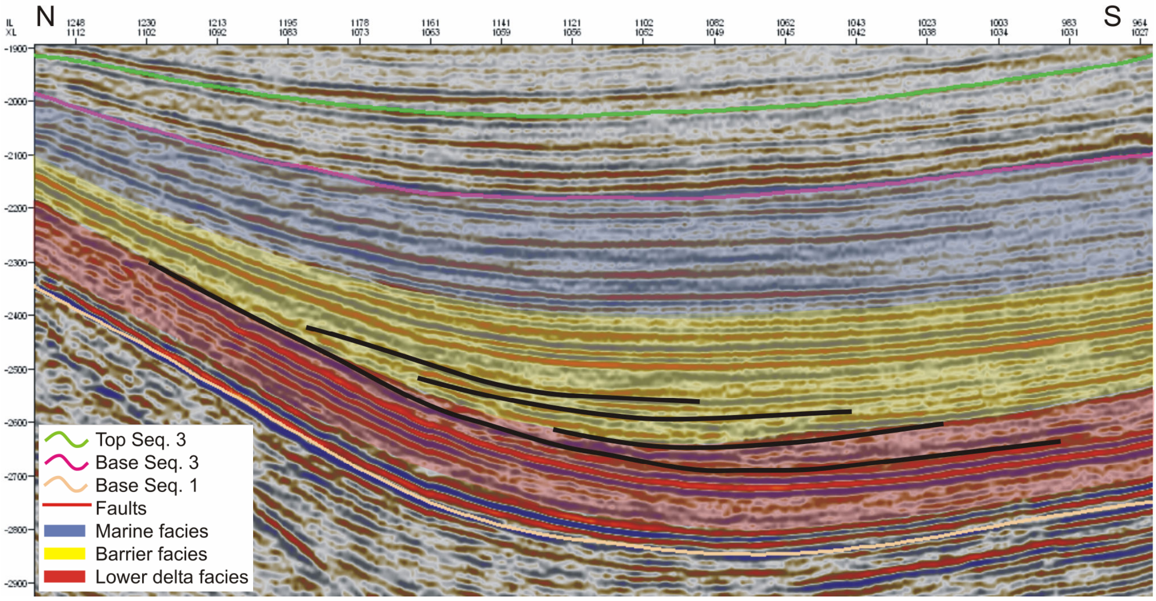



Figure B2: Just south of well F18_09, clear onlap within sequence 2 is visible. Beneath the black lines lower delta plain deposits are present. It can clearly be seen that these layers maintain their overall thickness, except for the most upper part. Apparently tectonic activity began in the ending stage of sedimentation of the lower delta deposits at this location. At the bottom a thin layer of sequence 1 is present.

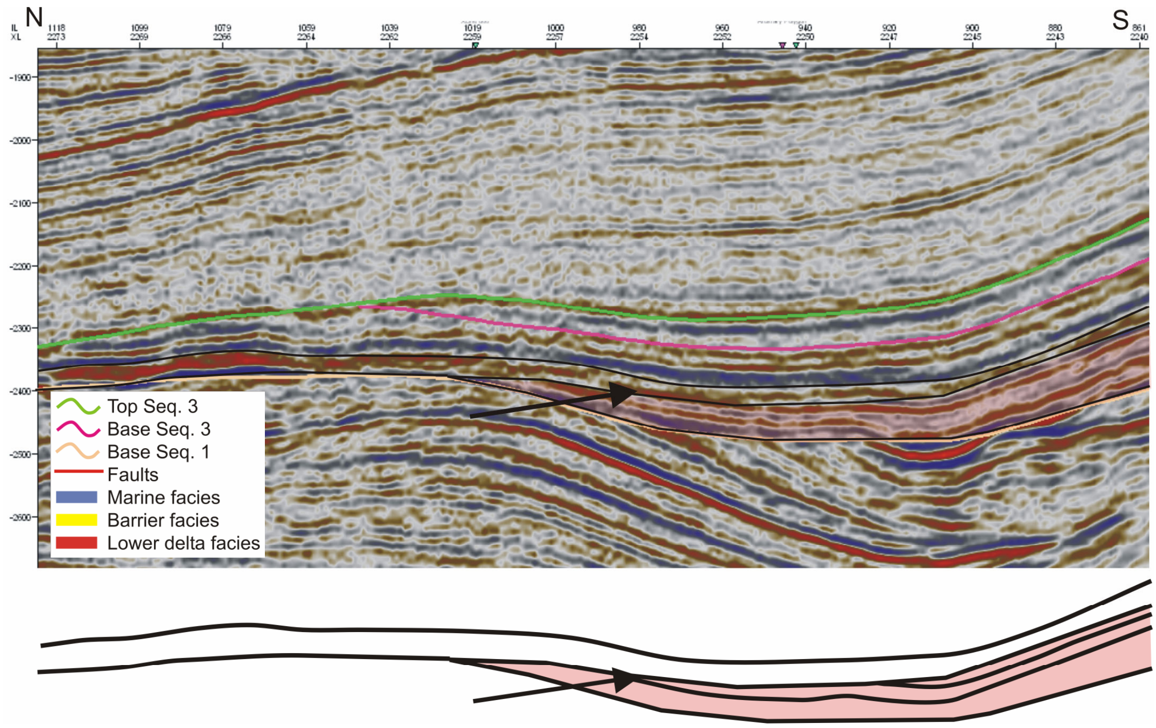



Figure B3: South of well G16_04, the lower delta plain and restricted lagoon deposits are being cut off by later deposits of sequence 2. The schematic diagram clarifies the truncation.

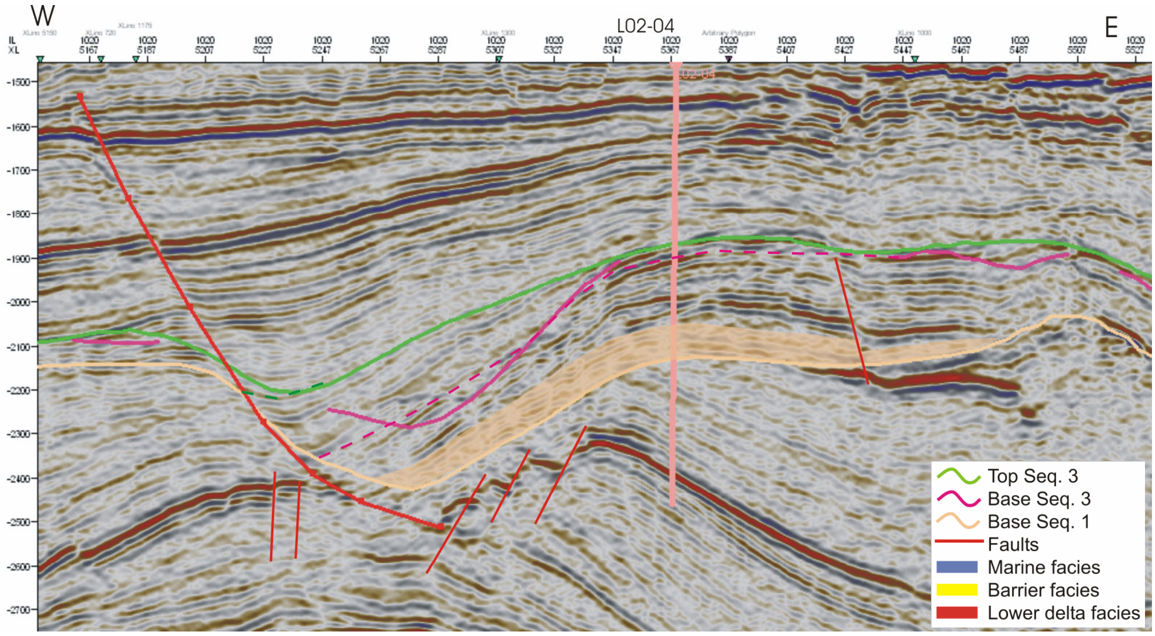



Figure B4: A halfgraben structure visible west of well L02_04. Left of the large fault the upper Jurassic deposits are much thinner, proving that the sediments of sequence 2 and 3 are synsedimentary. The regional interpreted lines aren't very accurate and have been reinterpreted, which is visualized by the dashed lines. The beige interpretation surface represents the deposits of sequence 1.

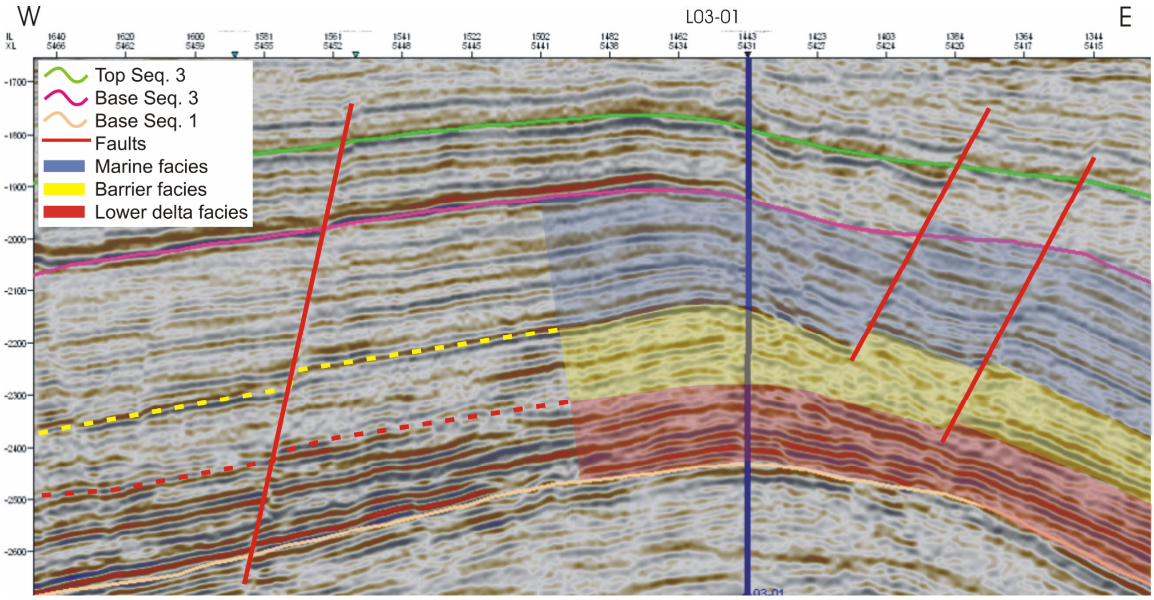



Figure B5: The three different seismic facies can clearly be seen near well L03_01. The different seismic facies contain the lower delta plain and closed lagoon at the base (red), barrier and open lagoon in the middle (yellow) and the marine environments (blue). Especially left of the interpreted intervals the three facies can be clearly distinguished.

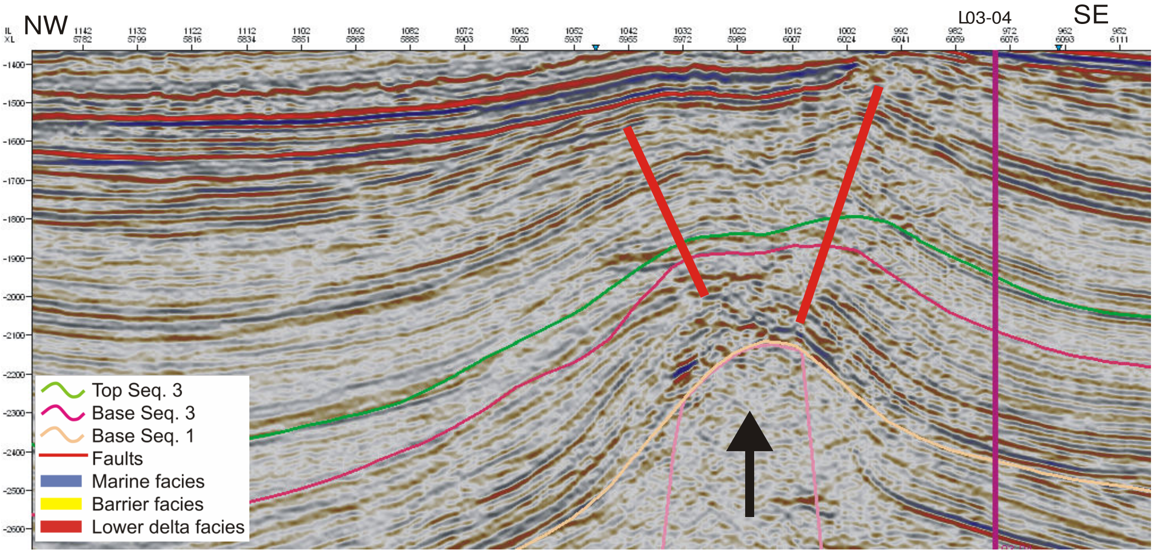



Figure B6: Salt doming northwest of well L03_04. As the thickness of the deposits of sequences 2 and 3 becomes thinner towards the dome, the salt has been active during their deposition.

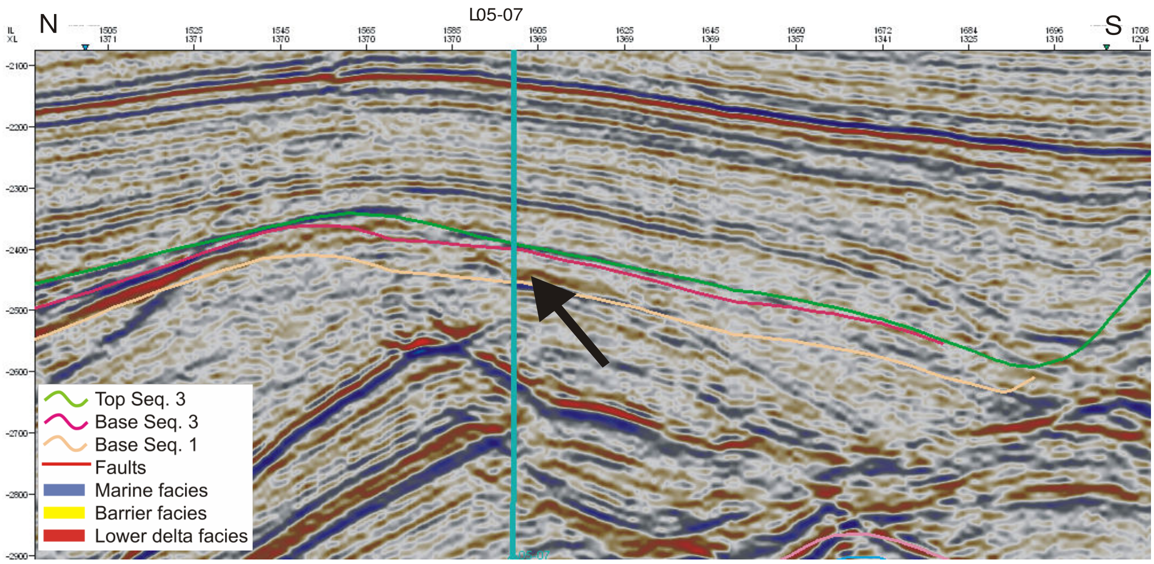



Figure B7: The sediments of sequence 2 are very thin in the southwest of the study area. This is visualized near well L05_07. As a result of the thin deposits, internal seismic reflectors are difficult to distinguish and even more difficult to continue along the image.

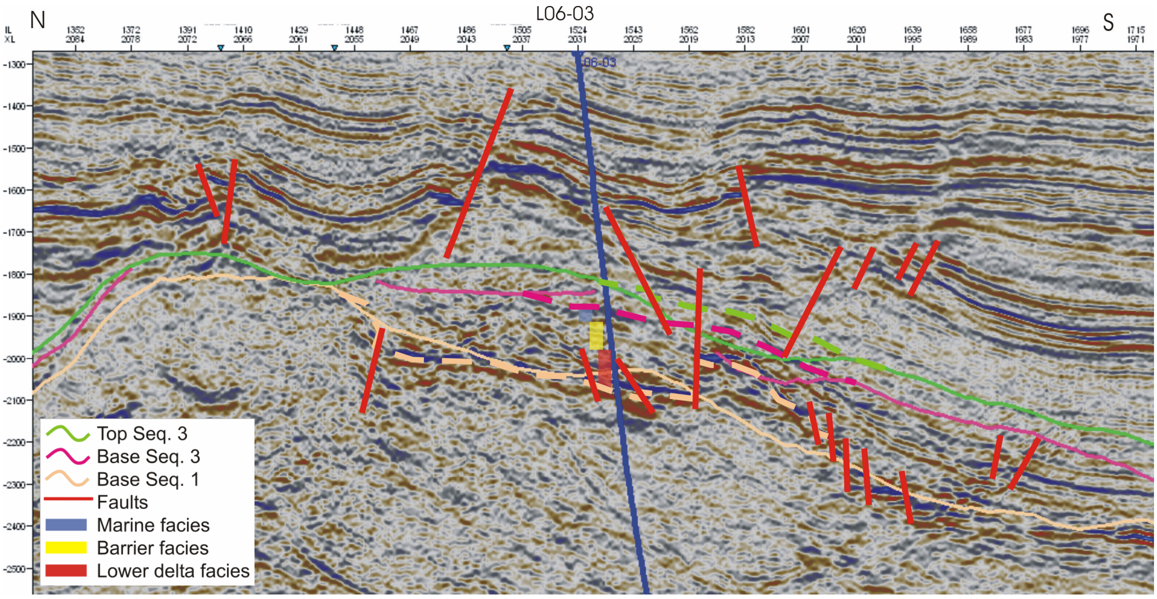



Figure B8: The salt structure beneath well L06_03 obviously distorts the above lying sediments. The sediments are frequently disrupted by faults. Just north of the well the sediments also show an irregular pattern. The regional interpreted sequence boundaries are also not very accurate. In the picture these lines have been re-interpreted, which is visualized by the dashed lines.

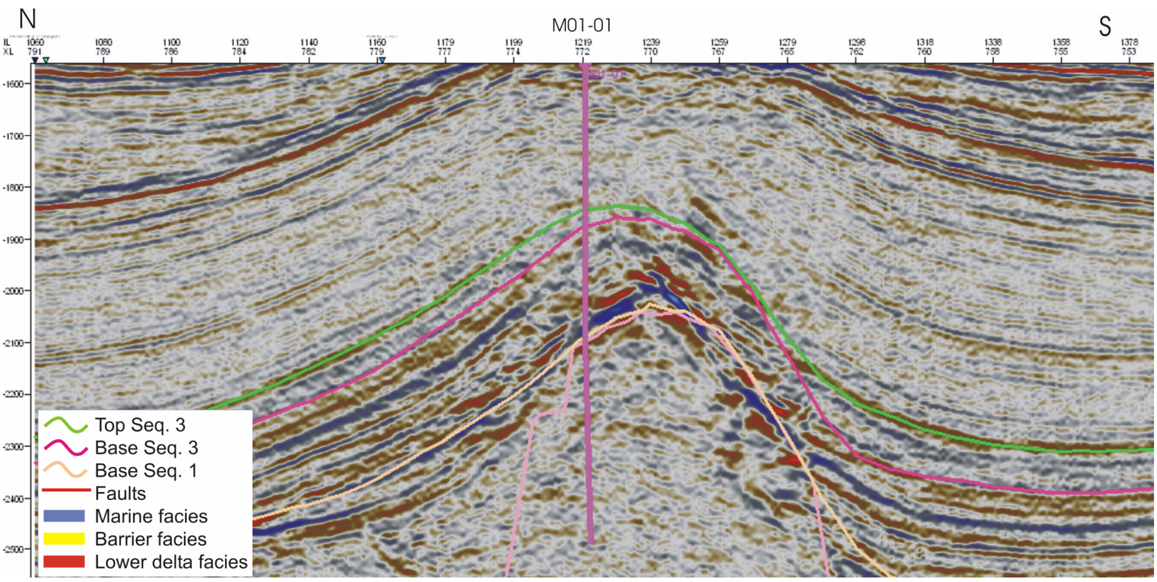
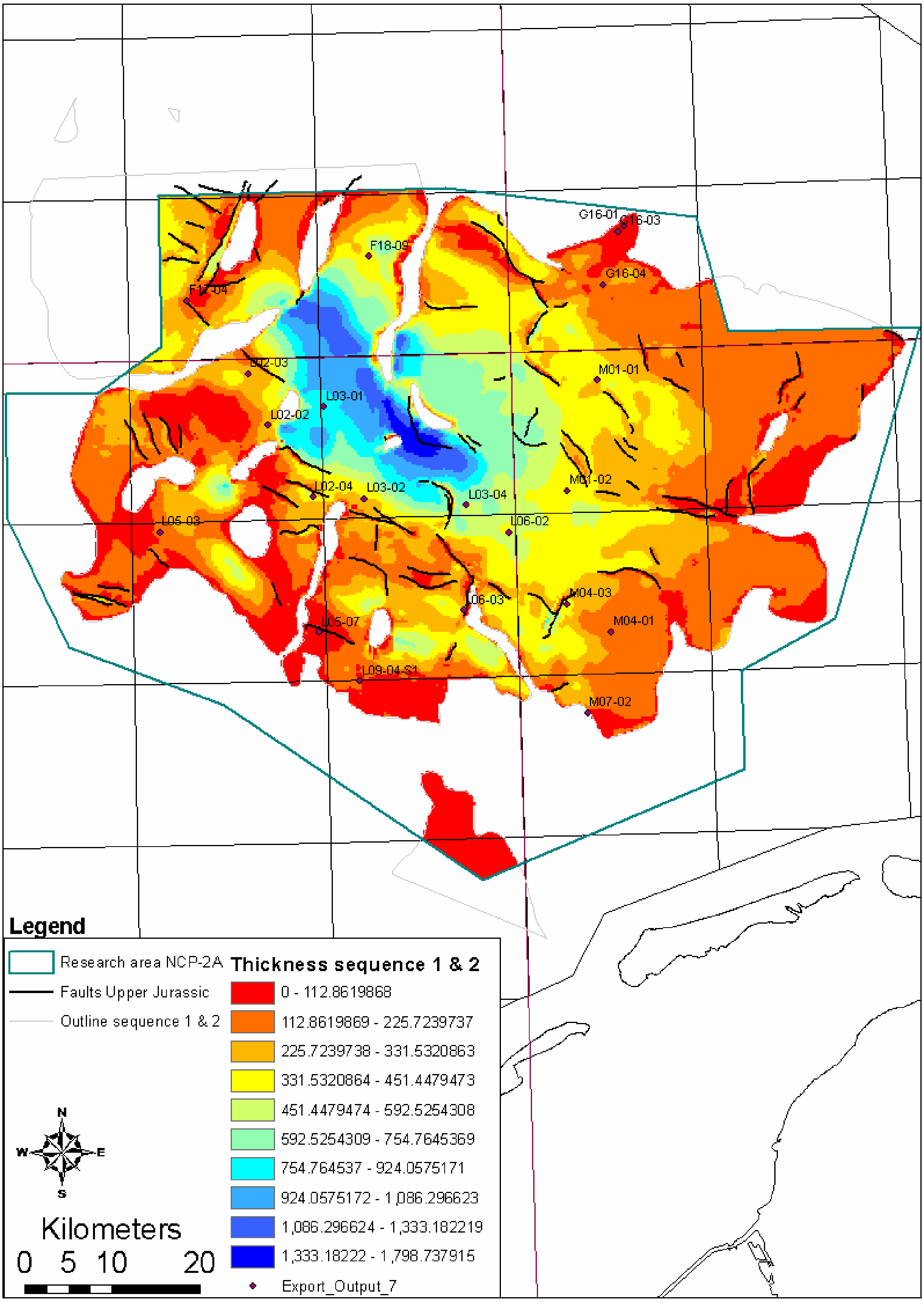
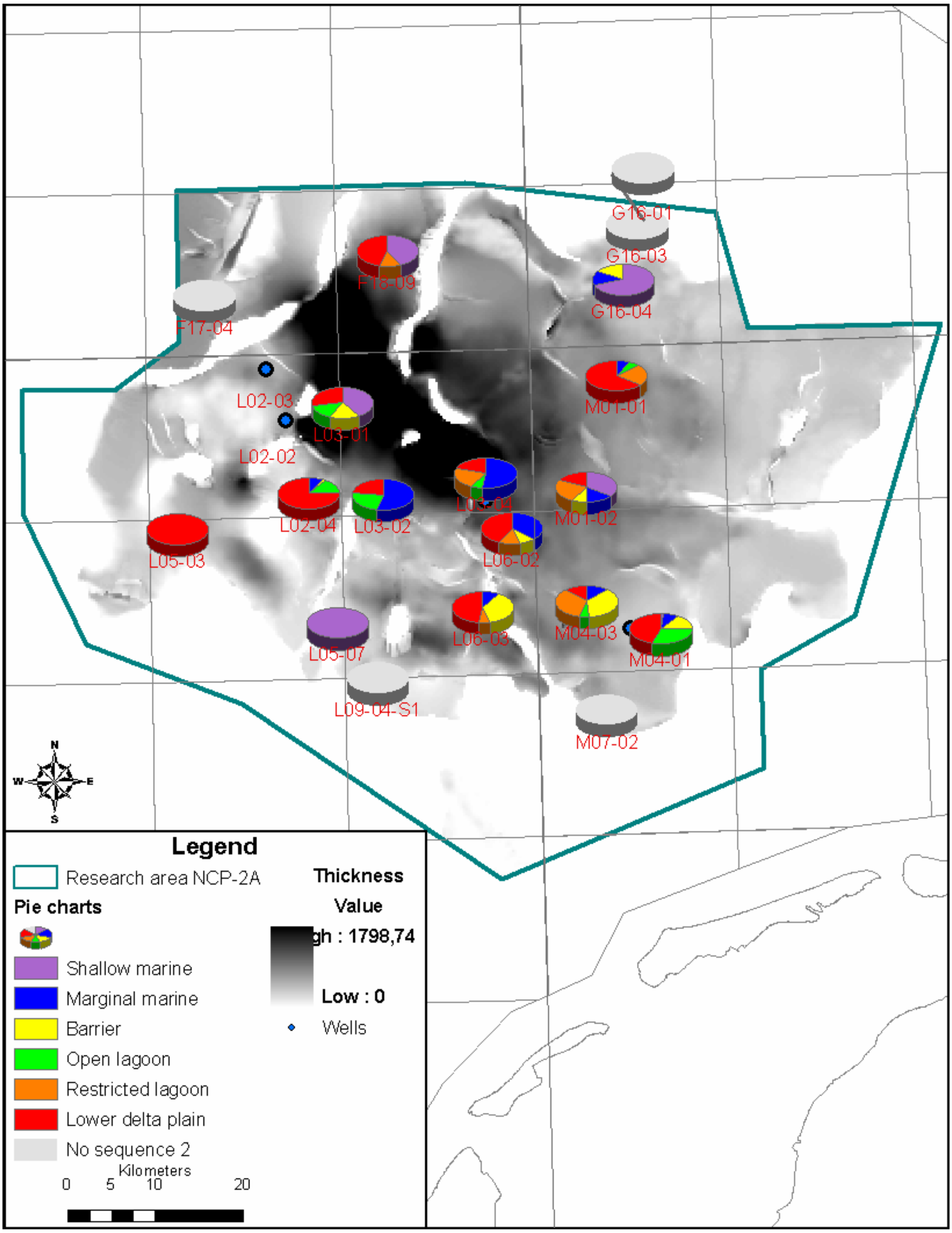



Figure B9: Salt doming took place after deposition of sequence 2 near well M01_01, as the thickness remains practically the same over the salt structure itself. Additionally, onlap is also absent towards the structure.

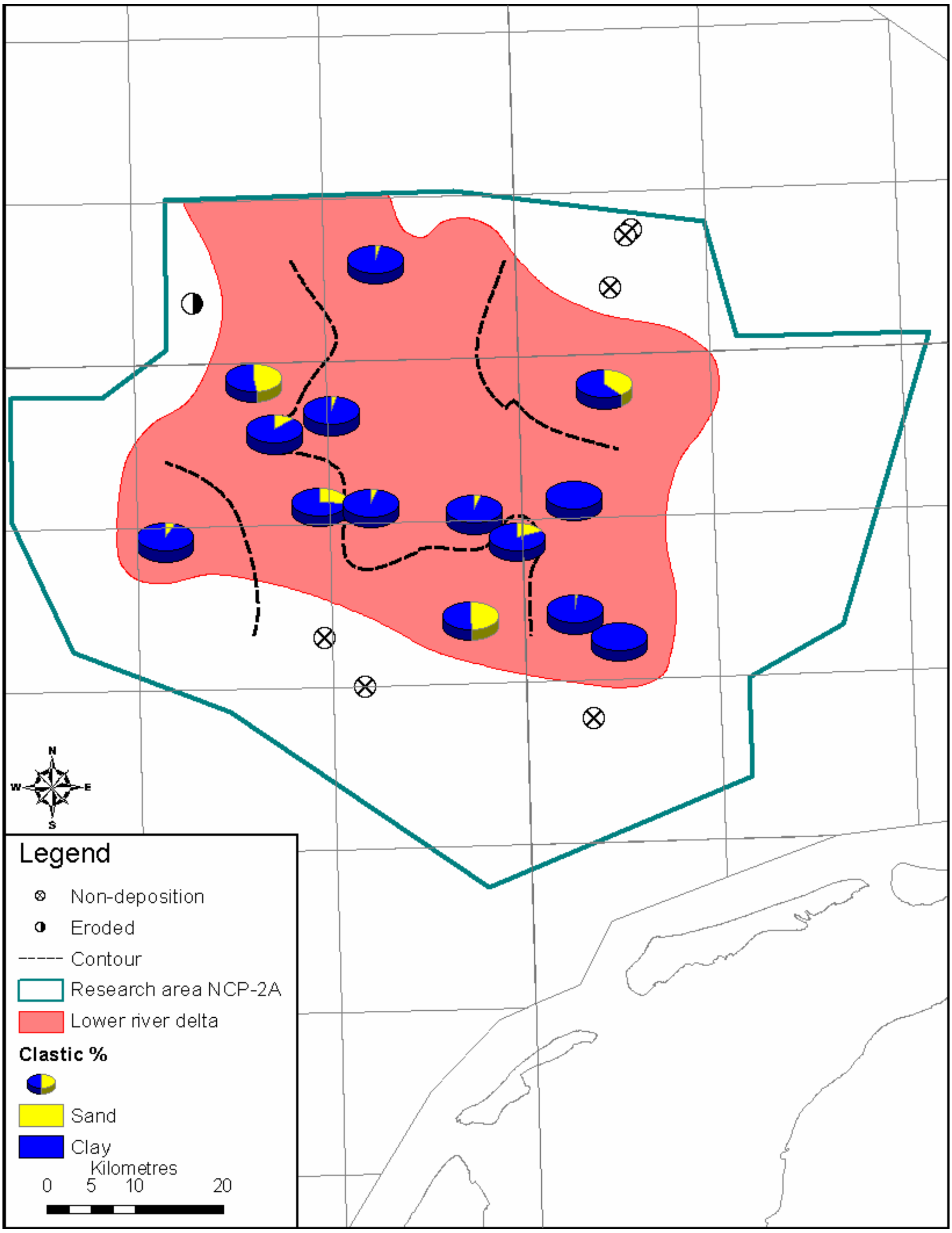
# C Thickness map



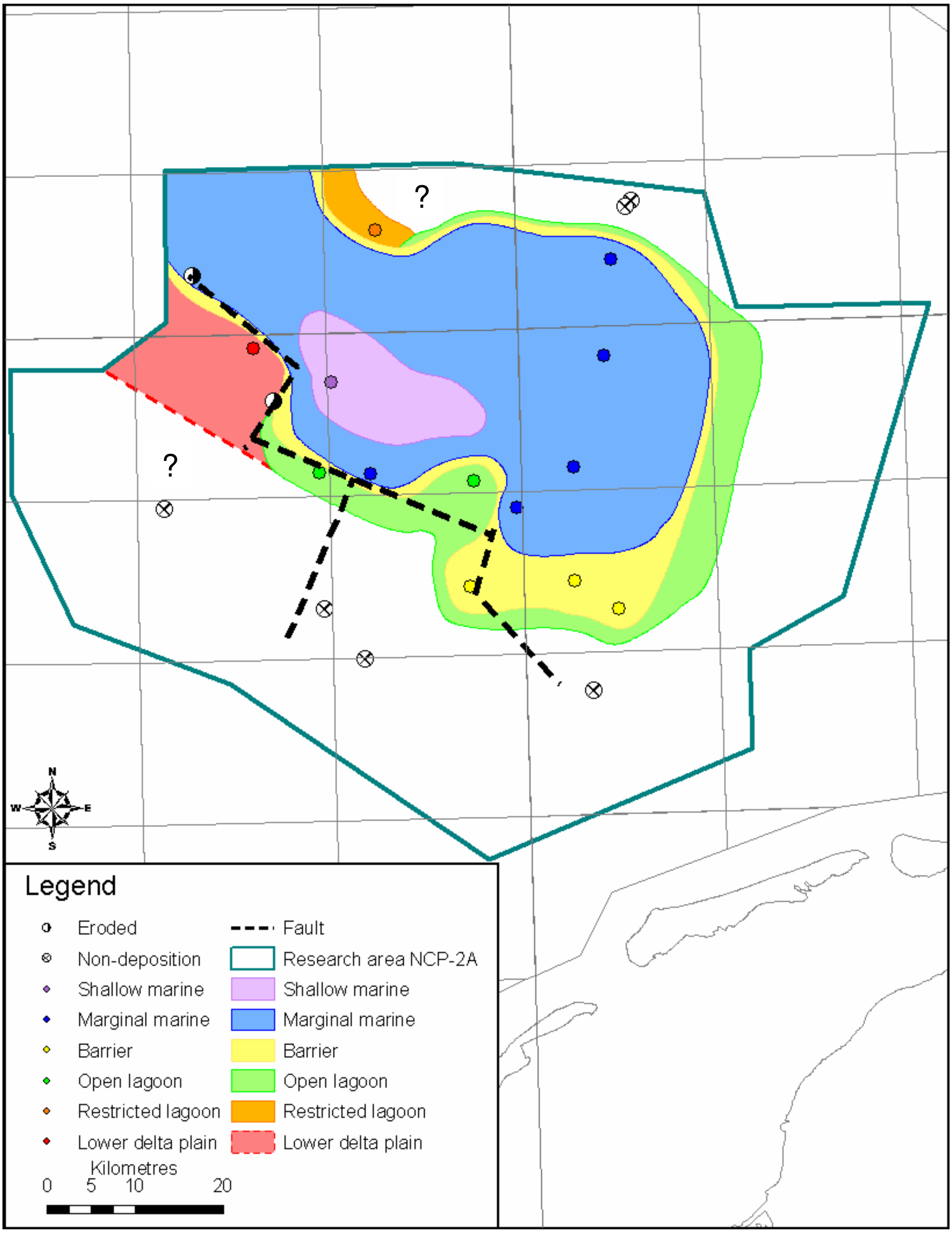
# D Pie-charts of the depositional environments



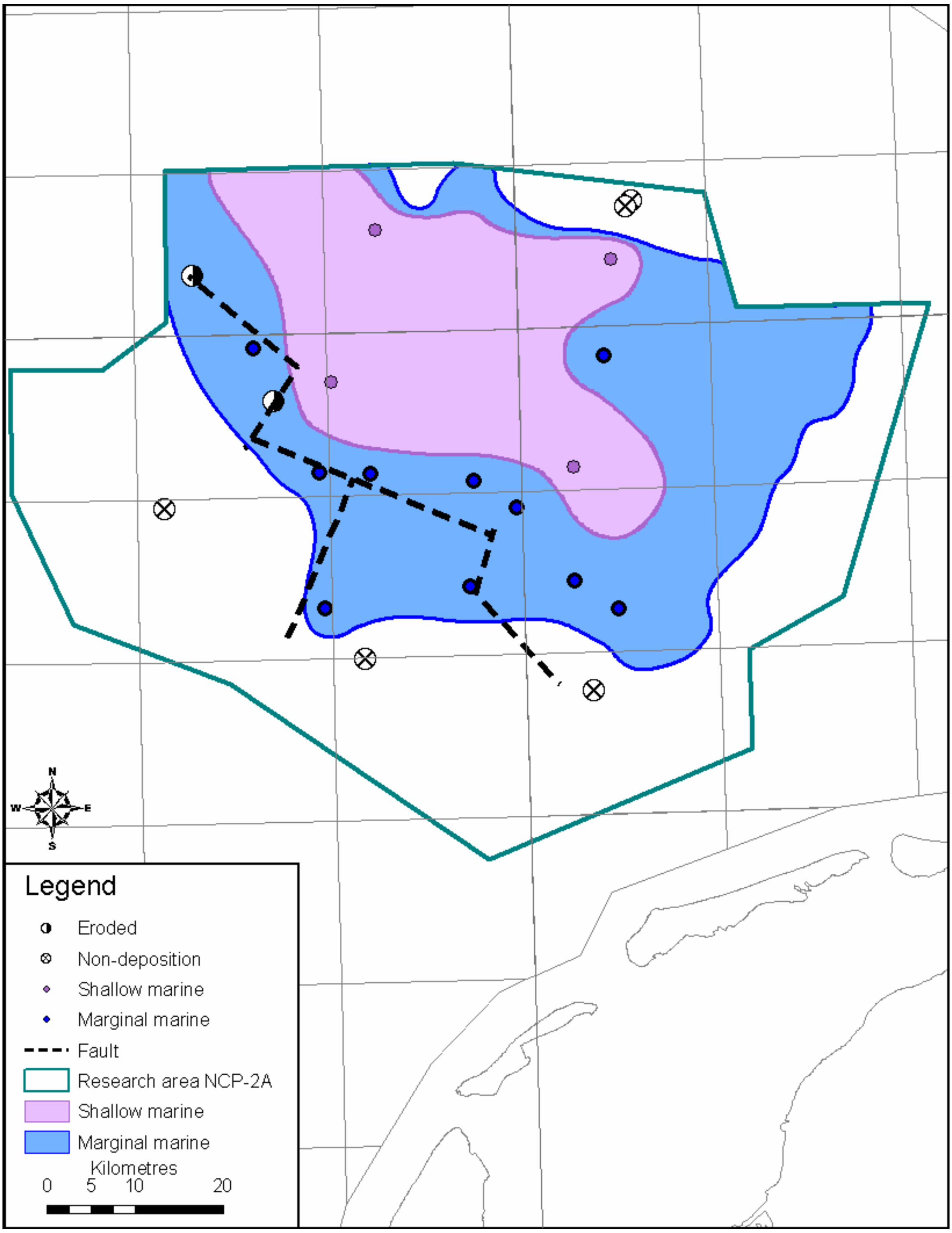
# A Map A: Initial situation



# B Map B: Situation during sequence 2



# C Map C: Final stage



# D Core descriptions

In this section the core descriptions of the studied wells are displayed. To display the cores clearly, the data of the described cores has been separated at certain intervals. Where it was possible, this was done at the boundaries of the intervals of cored sections.

Core descriptions of wells L06_02 and L06_03 are presented in the converted AppleCore layout within CoreCAD. These wells were described before the software of CoreCAD became available. All cored intervals in the other wells are described in CoreCAD and therefore have a slightly different layout. The displayed core descriptions are summarized below.

| Well | | | Well | |
|---|---|---|---|---|
| F17_04 | Part 1 | | L03_01 | |
| | Part 2 | | L03_03 | |
| F18_05 | Part 1 | | L05_07 | |
| | Part 2 | | L06_02 | Part 1 |
| | Part 3 | | | Part 2 |
| F18_09 | Part 1 | | | Part 3 |
| | Part 2 | | L06_03 | Part 1 |
| | Part 3 | | | Part 2 |
| | Part 4 | | | Part 3 |
| | Part 5 | | | Part 4 |
| G16_03 | Part 1 | | | Part 5 |
| | Part 2 | | | |
| L02_04 | Part 1 | | | |
| | Part 2 | | | |
| | Part 3 | | | |

# E Correlation panels

This section contains the correlation panels. The wells that have been used in the different panels are summarized as followed:

| | |
|---|---|
| Panel: N-S, most eastern. | Wells G16_01, G16_03, G16_04, M01_01, M01_02, L06_02, L06_03. |
| Panel: N-S, most western. | Wells F18_09, L03_01, L02_04 and L05_07. |
| Panel: NW-SE. | Wells F17_04, L03_01, L03_04, L06_02, M04_03 and M04_01. |
| Panel: W-E. | Wells L05_03, L02_04, L03_02, L03_04 and M01_02. |

In the correlation panels the interpreted depositional environments are displayed as followed:

Purple - Shallow marine
Blue - Marginal marine
Yellow - Barrier
Green - Open lagoon
Orange - Restricted lagoon
Red - Lower delta plain

The different lines that are present in the panels present the following:

B1 - Base of sequence 1
B2 - Base of sequence 2
B3 - Base of sequence 3
B4 - Top of sequence 3

2B - Time frame of map B
2C - Time frame of map C

The time frame of map A ('2A') is identical to B2, the base of sequence 2. The logs that are placed in each well are, if they were available: gamma ray log, sonic log, density log and the neutron log.

# F Seismic sections

The original interpreted seismic sections are included in this section.[1]

[1] These sections are only present in hardcopy and therefore are added in the original report. This original report is available at TNO - Built Environment and Geosciences, Business unit Geo energy and Geo information, in Utrecht.