Constraining the Triassic to Early Cretaceous structural and sedimentary evolution of the northern Dutch Central Graben; a seismic and well log data analysis.

Monica-Leigh Wolf, 23 May 2023, ***final version***

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Abstract

The structural evolution of the present-day Dutch offshore has been influenced by tectonic events coupled with halokinesis, eustatic changes and modifications in the rate of sediment supply. The research aims to disentangle the effects of these controlling factors in the Upper Jurassic – Early Cretaceous sediments of the Dutch Central Graben, by studying the tectonic-induced sedimentation at high resolution. It accounts for local tectonic and regional salt re-distribution features. The results show a better quantification of tectonic pulses that increases the resolution of the current broader tectono-stratigraphic framework. Reconstruction involves first-order restorations based on local kinematics and available 3D-seismics. The syn-rift sedimentation of the Upper Jurassic Schieland Group marks the onset of basin development, followed by Scruff Group sedimentation encompassing basin margins and subsequent basin center uplift into turtle anticlines. The well log control enabled a facies model and a quantification in tectonic successions, resulting in a higher order subdivision of the tectono-stratigraphic framework of the Late Callovian – Late Oxfordian deformation into five higher resolution tectonic pulses. These pulses are reflected in terms of increased tectonic activity followed by its subsequent decrease, while the correlation with available sea-level curves shows that they are not influenced by eustatic changes. Furthermore, our research also shows that the successions observed in the earlier Scruff Group are controlled dominantly by eustasy, as 3rd order sea-level fluctuations coincide with the lower order sedimentary cycles observed in well log data and are not linked to rifting mechanics. Differences in local basin development of the two studied transects show that local factors influence the tectonostratigraphic evolution significantly. These main controlling factors are linked with the interplay between fault activation and salt-re-distribution, resulting in a clear correlation of tectonic-induced sequences.

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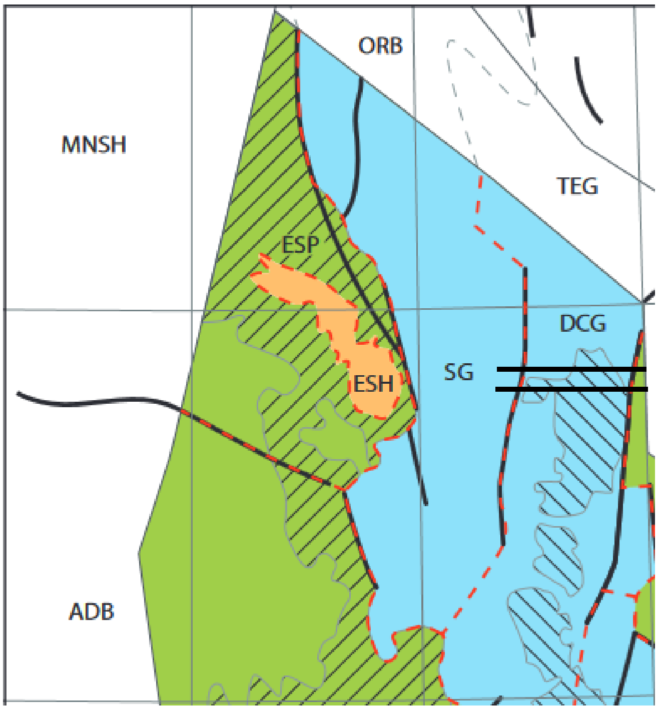
1. Introduction

Starting with Triassic times, the structural complexity of the Netherlands increased progressively because of the fragmentation of Pangea (Herngreen et al., 2003). Multiphase deformation resulted in the disintegration of the Southern Permian basin into complex sub-basins such as the Dutch Central Graben and the Step Graben. These grabens are part of the southernmost extension of the Central Graben of the North Sea located offshore the Netherlands with prolongations into the neighboring Germany and Denmark offshores (Ziegler, 1990; Trabucho-Alexandre et al., 2012). The available basin evolution models find that the major Dutch Central Graben rift system formed during the Early Jurassic, influenced by halokinesis, extensional faulting and eustasy (Bouroullec et al., 2018; Smit & Lafosse, 2020). The subsequent Cretaceous sedimentation pattern in the rift system has a high diachroneity due to local tectonic overprint into the syn-kinematic deposition of sedimentary sequences (Bouroullec et al., 2018).

Previous research has been conducted, both on the individual Dutch Central Graben (Abbink et al., 2006, Bouroullec et al., 2018, Herngreen et al., 2003) as well as on the broader North Sea Central Graben (Van Buchem & Smit, 2018, Verreussel et al., 2018)), while the adjacent Step Graben has received less attention (Smit and Lafosse, 2020). All studies distinguish between three depositional mega-sequences based on a combination of seismic and well data. Though the focus of these mega-sequences is to provide a well-constraint stratigraphic framework for the North Sea Central Graben, including the Dutch Central Graben, they account less for the tectonic development of the individual faults and sub-basins in the overall rift system. In these studies, generally coeval extension is assumed, which contrasts the large spatial and temporal variability observed in terms of lateral and temporal evolution. Tectonic processes such as the Kimmerian deformations (Herngreen, 2003) show great lateral variability throughout the basin, and are observed in relative subsidence differences. The tectono-stratigraphic framework is mostly based on eustatic changes within the half-graben, which is untenable as the sedimentary cyclicity indicates high-resolution phases of relative tectonic quiescence, inferring an evolutionary model characterized by high-resolution tectonic successions (Matenco & Haq, 2020). Furthermore, extensive halokinesis spatially and temporally associated with the moments and locations of fault activity has influenced the evolution of the depositional accommodation space, resulting in large thickness differences and structural asymmetries (Ten Veen et al., 2012).



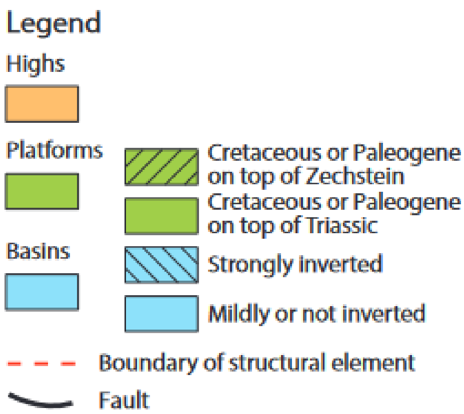


Figure 1: Location of the study area; two studied transects are marked by the black lines and perpendicular to the axis of the Dutch Central Graben. The lowermost section fully encompasses the strongly inverted area. The map shows Cretaceous inversion. DCG: Dutch Central Graben, SG: Step Graben. Base map by Kombrink, 2012.

These observations are particularly enhanced in the northern part of the Dutch Central Graben, where the more than 300m thick salt kinematics has largely decoupled deformation in the under- and overburden. Lastly, the Jurassic basin infill has a high diachroneity of depositional formations, with changes in the location of depocenters, resulting in a complex depositional and tectonic history in the basin (Bouroullec et al., 2018). The relatively coarse facies of the Upper Graben Formation might represent the start of the second Late Kimmerian tectonic phase as proposed by Herngreen (2003). This start has been questioned as no additional tectonic evidence has been found. However, the general interpretation is that the effects of inversion appear to decrease rapidly northwards. Building onto this knowledge, this study will attempt to find further evidence in the northern part of the Dutch Central Graben regarding the occurrence of the Late Kimmerian in the sequence.

High-resolution tectono-sedimentary reconstructions of systems such as the overly complex Dutch Central Graben, require a multi-discipline approach to highlight the mechanisms driving the allogenetic and autogenetic forcing. Matenco & Haq (2020) proposed a basic tectonic succession model applicable on all temporospatial scales for the evolution of such a sedimentary basin. It is a conceptual model where the balance between rates of creation of accommodation space and available sediment supply links the fault-induced depositional accommodation to basin kinematics. This approach builds upon the distinction between stratal features and facies with their own characterizations, proposed by Van Wagoner et al., (1990). Using a sequence-stratigraphic terminology based on shoreline movements is incomplete in such basins due to multiple sourcing directions, as the onset of kinematics is in non-marine settings (Einsele, 2000). The balance can also be expressed in sequences of basinward and sourceward shifting facies tracts (Matenco & Haq, 2020). An alternation of the two tracts is bounded by boundary sequences, defined as a tectonic succession. The tracts are reconstructed using seismic data, well logs and core samples. Using this approach and terminology, the tectonic interpretation does not rely on eustatic cyclicity or the tectonic setting, but adds a temporal factor and accounts for bathymetry. The temporal element is especially important to understand the relationship between regional tectonics, halokinetic intensity and the re-distribution of the Zechstein overburden (see also Ten Veen et al., 2012).

In this study, the main aim is to understand and constrain the factors controlling the Triassic to Early Cretaceous evolution of the sedimentation in the northern Dutch Central Graben by making use of an interplay between available seismic sections and well log data. Benefitting from the availability of a recent large scale 3D seismic survey in the northern Dutch offshore, we have chosen to interpret a number of key transects run E-W oriented (Figure 1) that are spatially correlated and where the deposition is correlated at higher resolution by the availability of well data such as high resolution stratigraphy and well logs. After a first-order seismic interpretation based on the Dutch standard stratigraphic nomenclature (dinoloket.nl), additional Fugro well logs (F03-06, F05-01, F05-03, F06-01-S1 and F09-01), cores and well-report data (nlog.nl and dinoloket.nl) are interpreted in a high-resolution analysis. This dataset is interpreted in terms of tectonic successions, controlled by the balance between rates of depositional accommodation and sediment supply. Compared to previously defined tectonic mega-sequences (Verreussel et al., 2018), our interpretation provides a higher resolution tectono-stratigraphic framework. It also improves upon the current understanding of decoupling deformation due to salt kinematics into the observed deposition, and the relative importance thereof when compared to the variability of sediment supply and eustatic movements.

2. Geological Framework

2.1 Tectonic evolution

The tectonic and structural evolution of the subsurface of the Dutch offshore area has been influenced by multiple deformational events intimately coupled with complex salt movements (i.e. halokinesis), as well described by extensive previous research (Ziegler, 1990; Herngreen et al., 2003; De Jager, 2007; Pharaoh et al., 2010; Bouroullec et al., 2018). Therefore, to reconstruct the tectonic history it is important to highlight the occurrence of key events and their influence in the study area. The Caledonian Orogeny marks the onset of the known tectonic events, followed by the Hercynian or Variscan orogenies. Paleozoic deformation was followed by Triassic - Early Cretaceous rifting, Late Cretaceous inversion and minor Tertiary reactivations (Verreussel et al., 2018).

Within the area of interest in the Dutch offshore, a key structure is the roughly N-S oriented Dutch Central Graben, the main focus in this studies (Figure 2). It is a complex half-graben structure bounded by salt-kinematics, which in the offshore Netherlands is bordered by the Step Graben in the west and the Schill Grund Platform and Terschelling basin in the east (Figure 2, Kombrink, 2012). While the overall structural geometry is similar across the entire graben, the local tectonic features are proven to be structurally complex, showing a great diachroneity and structural overprint (Verreussel et al., 2018).

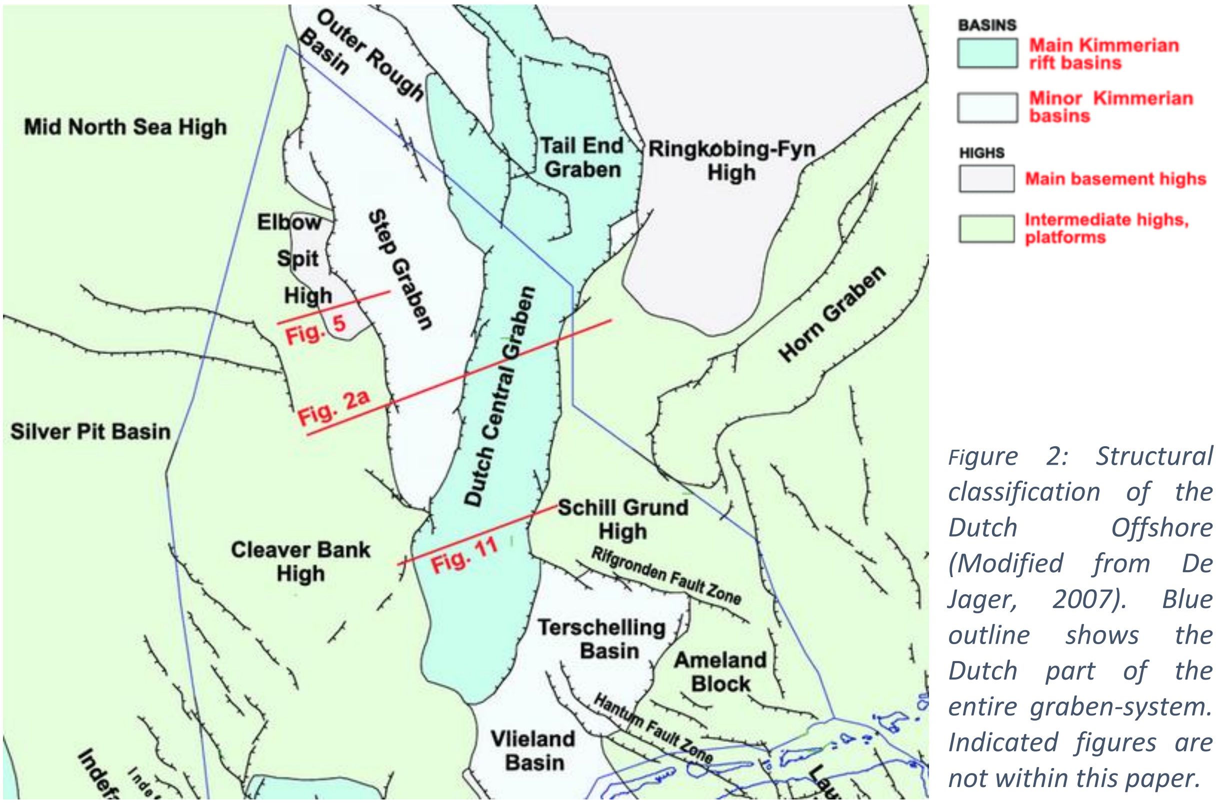


Figure 2: Structural classification of the Dutch Offshore (Modified from De Jager, 2007). Blue outline shows the Dutch part of the entire graben-system. Indicated figures are not within this paper.

2.1.1 Caledonian Orogeny

The Caledonian Orogeny commenced in the Late Cambrian, and ceased in the Early Devonian (Ziegler, 1990). This event resulted in the Caledonian fold belt, that follows the Laurussian suture zone (De Jager, 2007). The belt altered the metamorphic basement rocks that comprise the underburden of the Dutch Offshore, therefore, the basement has significantly weakened.

2.1.2 Variscan Orogeny

The formation of the supercontinent Pangea during the Variscan orogenic cycle led to closure of the Tethys Ocean and the subsequent formation of an extensive foreland basin north of the Variscan orogen (De Jager, 2007). This foredeep is the predecessor of the Southern Permian Basin (Herngreen et al., 2003). During the Late Permian, the basin environment changed to an arid climate due to the mountain belt south of the basin. Combined with further subsidence and an active connection to the Arctic Ocean, the depositional sequence changed to thick Zechstein evaporite members (Trabucho-Alexandre et al., 2012). The subsequent tectonic extension disintegrated the area into three smaller basins, all significantly subsiding due to thermal relaxation of the lithosphere combined with extensional tectonics in Middle to Late Triassic times. This subsidence resulted in further faulting that is particularly well observed by offsets in the Permian Rotliegend sandstones (Geluk, 2005).

2.1.3 Kimmerian Rifting Phase

Mesozoic rifting between Greenland and Scandinavia resulted in the break-up of Pangea (De Jager, 2007). The Triassic rifting propagated southwards along two branches, of which the eastern branch propagated into the North Sea area creating the Central and Viking grabens. Sedimentation occurred under continued thermal subsidence combined with a relative sea-level rise, which create regular facies patterns (Pharaoh et al., 2010). Syn-depositional faulting caused lateral thickness variations in the Middle to Late Triassic Buntsandstein, whereas the lower Buntsandstein sequence was deposited gradually and is thus of continuous thickness (Geluk, 2005). The variability of thickness created differential loading, which in combination with the increase of extensional tectonics resulted in the onset of diapirism of the Zechstein salt that follows the structural trends along the main diapirs and associated rim synclines. The diapirism has created differential subsidence and uplift, changing the basin geometry and depositional environments (Ziegler, 1990; Wong et al., 2007).

The Middle-Late Triassic extension was followed by an Early Jurassic interval of reduced tectonic activity, when smaller offsets faults controlled the deposition of the Altena Group. In the Toarcian, anoxic conditions changed the open marine facies, which resulted in the deposition of the thick shales of the Posidonia Shale Formation, an oil-source rock (Trabucho-Alexandre et al., 2012). Continuing an earlier phase or regional Early Jurassic uplift generally inferred to be driven by the emplacement of a sub-lithospheric thermal anomaly, during the Middle Jurassic mid-Kimmerian phase, the gradual uplift of the Dutch Central Graben along with a sea-level drop prompted widespread erosion. This resulted in the formation of a widespread unconformity overlying the Posidonia Shale Formation (Verreussel et al., 2018). Sedimentation became restricted to the Dutch Central Graben, while erosion continued on its flanks. Truncation of the Upper Jurassic and Triassic deposits occurred in the western part of the graben, a result of continued uplift (Underhill & Partington, 1993). During the onset of renewed Late Jurassic extension, accommodation space was rapidly created with frequent depocenter shifts, controlled by large-offset faulting as well as halokinesis (Bouroullec et al., 2018). Within the half-graben a high variability in lithofacies and depositional environments makes a correlation rather challenging (Verreussel et al., 2018).The Late Kimmerian phase coincides with a change to a sub-tropical climate during continued thermal subsidence of the Dutch Central Graben, and a relative sea-level rise resulting in the deposition of the Chalk Group (Van Wijhe, 1987).

2.1.4 Cretaceous inversion

A change in climate accompanied by further thermal subsidence and transgression resulted in deposition of distal facies encompassing the entire Dutch Central Graben, as well as its adjacent flanks in the footwall of the controlling normal faults. Although small inversional effects were observed also during the deposition of the Rijnland Group, the main inversion took place during the deposition of the Chalk Groups (Bouroullec et al., 2018), which resulted in the formation of the well-known base North

Sea Group unconformity observed in the entire North Sea and its adjacent onshore. In the Dutch Central Graben, the Cretaceous inversion is observed by the formation of a broad anticline structure and significant erosion up to the Triassic sediments, while Jurassic-Late Cretaceous deposits are still observed locally along its flanks or periclinal terminations (Van Wijhe, 1987). These structural features developed due to continuous relative uplift, with acceleration pulses during Campanian and Paleocene times, and with more reduced effects during the Late Eocene. The style of deformation shows a decoupling of the faults observed in the underburden of the overthickened Zechstein salt from deformation observed in its overburden (De Jager, 2007). Their research also found that while the half-graben was uplifted, the adjacent highs continued to subside, resulting in more accommodational space. During the last inversion pulse, an acceleration of halokinesis occurred. Basement faults have been frequently reactivated influencing the overlying basin geometry in disregard of the changing tectonic regimes. Faulting observed is mostly parallel and does not fan out; it does not seem influenced by later regional stress orientations. Along these basement faults subsequent salt movement affected the structural development of the basin (De Jager, 2007).

2.2 Litho-stratigraphy of Upper Jurassic and Early Cretaceous

Previous extensive research within the area was conducted, both on the individual Dutch Central Graben (Abbink et al., 2006, Bouroullec et al., 2018, Herngreen et al., 2003) and the broader North Sea Central Graben (Munsterman et al., 2012, Van Buchem & Smit, 2018, Verreussel et al., 2018). All studies separated three depositional mega-sequences (figure 3) based on the interpretation of seismic and well data;

Mega-sequence I: Mostly deposition of uniform marine shales, observed in the Altena group within the Dutch Central Graben, continuing the Triassic marine to continental deposition. The early Kimmerian (Late Triassic) extensional phase created a marine regression. Anoxic conditions during the Toarcian resulted in deposition of the Posidonia Shale formation, which is the most prominent oil source in the Netherlands.

Mega-sequence II: Significant Mid-Kimmerian large-scale tectonic activity resulted in important structural differentiation, causing uplift of the northernmost Central North Sea dome. The activity gradually shifted southward with time, resulting in an intra-Jurassic truncation decrease away from the dome. A difference in depositional sequences occurred in the northern and southern part of the Dutch Central Graben, the north became non-depositional until Middle Callovian, whereas the south did remain depositional.

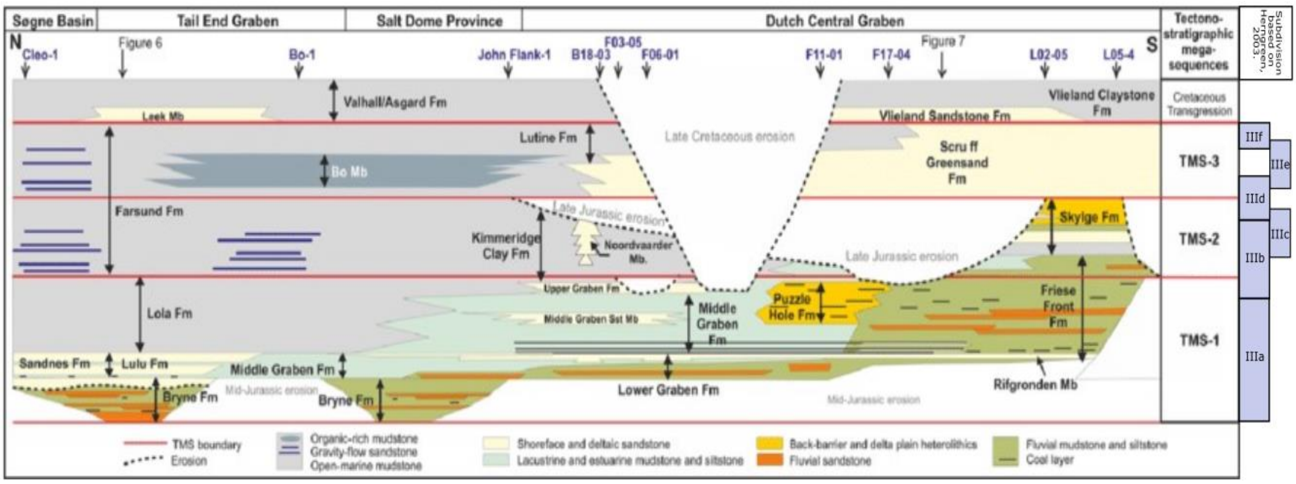


Figure 3: Wheeler diagram along a N-S transect through the Central Graben axis; Late Cretaceous inversion is mostly observed in the Northern Dutch Central Graben. TMS-1 to TMS-3 correspond with the subdivision proposed by Abbink, 2006. Subdivision proposed by Herngreen et at., 2003 is added. Altered from Verreussel et al., 2018.

The facies during this time were continental, however, evidence thereof was removed due to later deformation resulting in removal by severe truncation into Jurassic successions. Deposition subsequently changed from marine sandstones to shallow marine, sandy carbonates, and marls.

Mega-sequence III: Upper Jurassic – Lower Cretaceous deposits show a general gradual transgression southward. Marine transgression phases alternated with short-term progradation of tectonically controlled continental siliciclastics, influenced by syn-depositional tectonics and sea-level fluctuations. Oblique-slip effects in the extensional regime resulted in differential movement of fault blocks, later re-activated by halokinesis. The depositional area expanded during Early Kimmeridgian, leading to a complex sediment distribution as well as shifting depocenters. This was followed by a more uniform sedimentation pattern associated with a post-rift thermal phase. As this third and uppermost sequence proves to be structurally most complex, an additional subdivision of the stages within the megasequence was proposed. The general depositional setting and boundaries were defined by Van Adrichem Boogaert & Kouwe, (1993).

Within the graben, the lithostratigraphy of the third megasequence is comprised of the Central Graben Subgroup, the Scruff Group, the Rijnland Group and lastly the Chalk Group. The first unit is defined as a primary syn-rift sedimentation stage, with deposition taking place from Middle Callovian to Oxfordian. In literature these deposits are referred to as TMS-1 (Munsterman et al., 2012), IIIa (Herngreen et al., 2003) or sequence 1 (Abbink, 2006). The Central Graben Subgroup covers unit TMS-1 that consist of four different formations. Lithological descriptions and depositional setting of all groups are formally described by (NAM & RGD, 1980), amended by Herngreen & Wong, (1989); and Van Adrichem Boogaert & Kouwe, (1993). The lowermost lithological unit is the Lower Graben Formation (SLCL, middle Callovian – late Callovian), which is mainly fine-grained, well-sorted sandstones coarsening upwards, with intercalations of thin greyish brown silty to sandy claystones. This unit is mostly carbonatic intercalated with a few coal layers. Depositional setting is fluvial to deltaic, progressing into a sand-rich coastal plain facies upwards. The first distinct coal-bed within the formation marks the upper boundary of the group.

The Middle Graben Formation (SLCM, Early Oxfordian – Middle Oxfordian) is comprised of grey silty carbonaceous claystones, interbedded with one, sometimes two, sandstone layers that are characterized by coal beds. The environmental setting is a lacustrine - marginal marine embayment, to prograding lacustrine deltaic, and further to lacustrine – marginal marine. In the northern part of the Dutch Central Graben this formation is overlain by the Kimmeridge Clay Formation or the Upper Graben Formation. The Upper Graben Formation (SLCU, Late Oxfordian) has marginally marine greyish brown fine-grained carbonaceous sandstones, with relatively coarse silty clay successions. Based on the lithological facies, the environment changed from a fluvial deltaic setting to a lacustrine – marginal marine embayment, which represents a gradual marine transgression interfingered with a tectonically controlled middle Oxfordian progradational lacustrine deltaic environment.

The second sequence, Kimmeridgian – Early Portlandian (Tithonian), starts with the Kimmeridge Clay Formation (SGKI), part of the Scruff Group, which is the most important formation of the sequence. Referred to as stage IIIb-IIId (Herngreen et al., 2003), sequence 2 (Abbink, 2006), TMS-2 (Munsterman et al., 2012), this formation was deposited over a flat continental shelf and is comprised of olive-green silty carbonates, interbedded with thin dolomite streaks Van Adrichem Boogaert & Kouwe, (1993). The boundary with the Schieland Group is correlative as the group continues the transgressive trend, which fluctuates laterally. Within the northernmost blocks, the Puzzle Hole Formation gave way to the open marine Kimmeridge Clay Formation Van Adrichem Boogaert & Kouwe, (1993).

Sequence 3, Early Portlandian, is comprised of deposits encompassing all Jurassic basins. Herngreen et al., (2003) named it stage IIIe-IIIf, Munsterman et al., (2012) TMS-3 and Abbink, (2006) sequence 3. The sequence includes the Scruff Greensand often connected to the Lutine Formation, or the Clay Deep and is most developed in the southern part of the basin. The sequence represents an offshore environment (Abbink, 2006). Sequence 4 is the termination of the Jurassic rift sequence, from the Rijnland Group onwards. The transition in formations is a hiatus locally as most of the Rijnland Group is eroded over the Dutch Central Graben due to uplift (Van Adrichem Boogaert & Kouwe, (1993).

3. Methods

3.1 Salt-influenced basin approach

This project will quantify the correlation of the structural response and offsets between the sub-salt and overlying sequences, as well as the quantitative sedimentary and sedimentological response to the events of faulting and general tectonic-induced cyclicity. A sequential reconstruction of deformation and associated sedimentation in the Dutch Central Graben will be made by using the tectonic succession methodology (Matenco and Haq, 2020 and references therein). This approach is based on the observation that the controlling factors of classic sequence stratigraphy are significantly different from rift sequence controls. The classic tectono-stratigraphic approach focuses on the eustatic influence on basins and the variability of sediment influx established on stable passive continental margins. Whereas the true deformation history in most tectonics-influenced basins is further influenced by factors such as bathymetry or fault-related movement or associated with halokinesis.

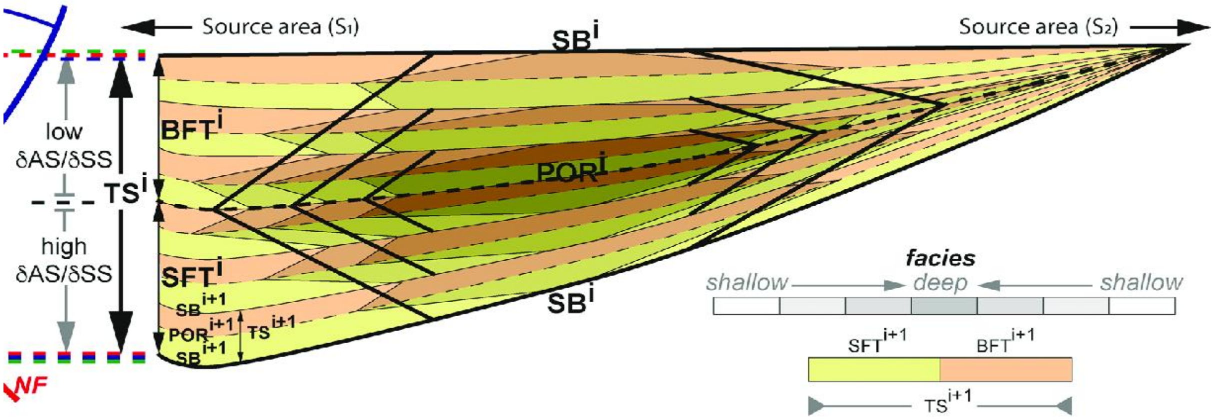


Figure 4: example of conceptual tectonic successions in a basin linked to an ocean; not influenced by halokinesis nor brittle deformation. Figure altered from Matenco & Haq, 2020.

The interaction between rate of creation of depositional space (δAS) and the rate of sediment supply (δSS), results in distinct facies and stratal features with their own characterizations, such as progradational (δAS/δSS =<1), aggradational (δAS/δSS =1), and retrogradational (δAS/δSS >1) successions (van Wagoner et al., 1990). A different subdivision can be proposed that takes an initial non-marine tectonic basin phase into account. Improving upon these successions by using them as a guide in the dynamic interaction of subsidence and uplift, conceptual tectonic successions are proposed. Both low and high order tectonic successions (TS) are based on the balance reflected in strata, such as regression and transgression. However, they are built upon by separating succession boundaries marked by diachronous fault-bounded unconformities with an erosional top (figure 4). This top is indicative for the post-tectonic relative quiescence of extensional systems. The tectonic successions are comprised of basinward migrating facies tracts (BFT) characterized by a low δAS/δSS, and sourceward migrating facies tracts (SFT) that have a high δAS/δSS, and a shallow water facies shift towards the sediment source. The alternation of these tectonic successions can be interpreted on different scales, gaining a better understanding of the tectonic history, such as subsidence or difference in sediment supply. Furthermore, the temporal scale can range from plate tectonic rift initiation up to individual fault movement.

Development of fault-controlled basins has been extensively studied. However, salt decoupling was not considered as an additional controlling factor. Bouroullec et al. (2018) has studied the Dutch Central Graben taking the decoupling Zechstein layer into account, and found that the results significantly differ from classic approaches, which was endorsed by earlier studies (e.g. Alves et al., 2003). This project, and approach, aims to disentangle the effects of multiphase salt tectonics and eustasy in a key area of the graben system, by studying the tectonic-induced sedimentation at high resolution. This involves a local restoration based on measuring and reconstructing the deformation seen in the system, based on local kinematics and insights from recently available 3D seismics, well log data, high-resolution stratigraphy, and available regional interpretations.

3.2 Seismic interpretation, tectonic reconstruction and well analysis

3.2.1 First order seismic interpretation

A combination between the Fugro 2017 public well log dataset and available 3D seismic surveys, resulted in a first-order interpretation of the Dutch offshore. To map the syn-kinematic unconformities and corresponding faults, a classical seismic interpretation approach of drawing reflector terminations is used. Additionally, the 3D model of the Dutch subsurface (DGM-deep, v5, TNO, 2019) aids in deducing relative ages of the boundaries and sedimentary units distinguished in the two studied transects. The interpretation of the transects is based on the Dutch standard stratigraphic nomenclature (dinoloket.nl). Section A is reconstructed using a combination of well logs F04-01, F06-01-S1 and F06-02, completed using well log F04-02-A, situated within a 1km radius. The presented transect shows seismic line 4614, but to reconstruct the entire transect, information from seismic line 4358 was used as well. Section 2 is comprised of well logs F05-01 and F05-03 reconstructed in seismic line 4230, approximately 9km South of transect A. The tectonic reconstruction of the chosen transects is re-evaluated by flattening significant unconformities within the stratigraphic units. A first-order estimation is obtained, as flattening does not take paleo-elevation nor paleo-bathymetry into account. Whenever these unconformity horizons terminate laterally, they are extrapolated or estimated. Important to note, this correlation does not take post-depositional displacement into account, even though most layers are affected by later events.

3.2.2 High-resolution well and seismic facies analysis

The first-order interpretation readily distinguished between tectonic sequences, based on seismic facies differentiation. Further high-resolution analysis of five wells gave insight in grain size variation and depositional facies, which strengthens this distinction, as the basinward and sourceward migrating facies tracts are reflected in depositional cycles found in the lithology. These trends are defined as parasequences (higher order cycles), sets thereof, and lower order cycles.

The conversion of the well logs is based on standard time-depth correlation, using seismic velocities proposed in DGM-deep (v5) and the VelMod dataset (nlog.nl). For the well log sequential analysis, a standard gamma-ray approach characterizes the sediment types. The neutron-density, sonic and electric logs guide to find trends in rock porosity and resistance of layers. A combination of these trends with core samples, results in a lithological interpretation and corresponding well log facies. By comparing the obtained data with core reports (nlog.nl) and the Dutch standard stratigraphic nomenclature (dinoloket.nl) a final interpretation of depositional environment and corresponding sedimentary cycles is obtained. The core reports ensure there are no identifying errors regarding lithological trends. The process of defining the trends in well logs, based on lithology and grain size changes proves time consuming, and is subject to the availability of well logs within the area of interest. A more straightforward approach independent of well control can be acquired by defining seismic facies corresponding to tectonic successions. By combining the observed lithological trends with stratal features of reflectors, such a seismic facies model based on basinward- and sourceward migrating facies tracts can be defined.

3.3 Seismic interpretation

The first-order seismic interpretation is based on distinguishing the different groups within the chosen transects (Table 1). An additional subdivision is made based on tracking unconformities along the seismic sections, which are representative for the entire area, and thus are applicable to a larger scale. The unconformities are usually clearest around faults and salt intrusions, but on some occasions, they are clearer in the basin center, e.g. the Posidonia Shale Formation. The area of significant interest is comprised of the Scruff and Schieland Groups, that hold information regarding seismic facies and most tectonic activity within the northern Dutch Central Graben. A high-resolution interpretation of the area will be conducted in later stages using the well and core log data.

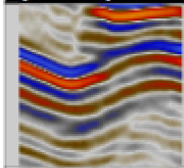
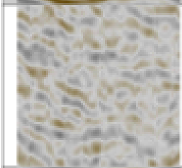
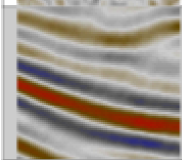
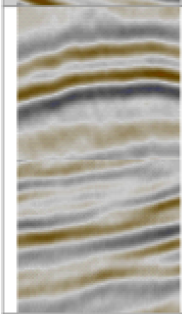
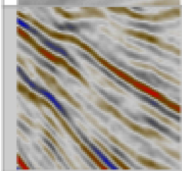
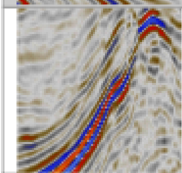
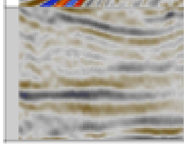
Seismic example (250ms)	Color and Name	General Characteristics
	Rotliegend Formation	Sharp reflector bounding the lower boundary of the Zechstein. Correlative below large salt intrusions. Varying seismic facies at depth.
	Zechstein Formation	Chaotic, low amplitude reflectors, high variability in thickness. Typical appearance for an evaporite.
	Triassic Groups	Medium amplitude reflectors, mostly continuous. There are locally high amplitude reflectors.
	Altena Group Posidonia Shale	Low to medium amplitude reflectors, somewhat continuous to discontinuous. Has an unconformity above the Posidonia Shale Formation. This layer is continuous.
	Upper Jurassic	Comprised of the Schieland and Scruff Group. Reflectors range from high amplitude to low amplitude, mostly continuous with a few discontinuous reflectors.
	Chalk Group	High amplitude reflectors gradually changing into lower amplitude. Variability in continuity.
	Rijnland Group	Low reflectivity, low amplitude-frequency. Discontinuous layers.

Table 1: seismic examples and general characteristics of different formations in the Dutch Central Graben and adjacent Schill Grund Platform and Step Graben.

4. Seismic interpretation

4.1 Section A

In section A – the northernmost section marked in figure 1 – the Jurassic basin infill is confined by two prominent Zechstein salt bodies (figure 5). The Zechstein formation is underlain by the Permian Rotliegend Formation which is truncated by large offset faults that are mostly confined beneath the salt. Between both graben flanks the Rotliegend formation has a discontinuous facies where reflectivity is influenced by the thick overlying salt. The continuity of the facies improves in the area of the Step Graben. Below the over-thickened Zechstein body in the Step Graben, the strata are slightly tilted westward, recorded by continuous to discontinuous reflectors. In the Dutch Central Graben the formation confined by hard-linked faults F1 and F2 subsided relatively during the late Permian; this is linked to thermal relaxation, which is less observed in section B (figure 6).

The Zechstein formation overlies the Rotliegend Formation and shows large lateral thickness variations. Deflation (i.e. thinning) is observed below the Triassic, and inflation along pre-existing faults labeled F1 and F2 bounding the half-graben. Due to the onset of diapirism along these faults, the salt reaches local highs of 1750ms, with lows of 5000ms within the center of the graben. Remobilization of salt influences the geometry of the overburden. In the Step Graben the Zechstein salt reaches local highs of 1750ms as well, with salt intrusions accommodated by faults F4 and F5. Interestingly, in the center of the Step Graben overthickening occurs as well, mostly during deposition of the Triassic formations. A small erosive surface within the Triassic shows that this inflation and subsequent uplift lasted until deposition of the Rijnland Group. The Trias Formation overlies the Zechstein Formation, and shows thickness variations of up to 500ms due to the salt remobilization. Within the Dutch Central Graben, a local thickness variation east of the center, which is comprised of syn-kinematic Triassic strata, is indicative for growth wedges (Figure 5). This structure shows a slight shift of the depocenter towards the east, which indicate that more accommodation space was available due to large offset faulting along fault F1. Evidence for subsidence of both flanks, and thus faulting of F1 and F2 is observed in the syn- and antiform of the Triassic top layer, while a low offset can be observed along fault F3. In the west, the Triassic sediments truncate the Kimmeridge Clay.

Overlying the Triassic formations, the Lower Jurassic Altena Group has large lateral thickness variations and is wedge shaped, which implies syn-kinematic deposition, with a westwards shift of the depocenter towards the center of the basin. These observations infer that the accommodation along the major sub-salt faults were similar, however, a third fault accommodated more offset along the western margin. The upper bounding unconformity, the Toarcian Posidonia Shale Formation, is deposited in the center of the graben and pinches out against the Upper Jurassic. Due to the contrasting lithologies in this formation, a differentiation in seismic facies occurs, where the low amplitude reflectors change from low frequency to high frequency. This distinctive deposition reflects a stagnation of the basin subsidence, as it pinches out before the basin margins. The depocenter is situated west of the graben's center, which likely reflects relatively more accommodation space created along its western flank. Within the Step Graben, the Posidonia Shale Formation was only deposited within a 200ms depression underneath position 6133.

Sedimentation ceased until the Callovian, and then resumed with continental facies of the Upper Jurassic sediments in the Dutch Central Graben. Overlain discordantly by Upper Jurassic sediments, the Altena group is separated by a significant angular unconformity, removing evidence for the non-depositional period as part of the depositional period was eroded too. The variability of the seismic facies in the Upper Jurassic sequence, comprised of the Schieland Group and Scruff Group, is distinctive for a syn-kinematic basin infill. The Upper Jurassic group thins outwards towards its margins, and shows a large shift in depocenter eastwards. Within the Upper Jurassic groups, a variability in seismic facies is observed where our first-order interpretation has observed four units separated by unconformities, which are most apparent along the eastern flank. All units are deformed in similar manner as the Altena and Triassic groups, influenced by salt withdrawal and subsidence in the basin center. Along the eastern margin, unit S1, the lowermost layers of the Jurassic, is comprised of onlapping layers, with a central depo-axis. Units S2 and S3 show a backstepping pattern with a depo-axis shift eastward and may be composed of the Kimmeridge Clay only. Unit S4 encompasses the older layers and is comprised of the Kimmeridge Clay Formation. Along the western margin of the basin all subunits truncate into this younger Kimmeridge Clay, likely as a result of relative Kimmerian uplift and subsequent erosion of the margin after deposition. Based on the observed overall western shift in accommodation space during the Triassic, which is different from the eastern one during the Jurassic, the slower uplift of the eastern salt diapir predates the western salt diapir uplift, which continued until the early Cretaceous.

The previously observed Upper Jurassic environmental shift from fluviatile well-sorted sandstone to a prograding lacustrine deltaic marl succession and medium sorted cemented sandstone, and to a marginally marine environment, overlain by the Kimmeridge clay (Van Adrichem Boogaert & Kouwe, 1993) combined with our interpretation demonstrates that the subdivision in possible tectonic successions can bee based on these broad differentiations in lithological facies. First-order observed aggradational onlap features along the eastern margin in unit S1 attest to such a subdivision. The western margin has significant truncation features which is either an overall progradational or eroded aggradational feature. Based on the observed evolution of the half graben, the Scruff and Schieland Group prove most tectonically complex, and provide most information regarding the basin tectonics.

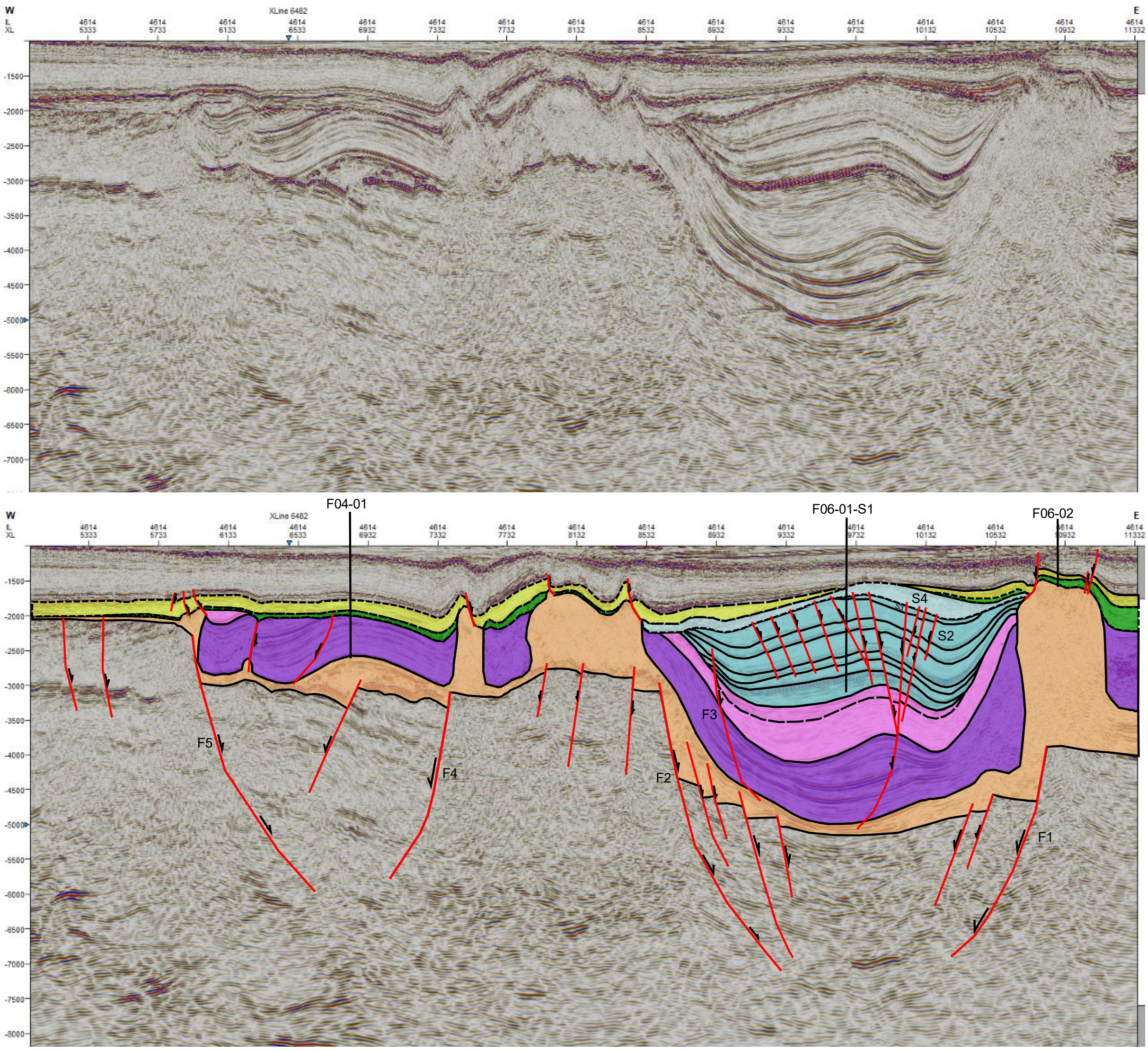


Figure 5: Seismic interpretation of the Dutch Central Graben and Step Graben of section A. See figure 1 for location of the transect. The Schieland and Scruff groups are subdivided in tectonic successions and sub-units (S1, S2, S3, S4). Five main faults were observed, four constraining the half-graben and one (F3) fault plane that accommodates salt diapirism within the DCG further South.

Further observations of the Upper Jurassic layers show clear terminations towards the graben flanks in the low amplitude, low frequency seismic facies. This type of facies is indicative for sourceward migrating facies tracts (Matenco & Haq, 2020). The high amplitude reflectors do not exhibit such a feature, but they seem to be relative uniform in environmental facies. The progradational previously observed in the lacustrine deltaic marl of the Middle Graben Formation (Van Adrichem Boogaert & Kouwe, 1993), is interpreted as a basinward facies tract. Within the half-graben, there are seven distinctive higher resolution tectonic successions, with one additional subsidence feature on the eastern side of the central uplift feature marked as unit S3, mapped within the Upper Jurassic Schieland and Scruff groups. Unit S1 can be subdivided in five higher resolution TS, unit S2 is an individual TS and unit S3 & S4 form a TS with individual SFT and BFT.

In the eastern part of the Dutch Central Graben, the Rijnland group overlies the Kimmeridge Clay Group. The former group has large thickness variations and is significantly removed beneath the base North Sea Supergroup unconformity, which is a result of uplift and erosion during the Late Cretaceous inversion. The Rijnland Group significantly thickens on the Schill Grund Platform, while in the Step Graben some syn-sedimentary features are observed due to large thickness differences in the layers.

Due to the overall Late Cretaceous inversion and erosion, the coeval Chalk group onlaps over much older formations, such as the Kimmeridge clay in the west (figure 5). The thickness of this formation has significant lateral variations and is better preserved with syn-kinematic deposition along the graben flanks, where the amount of inversion decreases. Outside the graben, the Chalk group is better preserved, although local syn-kinematic wedges associated with inversion can still be observed. Locally, the salt diapirism resulted in syn-depositional small offset faults in the Cretaceous and Paleogene that are rooted in the Zechstein salt. Along the diapir margins later, a flank failure created large offsets within the Chalk and Rijnland groups. The overall geometry of the Chalk Group reflects the syn-kinematic deposition during the Late Cretaceous-Paleocene inversion of the Dutch Central Graben.

4.2 Section B

The second transect is situated approximately 5 kilometers southwards, where the Dutch Central Graben appears to be more influenced by the diapiric salt movements, such as observed by the collapse structure along fault F3, subsequently inverted by later deformation (figure 6). The Triassic sediments thin out above this intrusion and follow the same overall structure, showing syn-sedimentary halokinesis. Significantly less Zechstein salt is observed in the graben structures. Similarly with the previous transect, the seismic facies of the Rotliegend are less continuous and has lower amplitudes beneath the graben when compared with its flanks.

The Triassic groups shows local thickness variations and syn-kinematic stratal features along the eastern flank of the DCG. The features here coincide with large-offset faulting along fault F1, creating significantly more accommodation space, and thus thicker deposition. Along the western flank the formation is of continuous thickness and truncates into the Kimmeridge clay. The center of the Triassic is slightly thicker due to coeval subsidence along both its flanks, with relative thinning along the western margin due to stagnant circumstances. The Zechstein and Triassic are both deformed in the large synformal geometry that mirrors the underlying controlling faults. Interestingly, in the Step Graben the Triassic sediments show little thickness variations, apart from syn-sedimentary thickening due to salt withdrawal along the western margin. The resulting subsidence accommodated ~650ms for the Altena Group as well as the Upper Jurassic sediments. Syn-kinematic uplift during the Late Cretaceous inversion of the Step Graben center resulted in partial erosion of Triassic sediments and further erosion of the Rijnland Group west of the center. Due to the erosional surface, the Triassic is also discordantly overlain directly by the Chalk Group.

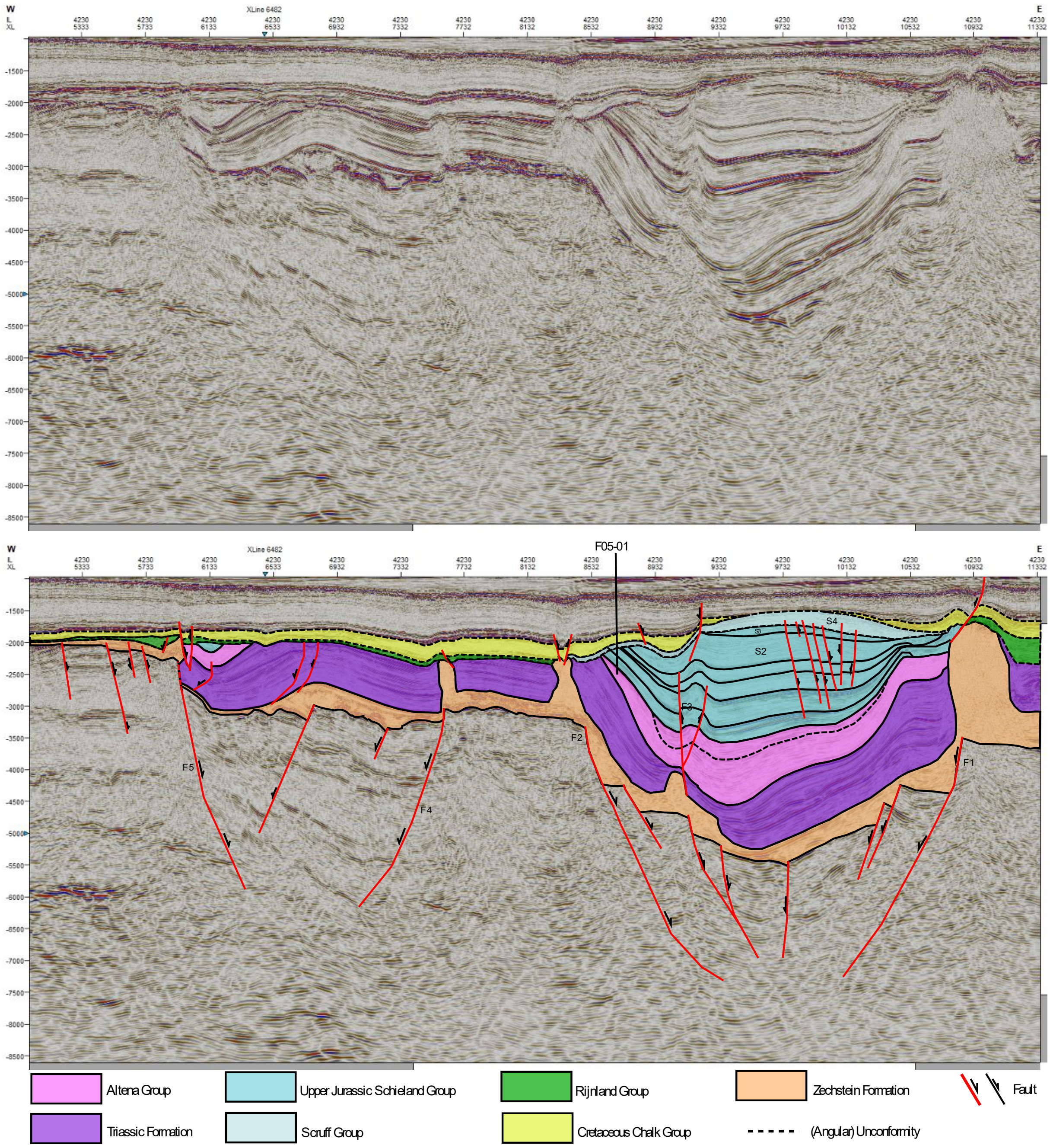


Figure 7: Seismic interpretation of the Dutch Central Graben and Step Graben in section B. See figure 1 for location. Four distinct subunits are defined in the Schieland and Scruff Groups (S1, S2, S3, S4). Five faults are labeled (F1 – F5) for a clear seismic description.

The Altena group is discontinuous in the rift shoulders due to lack of depositional space. The depocenter has shifted westward, as the layer significantly thickens towards the western margin. The formation seems to thin out eastwards, but due to syn-sedimentary faulting along F1 more accommodational space resulted in further deposition. In the west the Altena group truncates the Upper Jurassic Scruff and Schieland Groups. The thickness of these formations mirrors the gradual uplift of the bordering diapir. In this section the upper bounding unconformity is the Posidonia Shale Formation as well, but since the thickness differences are less apparent, it shows basin subsidence stagnation.

The Altena Group is overlain by both the Upper Jurassic Scruff and Schieland groups over an unconformity clearly observed in the basin center, but clear in correlation over the margins where the Posidonia Shale Formation pinches out. These Upper Jurassic sediments are similarly but less when compared with earlier deposited formations. The lower amount of thickness variability of the Jurassic sedimentation is in contrast with the previous transect and shows a slight eastward shift in depocenter. The Upper Jurassic sediments thin away from the center of the graben, which is indicative for a similar relative vertical movements of both bounding salt diapirs. The more rapid westward thinning attests to syn-salt tectonic sedimentation. In the east, an onlapping structure is observed, followed by a back-stepping pattern, which is marked by S2 and S3. Unit 2 has a depo-center shift towards the west, observed by a significant thickening. In contrast, units 3 and 4 shows a shift towards the east associated with aggradation followed by progradation, which is not observed in the west of the graben system, as all layers truncate into the Kimmeridge Clay, creating an angular unconformity. Similarly to section A, section B can be subdivided into BFTs and SFTs that are grouped in six different tectonic successions. The additional uplift event of the basin center resulted in faulting within the Upper Jurassic sediments, with faulting mostly rooted into the weaker Kimmeridge Clay. A potential flank collapse along the eastern diapir, reflected in a detached thin-skinned listric growth fault is associated with hanging wall stratigraphic wedges. This collapse likely started during TMS-2; in this case the hanging wall should be sandier relative to the footwall (Ten Veen, 2012).

The Rijnland Group was eroded from most of the Dutch Central Graben, but has a fairly continuous thickness along the Step Graben. Within the Schill Grund platform the group is thick due to more accommodation space. The Cretaceous Chalk group was deposited continuously onto the Kimmeridge clay, covering most of the Central Graben as a gradual southward shift resulted in an intra-Jurassic truncation decrease. The center was more eroded during inversion, which results in a seemingly large thickness difference. The seismic facies are characterized by low amplitude, high frequency reflectors. The layer thickness is uniform in the Step Graben, nearly unaffected by tectonic activity.

4.3 Depth conversion using seismic velocity model

The newest velocity model VELMOD-4a was released by TNO and Estimages (NLOG.nl). This model is made for time-depth conversion of large-scale seismic interpretations and the mapping thereof; to test the first-order interpretation this conversion was done for section A, using the calibrated average velocity. This model is comprised of 179 3D- and 136 2D-datasets that were digitized by TNO. Based on the orientation of the analyzed faults after this depth conversion it is clear the interpretation is feasible, as the normal faults are mostly oriented at a 60-degree angle; and no discrepancies are visible in the mapped formation horizons. The basin margins are clearly visible in this 1:1 depth conversion, depicted in appendix A (figure 31).

5. Tectonic reconstruction

5.1.1 Reconstruction of section A

Reconstruction of section A is based on flattening unconformities as well as predefined horizons from the first order interpretation. Onset of subsidence as well as faulting can be determined starting from the Germanic Trias groups and Altena group, followed by flattening distinctive subunits in the Upper Jurassic strata. Over-thickening in the Zechstein is observed in both salt intrusions due to Early Kimmerian remobilization of salt. However, this over-thickening is based on an extrapolated continuation of the Triassic. The Permian faulting creates a local syn- and antiform observed underneath the western diapir enhances this observation (figure 7A). This observation shows that fault F2 is coupled with the Permian basement. Within the Germanic Triassic groups, the syn-depositional basin subsidence linked to the Late Triassic rifting phase is observed by increasing accommodation space along the offset

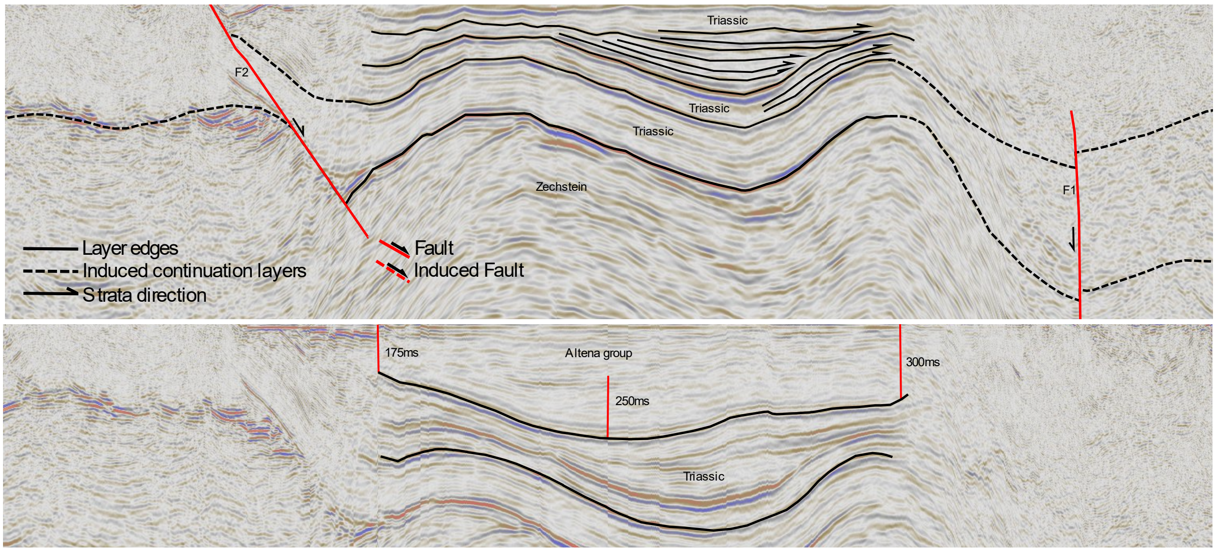


Figure 8A (top): Flattened Triassic top, large scale deformation patterns as well as fault accommodation. Faulting is induced from salt diapirs, not actual faults. Incorporated is a rim syncline in the Germanic Trias groups associated with salt movement. Figure 7B (bottom): Flattened Altena top, giving the amount of subsidence in the layer.

of faults F1 and F2. The location of the deep-rooted fault F1 implies upward propagation of the fault from the Permian Rotliegend. Along the eastern margin, a rim syncline associated with salt movement induces a significant compensatory subsidence of 200ms, which is decoupled from overburden (figure 7A). Within the rim syncline the reflectors onlap onto the underlying strata. The Upper Triassic shows lateral thickness variations, linked to the coeval rifting phase. From the flattened Altena top, there is syn-depositional subsidence up to 250ms in the Dutch Central Graben. This subsidence is accommodated by thermal relaxation and syn-sedimentary faulting along fault F1 resulting in 125ms more accommodation space in the eastern margin (figure 7B). The Altena group is deformed differently than under- and overburden: it is subsidence controlled, but is characterized by relative tectonic quiescence.

The Upper Jurassic top reveals a decrease in depositional space with a strong eastern depo-axis shift. Based on the stratal organization of reflectors of unit S3 and their terminations, the unit is deposited in a rim syncline. The downlaps are interpreted as tilted onlaps, which shows that the unit does not terminate due to low sedimentary influx, nor less accommodational space, but that the formation rather is a result of erosion of the Jurassic basin center (figure 8). The strong onlap shows that the unit is not influenced by faulting movements but salt diapirism. Unit S4 is deposited over a similar range as strata of units S1 and S2, overstepping previous basin margins. The strata are largely deposited at a slight tilt and terminate into underburden, indicative for the onset of rift termination or relative uplift of the sequence. The stratal organization does suggest salt withdrawal influences along the eastern margin and transgression. Induced continuation of unit S2 shows that in the west approximately 250ms of strata was eroded due to further uplift during deposition of unit S4 (figure 9).

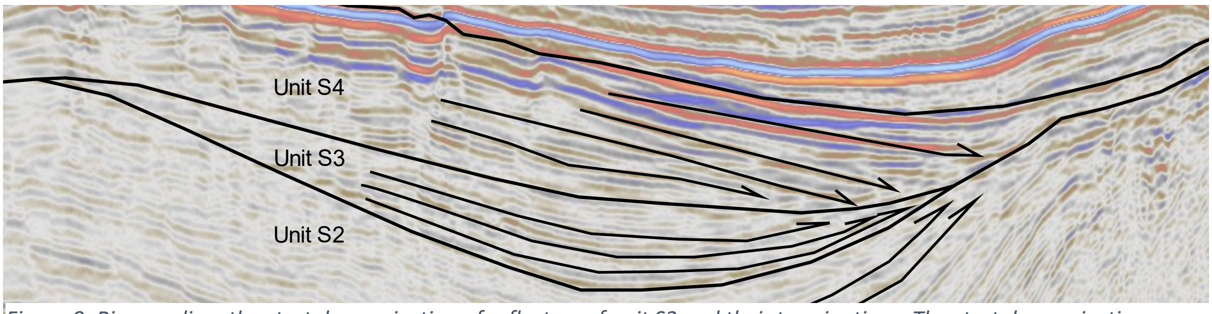


Figure 9: Rim syncline; the stratal organization of reflectors of unit S3 and their terminations. The stratal organization pattern is observed in the Upper Jurassic Schieland and Scruff Groups.

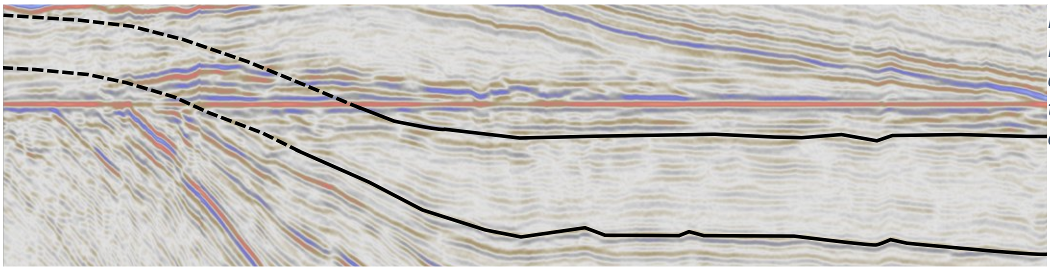


Figure 10: Expected continuation of the eroded top of unit S2.

Within the Schieland group two distinctive units are visible, one that shows aggradational features and one that shows regressive-type features. The depocenter of all strata shifted slightly eastwards, with a subsidence pattern along the eastern margin that influences underburden; a 50ms peripheral salt basin sink is observed (figure 10A). This is a similar structure as observed within the Triassic strata, associated with salt induced subsidence combined with low offset faulting along fault F1. The peripheral salt basin sinks further as S3 and S4 are deposited, accommodating an additional 125ms subsidence (figure 10B).

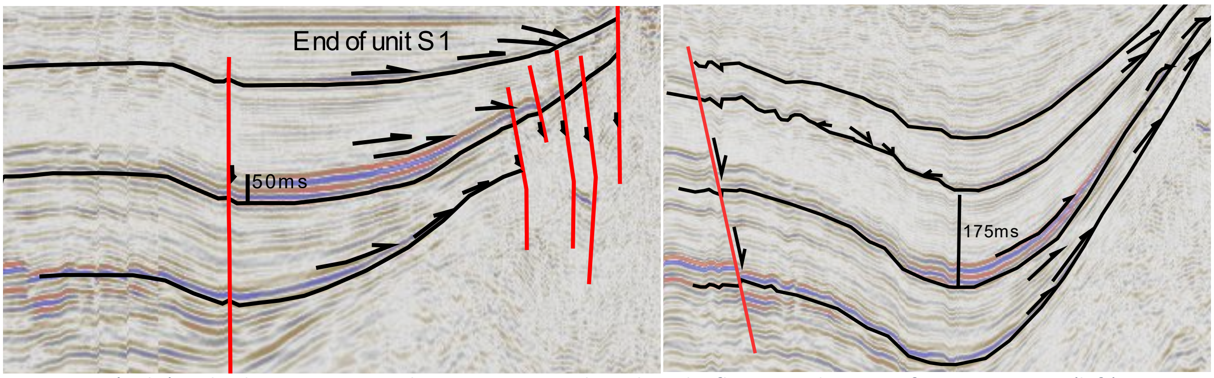


Figure 11A (right): Subsidence pattern in the Upper Jurassic based on the flat aggradation surface. Figure 10B (left): Subsidence pattern after flattening Kimmeridge clay.

An additional erosional event influenced the center of the Kimmeridge clay due to relative center uplift. The formation is syn-kinematic as the clay thickens in the flank and is mostly eroded at the top, with thickness differences of 250ms (figure 11). Relative timing of this second erosional event is Late Oxfordian – Early Kimmeridgian as the Rijnland group onlaps onto the previously uplifted Kimmeridge Clay. The low-offset faulting associated with the uplift terminates into the Kimmeridge clay, thus the event ceased during its deposition. These faults are not rooted into the Zechstein as they are decoupled from salt movement. The deposition of the Chalk group is of relative tectonic quiescence due to the relatively horizontal deposition, it mostly predates Cretaceous inversion and is a result of further subsidence and transgression. The transition between the Chalk Group and the Lower North Sea group shows a slight angular reflector termination of the stratal organization of the Chalk group (figure 11); a basin wide structural unconformity related to structural Cretaceous inversion after deposition rather than basin center uplift is observed in this section.

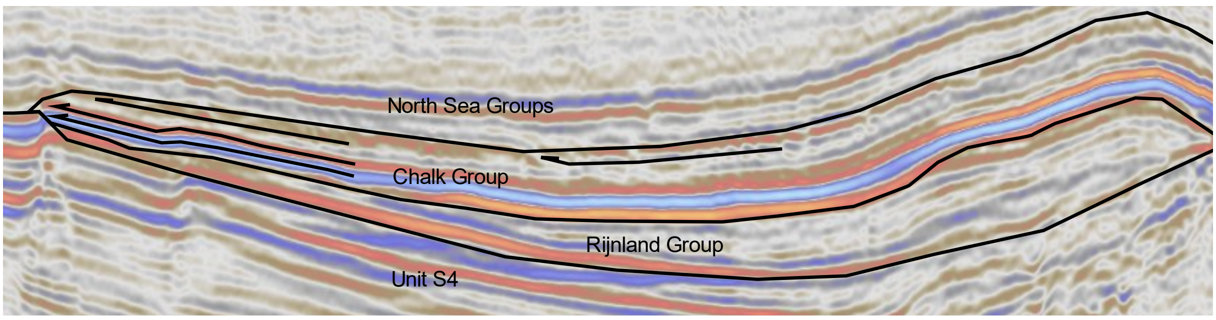


Figure 12: Reflector terminations within the chalk group indicative for the Cretaceous inversion.

5.1.2 Step Graben section A

Syn-depositional relative thickening of the Zechstein salt in the graben center and subsequent thinning along the western flank resulted in thickness variation within the Triassic Groups. A small erosive event occurred near the end of this thickening, as well as thinning along the eastern flank resulting in a small depression of approximately 200ms (figure 12A). Along the western flank the Altena group is syn-kinematically deposited within a local depression with apparent onlaps. As the Rijnland group has a continuous thickness, the salt remobilization within the entire half-graben stagnated during its deposition (figure 12B).

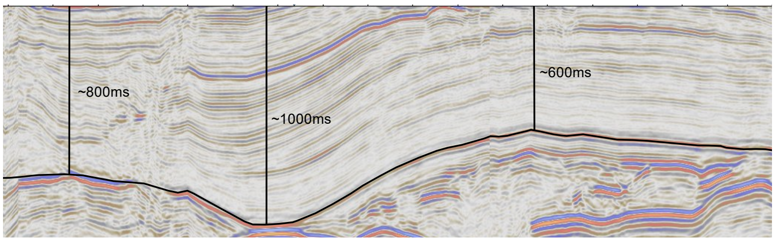
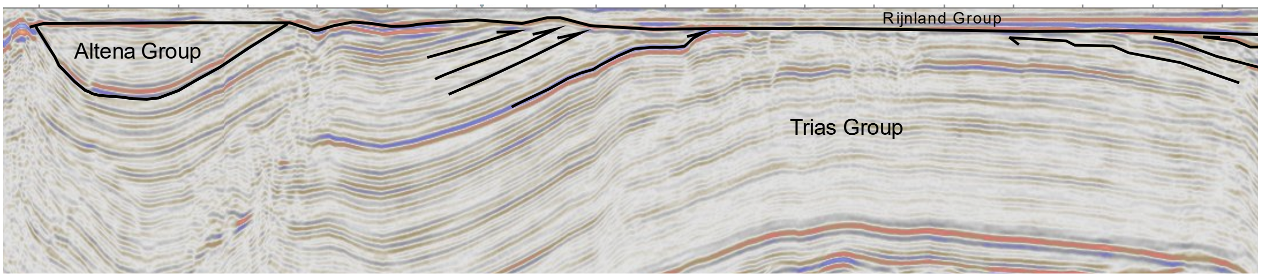


Figure 13A (Left): Thickness variations in the Trias Group.

Figure 12B (below): Relative timing of remobilization and subsequent uplift and sinking of the Trias Group. Angular truncation into the relative uniform thickness of the Rijnland Group.



5.2.1 Reconstruction of section B

Focusing on the deposition of the Upper Triassic, the fault F1 is clearly coupled with the Permian basement (figure 14), showing accommodational features due to thermal subsidence of the Permian. The fault penetrated upwards into the Triassic groups. Fault F2 is hard-linked with the Permian as well, propagating upwards (figure 14). The growth wedge observed in section A is also prominent in this section, indicative for relative syn-depositional faulting along F1. No offset faulting is observed along F3, most likely because the collapse and salt diapirism occurred here later. Along the western margin the layer significantly thins, linked to syn-sedimentary salt movement. After flattening the bottom of the Upper Jurassic sediments, a rim syncline within the Altena group along the western margin shows that salt withdrawal underneath the structure, combined with salt redistribution along fault F3 influenced the geometry of the basin (figure 13). Further evolution of the Altena group is similar to section A (figure 5), where the Posidonia Shale Formation was deposited during a phase of tectonic quiescence, as the consistent motion along fault F1 seems to stagnate and no significant subsidence is observed. The formation is decoupled from under- and overburden as deformation differs from chaotic brittle to more continuous. The second fault is visible in the structure, but the since the structure between both faults is different from the final interpretation, diapirism has not occurred yet (figure 5).

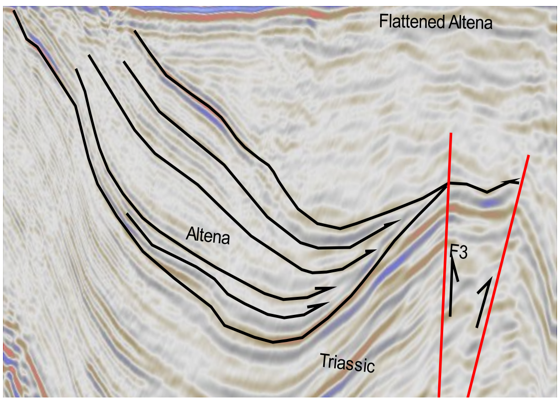


Figure 14: Interpretation of a structure within the Altena Group, linked to fault F3 and salt redistribution.

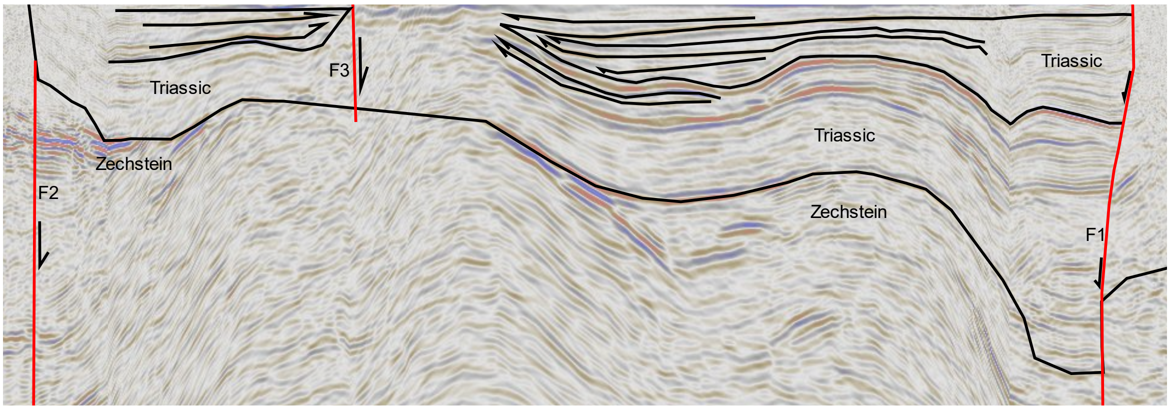


Figure 15: Growth structure in the Germanic Trias showing onlapping strata. Fault F1 is partially correlated to account for later salt diapirism. An additional growth structure confined by faults F2 and F3, and a clear hard-linked fault F2.

The onlapping unit S1 encompasses the entire basin and oversteps previous basin margins. Within the strata, large thickness variations are observed, linked to sub-salt faulting along fault F3. The layers west of this fault are significantly thinner due to less accommodational space (figure 15). Faulting along fault F1 ceased during deposition of unit S2 as the unit exhibits a backstepping pattern. As observed in section A, uplift related normal faults formed within the Upper Jurassic that continue into the Kimmeridge Clay, but are not rooted into the Zechstein.

From the flattening of the Chalk group, a clear difference in depositional depth is apparent for the Kimmeridge Clay. The truncation of the defined tectonic sequences along the western margin is related to erosion due to subsequent uplift in the west (figure 16). However, since the Kimmeridge Clay thickens in this part of the graben, relative uplift of the middle and eastern part of the graben must have occurred with a relative timing predating this erosional event and during the deposition of the Clay formation as it shows syn-kinematic features, which is in line with the late Oxfordian deformation event. The relative uplift also indicated by the erosional pattern is strengthened by the regressive depositional type of sequence S2 and S3 (figure 16). Based on this additional information an extra distinction can be made of the lower-order tectonic succession, where S1 is an SFT, and the other units comprise the BFT. The flattened Chalk Group shows a similar onlap pattern as the Rijnland Group, indicative for termination of uplift and gradual transgression. It shows a clear truncation at the top, related to the Cretaceous inversion.

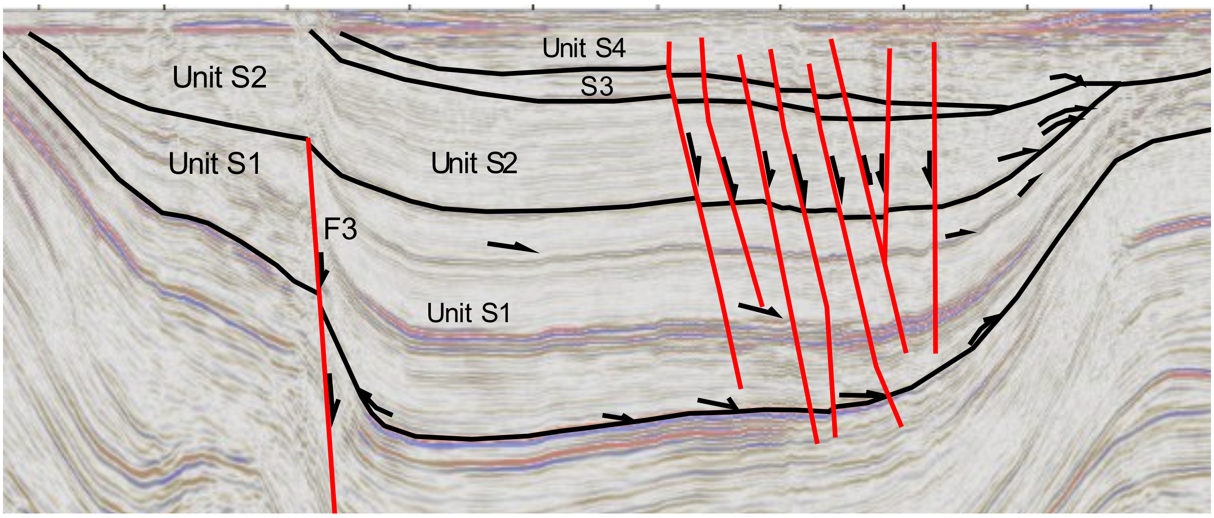


Figure 16: Enlargement of the subunits in the Jurassic Schieland Group showing depo-axis shifts.

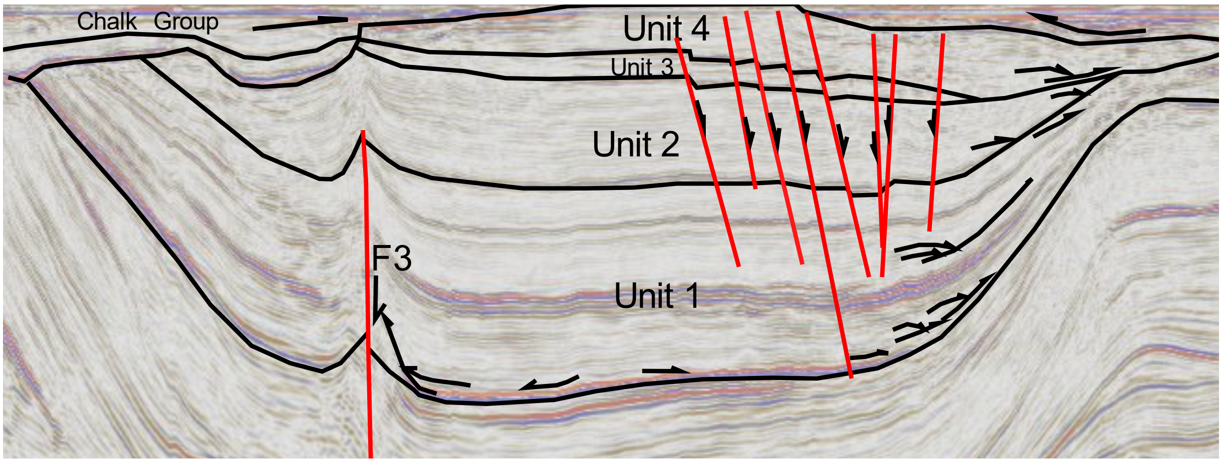


Figure 17: Flattened Chalk Group; provides further evidence for subdivision in tectonic successions. Truncation is apparent. Slight angular rotation of the Chalk group and reflector terminations are indicative for relative Kimmerian uplift during deposition.

6. Well analysis

6.1 Well log facies

Upon the analysis of wells F05-01, F05-03, F06-01-S1 and F09-03 recurring well log facies units can be distinguished (figure 17). The first facies reflect a strong boxcar pattern indicative for aggradational features, and is comprised of relatively high GR values, indicative for mostly silts and clays. The facies in non-aggradational parts of the basin shows a subtler coarsening upwards trend in these facies (lacustrine). Well log facies 2 has a gradual coarsening upwards in relatively high GR intervals, and high-density values in the marginal marine sequence. The third facies are similar; however, the coarsening upwards facies association is observed by multiple coarsening upwards parasequences and has low GR – high density intervals indicative for local coal layers in the marginal marine/lagoonal facies. Well log facies 4 reflects a strong gradual coarsening upwards sequence from relatively high GR and density values to relatively low GR values, mostly a change from clays to sands in the coastal plain facies. The entire facies association is comprised of an alternation of GR minima and maxima. Well log facies 5 reflects a fining upwards trend, with a strong alternation between high and low GR values in the shoreface facies. Well log facies 6 has very low GR values, relatively high sonic values, and is block shaped; this is indicative for a chalk-rich lithology.

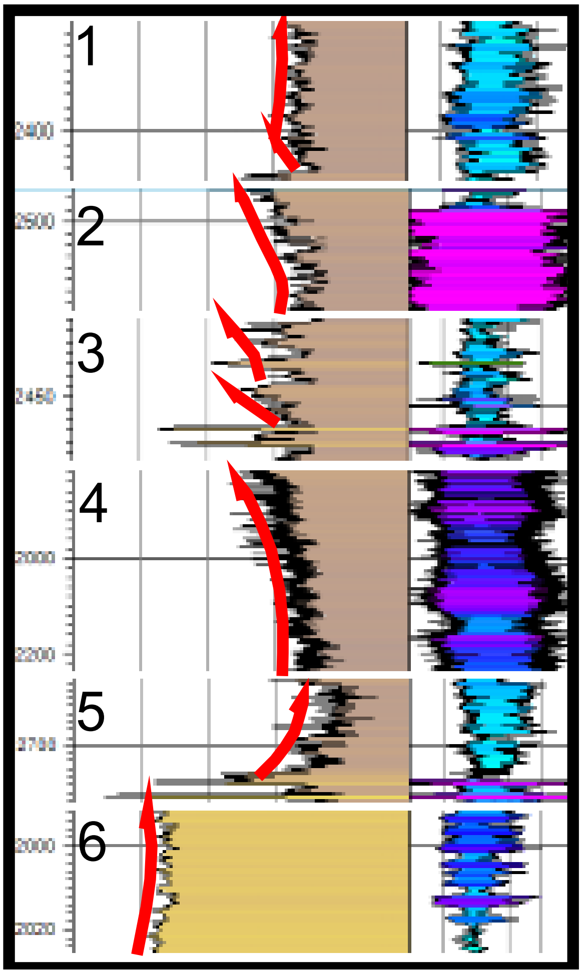


Figure 18: log classifications based on subdivisions of Cant (1992). This is a general subdivision as the facies can differ in each analyzed well due to thickness differences as well as mud-drilling influences. The log on the left reflects GR values (increasing towards the right), and on the right a combined density-neutron log.

6.2 Well log F05-03

The facies of well F05-03 (situated approximately 1km south of, but representative for, section B) changes from deltaic to fluvio-lacustrine (Lower Graben Formation and Middle Graben Formation) to marine embayment (Upper Graben Formation), ending in an openly marine to a proximal coastal environment (Scruff Group). The well log has a well-defined lower order cyclicity of three distinct sedimentary cycles; derived from the combined gamma and density-neutron logs. The logs provided grain size trends, well log facies are derived and improved upon using the Mobil well log report (figure 18).

The lower order cycles at the level of the parasequence sets provide information regarding the basin tectonics coupled with eustatic changes and the corresponding source climate. A higher-order subdivision shows great cyclicity; which can be subdivided in individual parasequences. These parasequences reflect generally autogenic processes, and are too small (usually less than 10m) to be correlated to seismic data. The desired basin tectonics coupled with changes in eustasy and the climate of the source area are reflected in the lower order cycles (Matenco & Haq, 2020). In the final interpretation the focus therefore lies on the lower order cycles.

Cycle 1 coincides with the mid to late Callovian Lower Graben Formation, and is comprised of an alternation of soft to very soft silty claystone and predominantly very fine to fine grained sandstone. The cycle transitions from shaly well-sorted rounded sandstone interbedded with claystone to silty shale and clay back to moderately sorted subangular sand dominated intervals. From the bottom the cycle is fining upwards, alternating between <6m relatively medium grained sandstones and silty shales/clays. Based on the deltaic depositional setting; such a trend represents the formation and lateral migration of delta-channels. Upon reversal, the cycle coarsens upwards and transitions from silty shales/clays back to relatively coarser sand dominated intervals. The sandbanks have a

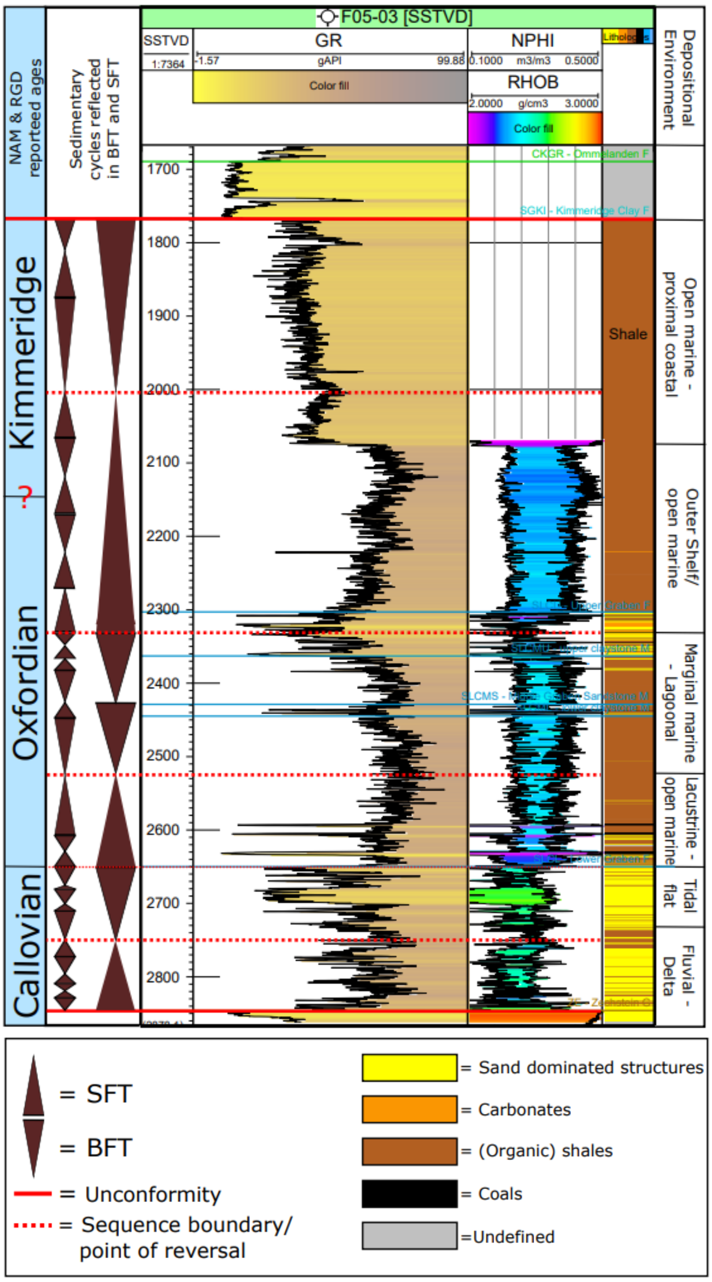


Figure 19: Well log analysis of F05-03. A subdivision of basinward- and sourceward migrating facies was made based on the gamma and neutron-density logs on the lower order scale, and higher order parasequences. A generalized lithological column, combined with the sedimentary facies (based on reports by the RGD, available at NLOG.nl and member information from dinoloket.nl). The depositional environment is derived based on trends, lithology and detailed reports (Van Adrichem Boogaert & Kouwe, 1993).

thickness of up to 25m and show a greater overall cyclicity; this most likely represents a tidal influence on the deposits. Cycle 2 coincides with the early to mid-Oxfordian Middle Graben Formation and part of the Upper Graben Formation. It consists of relatively fine-grained facies that has no significant trends. There is a subtle fining upwards followed by a coarsening upwards sequence. The bottom of the fining upwards trend is defined by a sequence that contains three coal layers, interbedded with facies with higher GR values: predominantly carbonaceous, slightly calcareous, clay- and siltstones. The highly laminated sequence is well-sorted and has low-energy particle sizes; a subtle sawtooth pattern combined with the absence of sandy deposits reflects a lacustrine environment with marine influences. The overlying lower order coarsening upwards sequence goes back to the sandy intervals of the Middle Graben Sandstone and the Upper Graben Formation, which is typical for a lagoonal to marginal marine setting.

In cycle 3 the lower cycle is defined by a subtle fining upwards resembling a serrate pattern. The lithology changes from dolomite interbedded with sandstone to predominantly claystone with stringers of dolomite. The presence of dolomite combined with the claystone shows an environmental shift to outer shelf/open marine. The upper part has relatively low GR values, shaped in a block-like pattern. The lithology shows an increase in sand within the claystone dominated interval. This might represent a shift into an open marine to proximal coastal setting. The Turonian to Maastrichtian Ommelanden Formation overlies the Upper Jurassic sediments, bounded by an erosional unconformity. The relatively low GR signal is shaped like a uniform block of mostly limestones. The depositional environment is representative for a relatively stable, low-energy carbonate shelf. The sedimentary cycles in this well log have a cyclicity that corresponds to 2-5 Ma. Interestingly almost no aggradational features were observed within the well log, as opposed to well log F05-01 which is situated along the western margin of the Dutch Central Graben. Therefore, the aggradational features are solely linked to the stratal pattern in the vicinity of the graben margins.

6.3 Well log F06-01-S1

Well F06-01-S1 penetrates section A and is comprised of the same formations as well F05-03; showing a similar lithological trend (figure 19). However, more accommodational space was available as the higher-order cycles are thicker. This is in line with the placement of both wells; well F06-01-S1 is more centered, and F05-03 is situated on top of a latter Zechstein intrusion; resulting

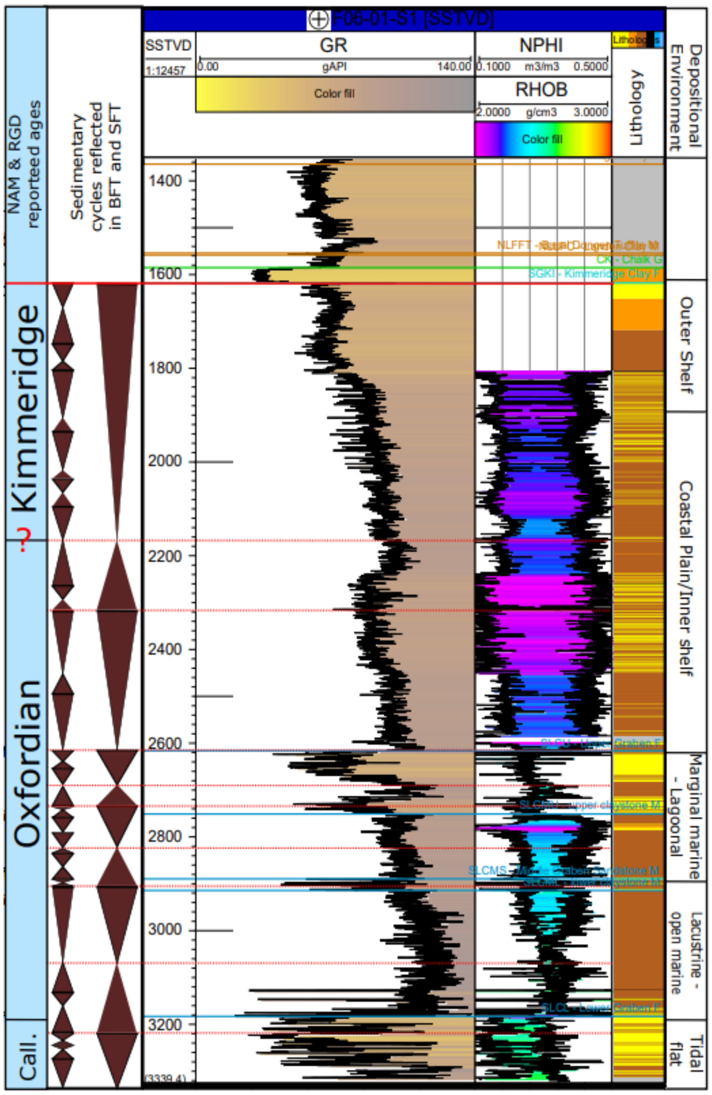


Figure 20: Well log analysis of F06-01-S1; legends and data references are defined in figure 18. The age constraints are correlative between the Oxfordian and Kimmeridge due to contradicting fossil-contents in the members (based on NLOG.nl reports by the RGD and Mobil).

in compaction/less accommodational space. This resulted in two more lower order cycles. The subdivision in lower order cycles proves different as cycle one has a 'reversed pattern'. This pattern is observed on seismic data and results from the fact that only in half of the late Callovian Lower Graben Formation well logs were available. Therefore, the lowermost part of the first cycle is not depicted in the well log. The visible part of cycle 1 changes from a claystone dominated sequence up to medium grained massive sandstone beds alternated with sandy and silty claystones, which may reflect most likely a tidal flat.

Cycle 2 reflects a lacustrine – open marine environment and coincides with the upper part of the Lower Graben Formation, and part of the Early Oxfordian Middle Graben Formation. The base of the lower interval contains seven distinct coal layers. The two uppermost coal layers are similar to those observed in well log F05-03, but the lowermost are better observed in well log F06-01-S1. A fining upwards sequence is clear, changing from thick sandstone beds to a claystone. From the point of reversal upwards a subtle serrate pattern with a slight coarsening upwards trend where the facies become siltier, coming to a halt at the first distinct siltstone of the Middle Graben Sandstone Formation. The marginal marine third cycle encompasses both the Mid-Oxfordian Middle Graben Formation and the Late-Oxfordian Upper Graben Formation. It is comprised of mostly fine grained facies; similar to that observed in the upper part of cycle 2. The bottom of the fining upwards sequence is comprised of silty sandstone with two additional distinct coal layers changing into a soft claystone. The top of the overlying coarsening sequence is defined as the first Upper Graben sandstone.

Cycle 4 is confined to the Late Oxfordian Upper Graben Formation and based on the very distinct higher order double funnel cyclicity of this lagoonal formation as defined by Van Adrichem Boogaert & Kouwe (1993). The depositional facies changes from dolomitic siltstone to shaly claystone in the fining upwards cycle, and from shaly claystone to fine grained well-sorted sandstone interbedded with two coal layers. Cycle 5 and 6 are observed in the Late Oxfordian – Late Tithonian Kimmeridge clay. Cycle 5 is comprised of one coarsening upwards sequence with relatively high GR values, and a subtle serrate pattern. It gradually coarsens upwards from a shaly clay to a more silty clay. The fining up sequence of cycle 6 reflects a change from sandy silts to claystone, whereas the coarsening upwards sequence changes from claystone to an organic-rich siltstone as well as a very fine poorly sorted sandstone containing shell fragments (NLOG composite well log of F06-01-S1). The depositional environment changes from a coastal plain to the outer shelf. The Upper Jurassic sediments are discordantly overlain by the fully marine Upper Cretaceous Chalk Group, marking an erosional unconformity. It is a low GR chalk mudstone that contains undefined fossils. Unlike well F05-03, the distinctive subgroup is not indicated, therefore accurate more detailed dating cannot be defined. The recurring cyclicity is 2-5 Ma, which was also observed in F05-03.

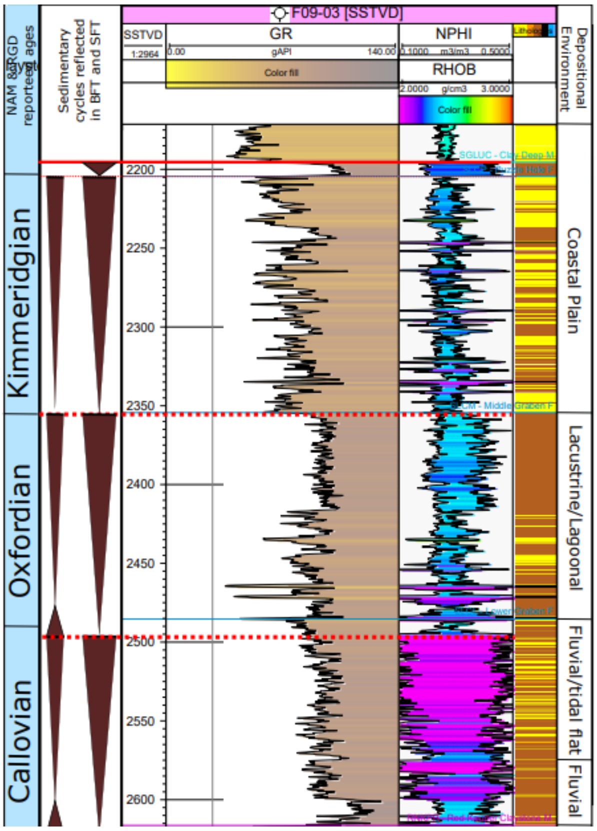


Figure 21: Classification of well log F09-03. Legend and references are provided in figure 18.

6.4 Well log F05-01 and F09-03

Uncertainty along the western basin margin in respect to the truncation of the Upper Jurassic sediments can be deciphered by analyzing well log F05-01 (penetrating seismic section B). In order to understand whether the truncation reflects a progradation or eroded aggradation, a gamma log combined with a density-neutron log of the well has been analyzed. Well log F05-01 (figure 21) starts on top of the diachronous Posidonia Shale Formation unconformity, which marks the first succession boundary. The depositional environment changes upwards from deltaic to fluvio-lacustrine (Lower Graben Formation and Middle Graben Formation) to marginal marine embayment (Upper Graben Formation) and ends openly marine (Scruff and Chalk Group). As opposed to previous well logs, not situated in the vicinity of basin margins, only one clear lower order aggradational sedimentary cycle can be distinguished in the grain size trends. This observation is in agreement with the previous hypothesis that the erosionally truncated groups were either aggradational or progradational. The higher order subdivision shows that the Chalk Group, Kimmeridge Clay, most of the Middle Graben, and Aalburg Formation are comprised of aggrading trends, some closely resembling a prograding trend (well log facies 1). In parts of the Central Graben subgroup cyclicity can be observed; these parasequences reflect the autogenic processes of the basin. This cyclicity is best observed in the Upper Graben Formation that reflects two cycles of <20m and the Lower Graben Formation that contains two cycles of <30m. One small reversal pattern is observed in the Middle Graben sandstones.

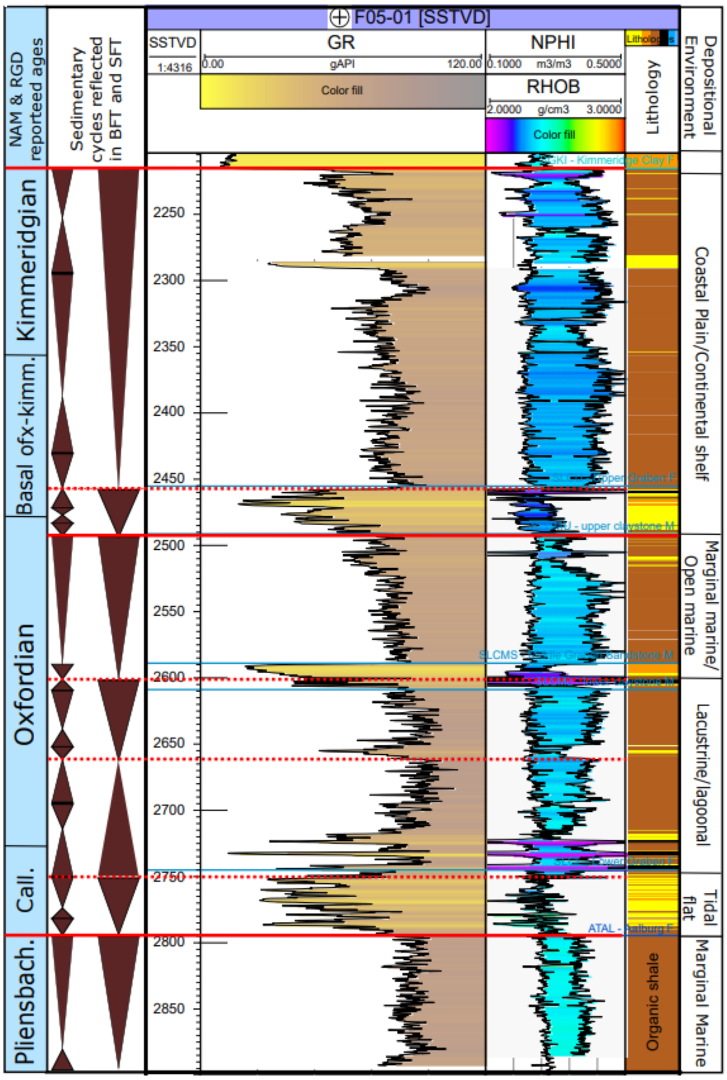


Figure 22: Well analysis of F05-01. The age constraints are carefully researched and based on fossil and isotope reports available on NLOG.nl. The legend and other references are included in figure 18.

In support of the first-order interpretation of the Upper Jurassic sediments along the eastern flank within the Dutch Central Graben, a short interpretation is provided for well log F09-03 (figure 20). Important to note is that this well is located 13km south of section B; and upon further analysis is not representable for either section. The aim was solely to understand the behavior of the trends in both flanks, and how they would change based on the corresponding faulting sequences. No different trends were found in the Lower Graben Formation as well as the Middle Graben Formation, comprised mostly of well log facies 4; some subtle coarsening upwards trends are observed. The Puzzle Hole Formation is mostly progradational with the occassional aggradational sequence (well log facies 2).

6.5 Well log F03-06

Well log F06-01-S1 is the only well log located in the basin center where the sedimentological facies and its log expression seems less affected by the faulting present at the basin margin. To strengthen whether the sedimentary cycles reflect allogenic factors rather than autocyclicity, a similar well log should provide a similar organization of the sedimentary cycles. Well log F03-06 provides this information (figure 22).

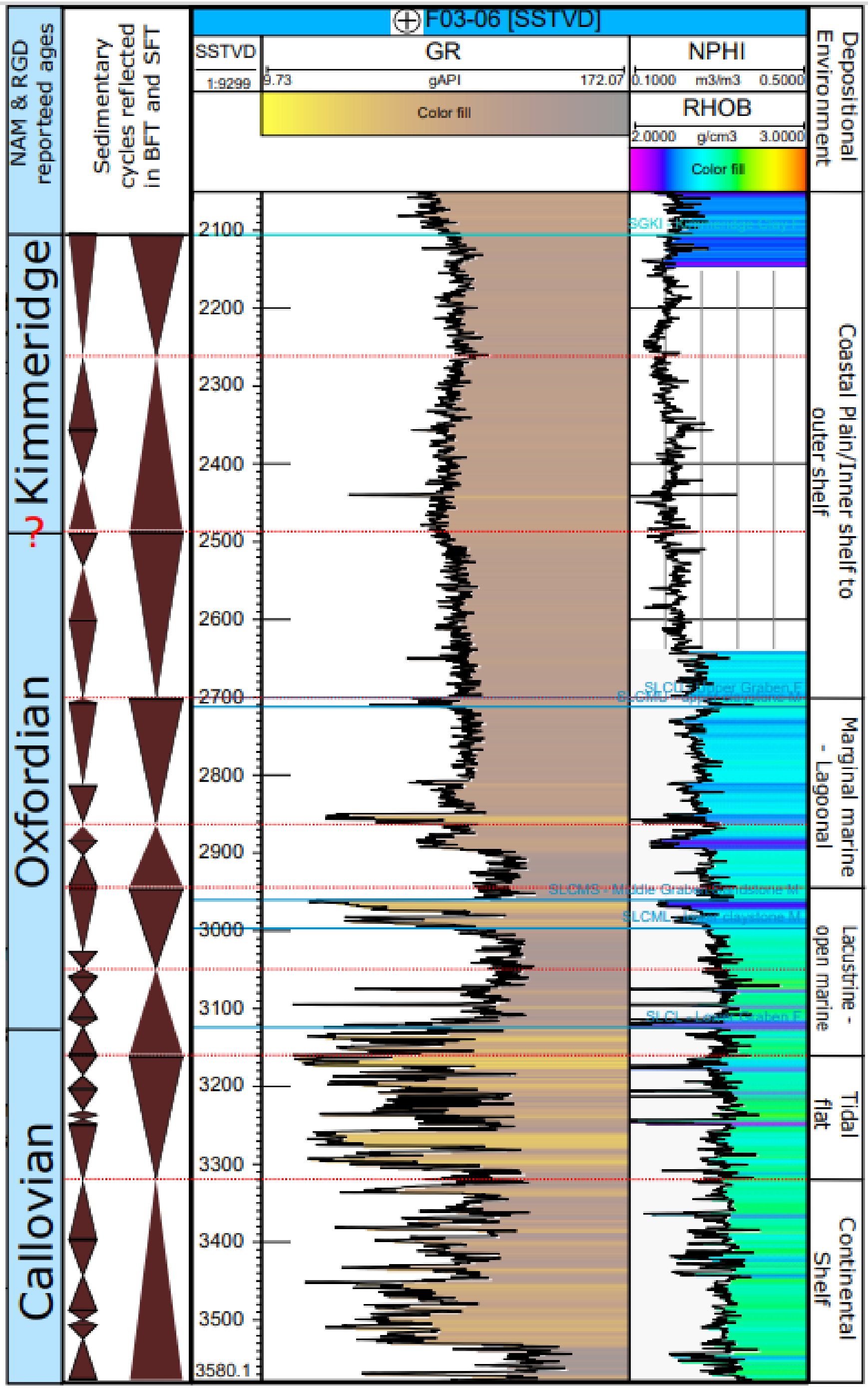


Figure 23: Well analysis of well F03-06. The age constraints are closely correlated to Van Adrichem-Boogaert & Kouwe as provided by dinoloket.nl. Legend and further references are included in figure 18.

The first cycle is complete, as the well log runs through the SFT as well that was missing in well log F06-01-S1. The second and third sedimentary cycles are identical in both wells. Interestingly, the Upper Graben Formation is nearly missing from well log F03-06, and seems to be a result of little to no sedimentation in the northern area. As the Upper Graben Formation is less deposited in this well, we cannot define an individual lower order cycle. However, the fourth 'missing' lower order tectonic cycle is reflected in a higher order sedimentary cycle. The Kimmeridge Clay is subdivided in two identical cycles when comparing both wells. The fourth and fifth sedimentary cycle, in well F03-06 and F06-01-S1 respectively, are marked by a single BFT, whereas the last cycle have both a SFT and BFT. As the general structures are identical in both wells, it becomes clear that autocyclicity at the level of parasequence sets can be ruled out. Furthermore, the depositional evolution of both basin parts is nearly identical.

7. High resolution seismic analysis combined with well logs

7.1 High resolution seismic facies analysis

Wells F05-03 and F06-01-S1 provide a high-resolution framework for the analysis of tectonic successions within the seismic data. Well F05-01 coincides with the accommodational space created by faulting along fault F1, whereas well F05-03 is situated on top of fault F3 and reflects salt movement upwards (figure 24, 25). Therefore, these two marginal wells demonstrate tectonics better, whereas F06-01-S1 might represent auto-cyclicity as lower order sea-level changes cannot be ruled out based on one well log. The lithofacies can be predicted using a seismic facies model based on basinward- and sourceward migrating facies tracts, which can be verified in section B, as only section A has feasible well log control.

As observed in the first order seismic interpretation, the combination with well logs F05-01 and F09-03 shows a basinward migrating facies associated with aggradational features along the margins, whereas well logs F05-03 and F06-01-S1, these facies are more commonly defined by progradational trends. Reflected in the well log data, these aggradational and progradational trends are comprised of highly differential facies; ranging from sands to clays, and occasionally coal layers. As a result of these strong contrasts, the corresponding reflectors have a high amplitude and are very clearly defined in the seismic lines, observed in example 1 (figure 23). Further characteristics are a low-intermediate frequency, continuous reflectors, example 2 & 3 and might show downlap in the basin center when the facies has lower contrasts, example 3. In the basin center the basinward migrating facies become less prominent. The defined sourceward migrating facies in the well logs consist of mostly clays and shales; therefore lacks strong lithological contrasts, resulting in low amplitude reflectors, example 4. Along the margins these facies are truncated, or show strong onlap over underburden, example 5.

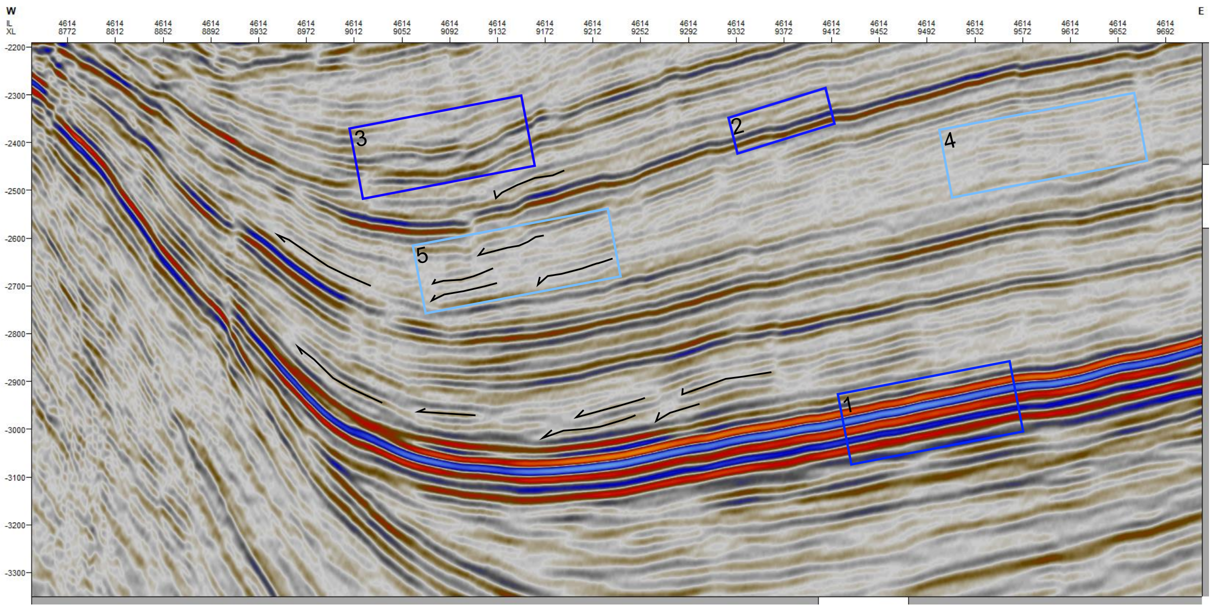


Figure 24: High-resolution analysis of seismic facies based on section A, confined to the Upper Jurassic sediments. Dark blue examples are BFTs whereas light blue examples are SFTs. Their appearance is arbitrary along the entire basin, but dominant features provide a clear subdivision.

7.2 Classification supported by well control section A

Given the location of well F06-01-S1 at far distanced from the marginally controlling faults or salt diapirs, the presence of well-defined cyclicity in thick Upper Jurassic sediments combined with a high sedimentation rate, and no external seismic truncation, makes the crossing seismic section a good starting point to classify using the newly defined high-resolution seismic facies analysis. It is important to understand whether the cyclicity is solely eustasy-driven, or controlled by tectonics. The well log is used to support the interpreted basinward- and sourceward migrating facies (figure 24). Well log F06-01-S1 defined six lower order cycles only, and the cyclicity seemed less well-defined than what is observed in the seismic section. The placement of the well log resulted in neglecting two sourceward migrating facies tracts, which were clearly visible using the seismic facies analysis. Therefore, a seventh tectonic succession could be defined, as well as the missing fining upward sequence of the first tectonic succession. The combined analysis finds that a continuous cyclic alternation is apparent (figure 24).

The first tectonic succession is deposited on top of the erosional unconformity of the Lower Jurassic Altena Group. Both the SFT and BFT are equally thick in the center; the basinward migrating facies tract defined has the highest amplitude in the section and is more widespread along the margins. The second tectonic succession is comprised of a much thicker SFT. The observed BFT extends further eastwards, but terminates before the basin margins onto the underlying SFT in the west. The third tectonic

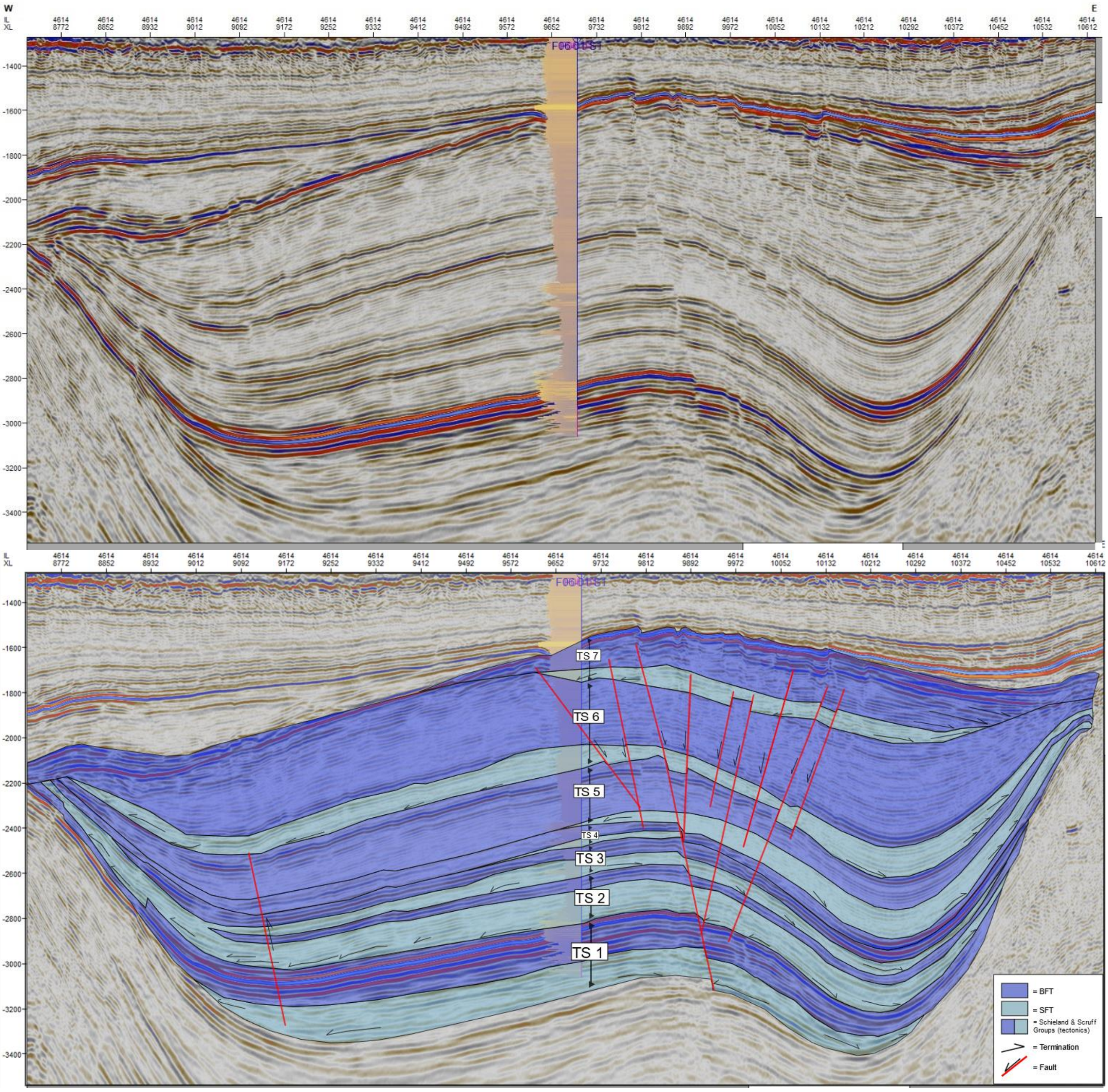


Figure 25: high-resolution tectonic succession interpretation. The analysis is restricted to the Upper Jurassic basin infill. The subdivision is based on the high-order seismic facies classification, combined with the well log classification.

succession has equally thick parts, the SFT terminates before basin margins; the BFT extends further laterally. Tectonic successions 4 and 5 have a very small SFT that is restricted to the eastern part of the basin. Both are overlain by a prominent thick BFT's that show apparent onlaps in the clinoformal reflectors. These reflectors are of intermediate amplitude and are predominantly defined based on other characteristics such as the termination of reflectors and the stratal organization. Both tectonic successions are linked to eroded aggradation, meaning that the western part has been eroded. The sixth succession has a thin basin-wide SFT, and a much thicker over-stepping BFT. The last tectonic succession oversteps basin margins, with a similar SFT to TS 4 & 5 with a thick high-amplitude BFT. The last two successions overstep the basin margins, and result in the apparent erosional truncation of the lower tectonic successions. Tectonic successions 5, 6 and 7 are in the Kimmeridge Clay and are predominantly comprised of BFT's overstepping the basin margins.

7.3 Combined well log and seismic facies section 4162

In an aim to project both well log F05-01 and F05-03 onto a section to link the grain size trends to the seismic section, a different section was chosen to interpret. Using mostly the predefined high-resolution seismic facies analysis, the entire Upper Jurassic part of the basin was subdivided in BFT and SFT trends. As no previous first-order interpretation was performed on section 4162, the predefined high-resolution seismic facies analysis was only supported by the well log interpretation, and therefore is a good section to test the tectonic successions model (figure 25).

In this section six tectonic successions were defined, whereas a seventh was found in section A. It becomes clear that the well log classification in BFT's and SFT's into the lower order cycles is too generalized, as well log F05-03 only found 3 sedimentary cycles. The first tectonic succession starts on top of the erosional unconformity of the Altena Group; with equally thick well-developed parts. The lower sourceward migrating facies tract is restricted to the basin center again; it slightly continues west of the salt tear intrusion, but pinches out before the basin margins, showing a strong onlap over the Altena Group. The overlying basinward migrating facies tract encompasses the entire basin. Tectonic succession 2 and 3 are slightly thinner, but have the same pronounced features, and follows the defined seismic facies analysis. The sourceward migrating facies tract of TS 3 discontinues west of the intrusion, whereas that of TS 2 truncates into the upper tectonic succession, following the entire basin margin in the west. Tectonic succession 4 is very thin, and either discontinues in the western margin, or the BFT merges with the two underlying tectonic successions. Both TS 5 & 6 show an angular erosion pattern in the basinward migrating facies tracts, as well as an angular erosion pattern showing a large angular rotation in strata, and the TS are significantly thicker than underlying TS. TS 5 has a pronounced SFT which may have been deposited after a strong erosional event, likely after TS 4. During the deposition of these two last TS a coeval margin uplift occurred followed by erosive events. Interestingly, the tectonic successions seem to gain more depositional space in the eastern margin, seemingly building out eastwards. In the basin center, the BFT's of TS 3, 4 and 5 are defined by intermediate amplitudes, and therefore the subdivision was mostly based on additional defined features of the seismic facies analysis.

Comparing both sections, it becomes clear that section 4162 is influenced by more sediment-starved SFT's, which may reflect a farther location of the source area. The first four tectonic successions have evolved in similar fashion, however, the upper Kimmeridge Clay successions are developed in different settings. In section A both TS 6-7 are nearly mostly comprised of BFT's; indicative for either a high sediment supply or rapid subsidence. Knowing the history of the area, the latter seems unlikely given the timing. In section 4162 the fifth succession is sediment-starved, or influenced by rapid uplift and subsequent erosion. Based on the features of the BFTs the latter deems more feasible. Therefore, it seems that salt-driven uplift has played a larger role in the southern part of the Dutch Central Graben, whereas a high sediment supply was available in the northern part. The well log analysis showed that the tectonic successions were 2-5 Ma; where the largest successions were found in the Kimmeridge Clay. These successions were proven to be more complex, and should be subdivided into more cycles, returning a smaller cyclicity of up to 3 Ma. Comparing these results to the first-order interpretation, it becomes clear that the well logs provided a clearer subdivision into seismic facies representative for the tracts. The number of tectonic successions were overestimated in the first-order interpretation, resulting in 1-2 extra successions.

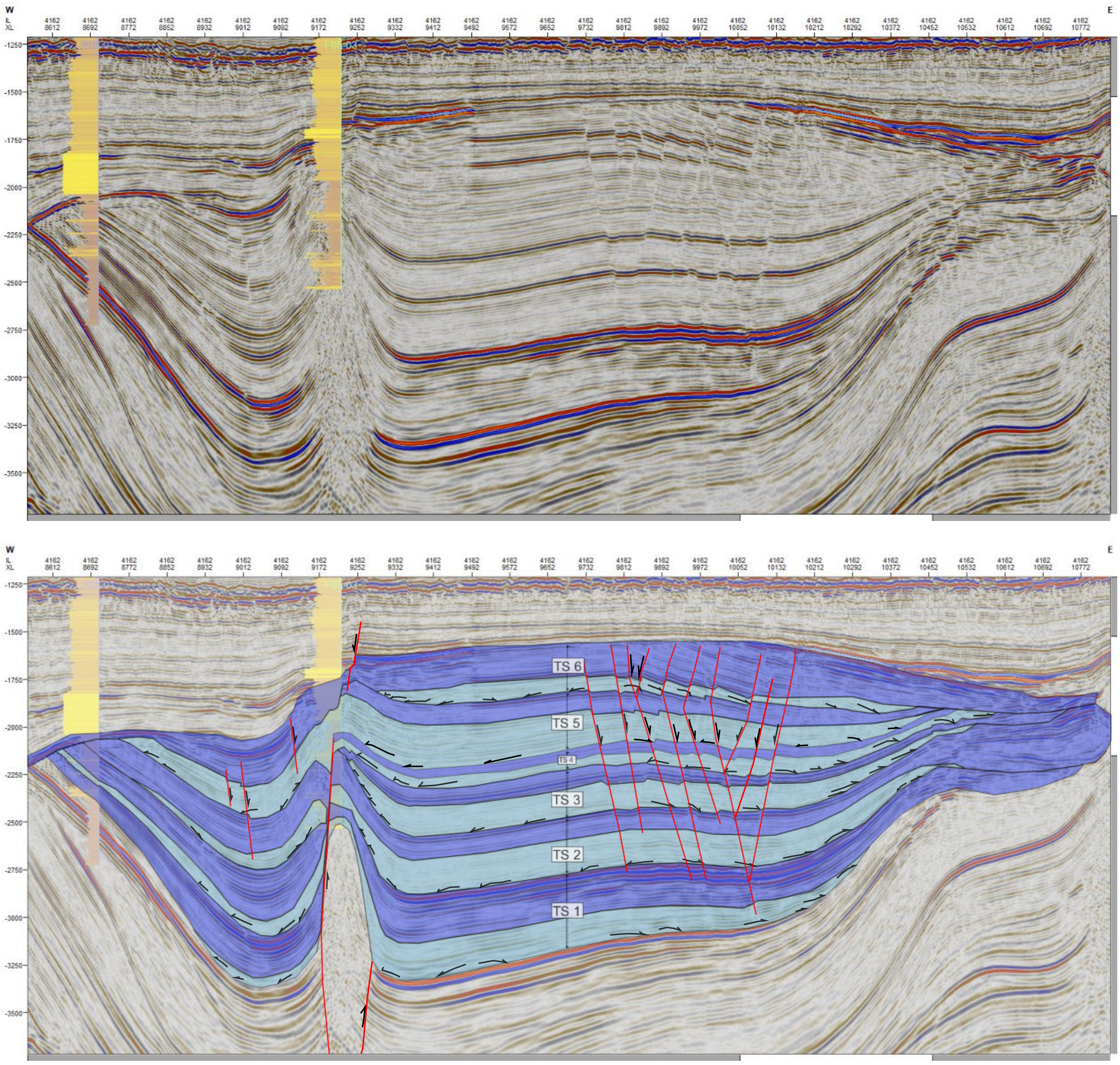


Figure 26: High-resolution interpretation of the Upper Jurassic with well control, based on the seismic facies analysis. The sequence is subdivided in tectonic successions. Legend is in figure 24.

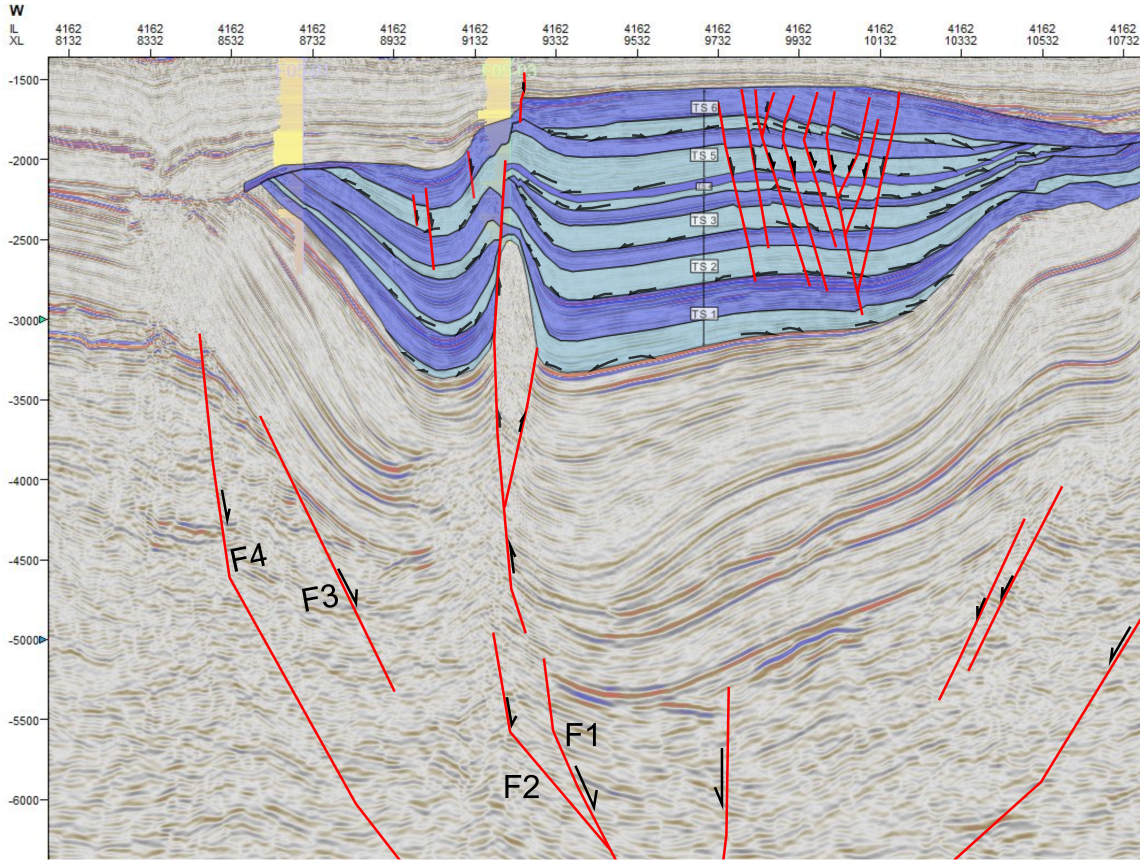


Figure 27: Section 4612 zoomed out to depict the basement faulting that correlate to the well log information. Legend in figure 24.

Figure 26 illustrates how to wells and corresponding seismic and log facies analysis correlate with the basement faulting. It becomes apparent that the sequences in well F05-01 (left) are directly influenced by fault F3, and possibly F4. Well F05-03 is influenced by basement faults F1 and F2. This might explain the major differences in thickness in BFTs and SFTs on either side of the salt tear intrusion in the basin. As discussed, BFTs are the result of a high sediment supply or rapid subsidence. Figure 26 shows that the western flank is sourced by the uplifts above the marginal faults F3 and F4; the BFTs significantly thicken on this flank as is observed within both well F05-01 and the seismic facies model. Therefore, more subsidence must have occurred along this flank than in the basin center below well F05-03; which shows the BFTs are tectonic driven rather than a result of autocyclicity or eustasy. Well F05-03 is comprised of less alternations in TS as the eastern part of the basin as well, with much thinner BFTs and SFTs. This seems to be the result of faulting in F1 and F2 up until after the fourth TS, after that a large sediment starved SFT occurs, which could coincide with the strong upwards salt movement underneath this well. This model can be compared with section A (figure 24), where the first 5 TS coincide with the first 4 TS in section 4162. However, in section A no salt tear intrusion occurs in the basin center. Therefore, no dominant sediment starved SFT is observed in TS 6. The BFT of TS 6 oversteps basin margins and therefore has a larger sediment-supply. This transgression cannot be linked to tectonics specifically, and therefore must be sea-level driven. The small SFT within the last tectonic succession might coincide with a relative uplift. Therefore, the last two TS of section A are not allocyclic, whereas only the last TS of section 4162 is autocyclic; which means both sections have 5 allocyclic tectonic successions. No evidence for the late Kimmerian uplift is reflected in the non-allocyclic successions. It is, however, reflected in the stratal tilt within the BFT in TS 6 (4162). Lastly, as a general observation is the clear thinning and pinching out of SFTs along the basin margins. This is linked to subsequent salt withdrawal from the basin center into the marginal diapirs, resulting in coeval basin subsidence and marginal uplift.

8. Discussion

8.1 Regional substantiation of seismic reconstructions

The interpretation and subsequent reconstruction of the seismic section corresponds with general existing ideas regarding the evolution of the Dutch Central Graben. General ideas are in line with previous research, such as the decoupling function of the Zechstein salt thickness. Based on the first order interpretation of both sections it becomes clear that the Upper Jurassic infill is confined to basin margins that are controlled by extensive salt halokinesis, as the bordering Step Graben does not contain the Callovian to Oxfordian Schieland Group in section A. In section B the Upper Jurassic strata seems to occur in the Step Graben, due to the larger accommodation provided by fault F5 in the Permian basement (figure 6). Furthermore, the Step Graben is not influenced by other large scale tectonic processes, such as thermal relaxation, and therefore sinking response as the Dutch Central Graben. The thermal relaxation of the Dutch Central Graben is reflected in the stratal tilt of the Rotliegend timed late Permian. The Step Graben exhibits overthickening (figure 5, 6), but no stratal tilt in relationship to thermal relaxation were observed; a result in line with conclusions by Geluk, (2005) and De Jager, (2007). Furthermore, the Zechstein salt decoupled deformation, as the faulting in the under- and overburden evolved individually for a significant time during the Triassic to Early Cretaceous tectonic activity. This difference in evolution is accommodated by diapirism along the major faulting systems (fault F1 & F2 in figure 5 and 6), as the fault configuration favored salt movement as a result of differential loading. These observations are in agreement with the proposed thick-skinned faulting behavior in the Dutch Central Graben (Ten Veen et al., 2012) as well as earlier structural tectonic interpretations (Bouroullec et al., 2018; Pharaoh et al., 2010). An exception to this clear decoupling seems to be fault F3 in section B (figure 6) as the faulting below the Zechstein appears to align with this faulting behavior. The fault may have propagated upwards through the Zechstein salt. Ten Veen et al. (2012), described such behavior can occur when the salt withdrawal results in a locally thin enough layer during the formation of faults. The influence of the basement faulting is reflected in offset in the Triassic sediments, whereas most of the Altena Group seems unaffected by most tectonics. This is in line with the Early Jurassic interval of tectonic quiescence (Trabucho-Alexandre et al., 2012). A later reactivation of salt movement upwards resulted in a reverse faulting pattern, hence the seemingly decoupled rheological behavior of the formations divided by the Zechstein.

The depth conversion of the first-order structural interpretation shows that the basement faults are oriented at approximately 60 degrees (figure 31); the reactivation of faults disregarded changes in tectonic regimes. The faults are mostly parallel, and do not seem influenced by later regional stress orientations, as previously described by De Jager, (2007). Based on further tectonic reconstructions there seems to be a complex connection between the rate of Permian basement faulting and the differential loading and stratal organization of all overlying formations into syn- and antiforms. Structural trends related to an increase of extensional tectonic intensity such as rim synclines are observed in the Triassic sediments, affecting basin distribution. The Callovian to Oxfordian strata of the Schieland Group show eastward depocenter shifts based on this rate, as well as thickness differences and rim synclinal configuration (see chapter 5, figure 7 to 16). Based on this depocenter shift, salt withdrawal from the basin center regulates the amount of accommodation space, correlated with diapiric growth along the margins, which is in line with Ziegler, (1990); Fattah et al., (2012) & Verweij et al., (2009). The salt movement along major faults in both the Dutch Central Graben and Step Graben accounts for the locations of basin margins, as previously described by Remmelts (1995; 1996) & Davidson et al. (2000).

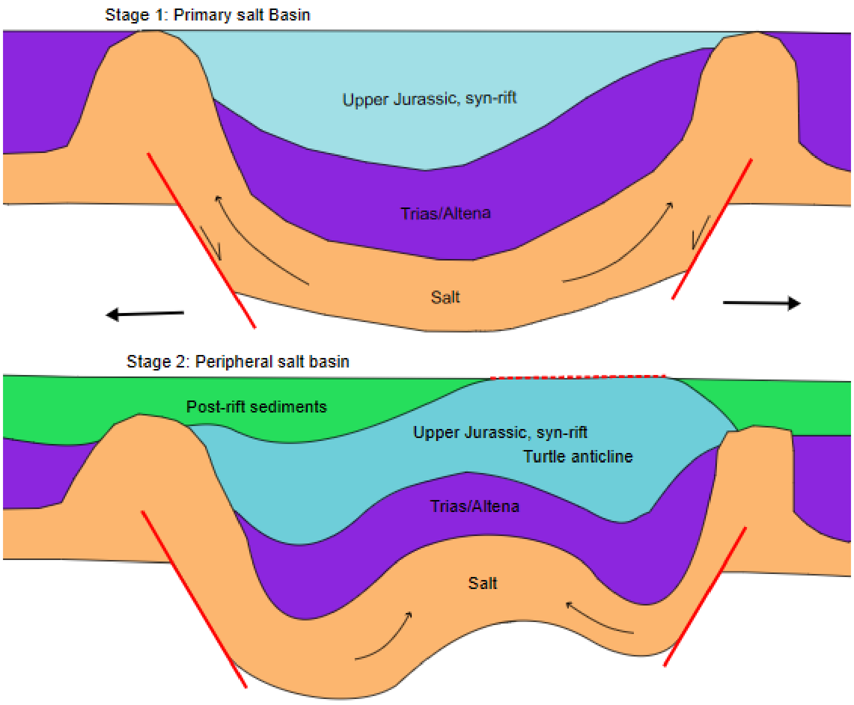
The stratal configuration of the Triassic groups in the Step Graben shows an uplift coeval with the subsidence of the Dutch Central Graben, resulting in erosion of the Mesozoic cover, first described by Geluk & Röhling, 1999. In section A, less subsidence of the Dutch Central Graben and therefore corresponding uplift in the Step Graben took place than in section B. Comparing both sections, significantly less salt is available towards the south, as well as more subsidence (section B, figure 6). This is in line with the original depositional thickness of the salt layers as described by Ten Veen et al., 2012 & Hernandez et al., 2018. Lastly, structural features of slight angular rotation observed in the Chalk Group reflector terminations are influenced by the Late Cretaceous inversion (in line with Van Wijhe, 1987; De Jager, 2007), and therefore show that an additional event occurs later than the observed additional uplift timed during the Kimmerian tectonic phase.

8.2 Implications and applications of defined tectonic successions

8.2.1 Structural evolution of the Upper Jurassic to Early Cretaceous

The Upper Jurassic depo-axes shifts and changing accommodation space are controlled by salt redistribution. However, figure 26 relates the basement faulting to the basin kinematics; showing an additional increase in accommodational space along the basin margin due to the fault movement. Initial salt redistribution is driven upwards along pre-existing fault structures and redistributed along the basin center as a result of faulting and reactivation thereof, as well as the subsequent fall of diapirs. This observation is in line with Remmelts, (1995, 1996) and Vendeville & Jackson, (1992). We therefore conclude that the Upper Jurassic accommodation space is created by halokinesis enhanced by large-scale extensional fault movement. Ten Veen et al. (2012) concluded that most salt movement was linked to the Upper Jurassic Late Kimmerian rifting phase; our observation strengthens this previous inference. It also strengthens the observed Callovian timing of the rift onset within the Dutch Central Graben, endorsed by De Jager (2007) and Pharaoh et al., (2010).

Asymmetrical salt withdrawal during deposition of the Lower Jurassic Altena Group resulted in an over-thickened formation (Bouroullec et al., 2018). As the Toarcian Posidonia Shale Formation reflects a stagnation of basin subsidence (Herngreen et al., 2003), relative salt withdrawal must have come to a halt, resulting in a primary salt basin (figure 27). A relative period of tectonic quiescence followed, with tectonic pulses creating accommodational space during this primary salt basin phase, also described by Bouroullec et al., (2018). The phases of relative tectonic quiescence correspond to TMS-1 defined by Verreussel et al., (2018). In stage 2, uplift was observed relatively timed during the deposition of the Kimmeridge Clay, as we observed stratal onlap of the Rijnland and erosion of the Chalk Group. The resulting long wavelength 'turtle-back anticline', or peripheral salt basin, best developed in section B, seems to be timed late Oxfordian – Kimmeridgian. This age constraint is based on tectonic reconstructions (figure 6, 16) and the combined seismic and well classification (figure 24). Unit 3 (figure 6) is a product of basin center erosion as a result of relative uplift, rather than a sedimentation feature, observed in the structural reconstruction. The extensional growth faulting seems to be a result of a salt sheet subject to withdrawal, but along the eastern margin a listric growth fault system seems to be developed linked to relative uplift (figure 24, 25). This behavior was readily described by Bouroullec et al., (2018). Significant erosion of the Kimmeridge Clay reflected in structural angular unconformities (figure 5, 6, 9, 15) combined with uplift, timed before predefined inversion events, requires an additional event unrelated to the compressional phase. The asymmetric turtle anticline, or 'turtle anticline', formed due to listric basement faulting in the early stages, and was later influenced by the Late Cretaceous inversion that ultimately resulted in stage 2 (Maduit et al., 1997). This is in line with



observations of Ten Veen et al., 2012; stating that most salt-movement is linked to the Mid-Late Kimmerian. It also agrees with the described rift climax of TMS-2 (Verreussel et al., 2018), as the rift climax is characterized by deformation concentrated over the major fault systems bounding the basin (Gupta et al., 1998). This suggests that the Schieland Group has been influenced by significantly more tectonics and subsequent halokinesis than the Scruff Group.

Figure 28: basin evolution reflected in salt movement. Stage 1 resembles the extensional phase that was followed by a period of relative tectonic quiescence. Stage 2 marks the onset of a non-compressional related uplift that resulted in a peripheral salt basin. Listric faulting combined with the subsequent 'fall' of salt diapirs resulted in an asymmetrical turtle anticline.

Furthermore, the thickness of the first five tectonic successions in both defined sections (figure 24 – 26) is controlled by either tectonic quiescence or activity, whereas the Scruff Group successions were altered by the late Cretaceous inversion resulting in a peripheral salt basin.

8.2.2 Eustatic and sedimentary evolution of the Upper Jurassic to Early Cretaceous

Generally, the tectonic successions in the Upper Jurassic sediments reflect a sea-level rise in the large-scale lower order cyclicity from the Oxfordian onwards, observed in the well log analysis (figure 18 – 22). Fossil contents in the Callovian Lower Graben Formation, based on core reports of well F06-01-S1 (NLOG.nl), are predominantly indicative for relatively cool and wet environments. This is in line with a late Callovian severe cooling event (Dromart et al., 2003) followed by a gradual temperature and subsequent

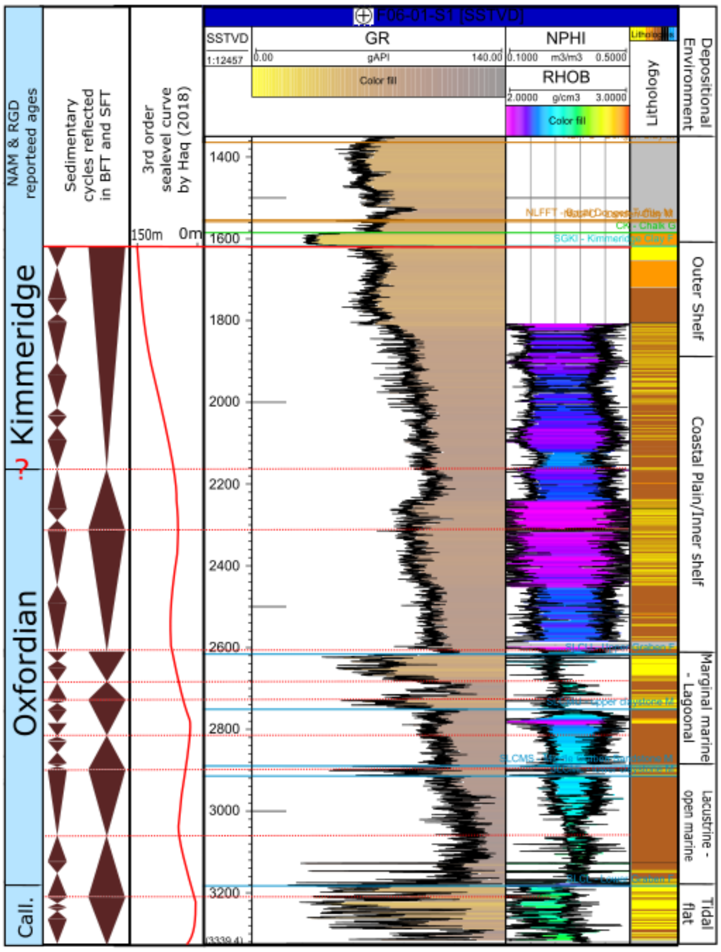


Figure 29: correlation of the well analysis with the 3rd order sea-level fluctuations of the North Sea during the Jurassic as proposed by Haq, 2018.

sea-level rise (Abbink et al., 2006). The duration of the defined sedimentary cycles is to 2 – 5 Ma (figure 18 – 22), and therefore the associated tectonic successions are not resembled by either 2nd nor 3rd order sea-level changes. An exemption is the lower order cyclicity observed during sedimentation of the Late Oxfordian Upper Graben Formation which coincides with the fluctuations of the Eurocentric short-term sea-level proposed by Haq (2018). The Kimmeridgian largely coincides with the long-term sea-level curve (figure 28); this is in line with the differences in tectonic successions observed in the Kimmeridge Clay. As the formation has a general eustatic driver, influenced by autocyclicity towards a warmer environment. The fossil and associated isotope contents are in line with a subtropical autogenic influence (Wierzbowski, 2015). This observation can also be linked to the rift climax of TMS-2 ascribed to the Kimmeridge Clay (Verreussel, 2018).

8.2.3 Subdivision of tectonic successions and local deviations

The structural and sedimentary evolution of the Upper Jurassic within the Dutch Central Graben was reconstructed using the high-resolution combined well log and seismic data analysis (figure 24, 25). The seismic facies analysis regarding BFTs and SFTs are in line with Matenco & Haq, 2020. The sourceward migrating facies tracts are defined as low amplitude, medium frequency reflectors that are somewhat discontinuous; their amplitude increases along basin margins due to coarser facies. The basinward migrating facies tracts are observed as high amplitude and continuous reflectors. In the first-order seismic interpretation a subdivision was made based on the variety in amplitudes; apparent onlaps were defined as basinward migrating facies tracts. However, it seems these onlap geometries are rather a result of coarser facies resulting in higher amplitude sourceward migrating facies tracts. The subdivision in BFTs and SFTs is controlled by the rate of subsidence and subsequent sediment influx. During high tectonic activity resulting in increased salt withdrawal, the relative rate of sediment supply is too slow to fill the full basin; resulting in a sourceward migrating facies tract. The observed onlap geometries reflects a change back to tectonic quiescence, which is eventually recorded in basinward migrating facies tracts. Due to low tectonic activity, less subsidence and thus relatively more sediment influx results in sequences overstepping margins. As observed in well log F05-01 (figure 21), the strata along the margins is predominantly aggradational. This behavior of sedimentation combined with tectonics has been reconstructed in figure 29.

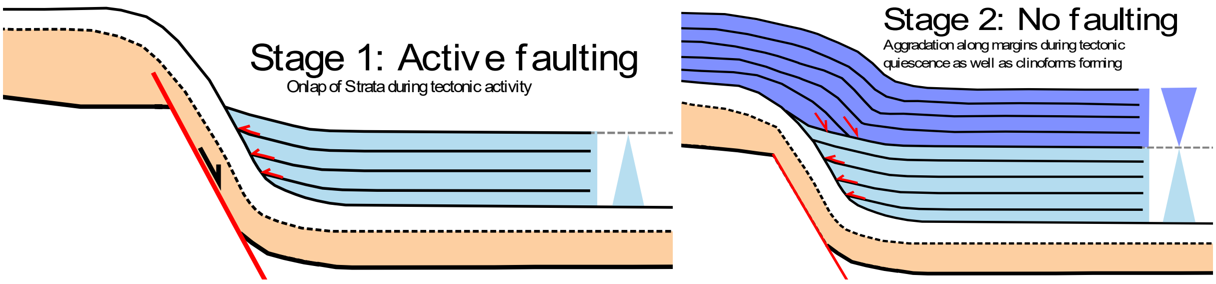


Figure 30: Model for coupled tectonic activity and the corresponding depositional sequences defined in the Late Callovian - Late Oxfordian sediments of the Dutch Central Graben. Stage 1 is controlled by active large offset faulting, resulting in significant salt movement and corresponding subsidence in the basin center coinciding with relative diapiric uplift. The sediments reflect SFTs. In stage 2 the sediments reflect BFTs, formed during tectonic quiescence and thus no significant subsidence.

Overall, section A (figure 24) seems to be less influenced by strong halokinesis and related subsalt faulting; this section shows a general reversal from SFT dominated tectonic successions to a BFT domination. This gradual change is in line with the lower order subdivision proposed by Matenco & Haq, (2020) depicted in figure 4, and used for reconstruction in figure 29. It reflects a change from intensive tectonic activity towards a period of more tectonic quiescence. Section 4162 (figure 25) does not show a clear difference into this lower order subdivision. However, the first five tectonic successions, deposited during large scale tectonic pulses, show a facies distribution different from typical facies distribution in salt-free basins similar to the Dutch Central Graben. Furthermore, only small facies changes are observed across the syn-depositional structures, as they rather reflect differences due to changes in tectonic activity than being eustasy driven. These observations are in line with Mannie et al. (2016), describing influences of halokinesis on a rift system.

In both the first-order interpretation and the well-controlled seismic classification, one more tectonic succession was defined in the northern section (figure 5, 6, 24 & 25). This extra tectonic succession is dominated by BFTs and thus deepening of the sea. Reasoning for this difference might be early salt remobilization into the small upwards propagation in the center of the graben. Due to the influx of more salt back into the basin center, less accommodational space became available. This corresponds with the stagnation of faulting along basement faults truncating the Permian deposits. This also explains why the turtle anticline of section B (figure 6) is more pronounced; the Late Cretaceous inversion was able to influence this region more. This observation is in line with the general understanding that inversion effects rapidly decrease towards the north Herngreen (2003). Furthermore, section 4612 (figure 25) seems to have a more consistent alternation of BFT and SFT thicknesses. The collapse structure above fault F1 and F2 (figure 26) that is missing from section A (figure 24), might have been the main controlling factor. Well log F05-03 shows that the influence of salt uplift along fault F3 (figure 6) resulted in less sedimentary cycles due to less accommodational space. Figure 26 shows how wells directly correlate to underlying faulting mechanisms in section 4162; local forcing missing in section A (figure 24). These observations lead to the understanding that local factors can significantly influence basin development.

8.2.4 Tectonostratigraphic framework

The classic tectonostratigraphic framework for the Dutch Central Graben is focused on eustatic influences and sedimentary variability on stable continental margins. This research proves such an approach is incomplete as the rate of accommodation is regulated by fault-controlled halokinesis. The general proposed evolution of the Upper Jurassic – Early Cretaceous sedimentary sequences into tectonic megasequences (Verreussel, 2018) is of significant lower resolution than the tectonic successions defined in this research (figure 24, 25). Within TMS-1, an additional subdivision into 5 tectonic successions were observed in both section 4162 and section A. These successions correspond to the continental facies of the Schieland Group; and were found to be salt driven controlled by faulting. Quantifying these tectonic successions further (figure 27), the thicknesses of the defined tectonic successions (figure 24, 25) should correspond to the amount of tectonic subsidence. TS 1 is a thick cycle, indicative for strong subsidence during the early rift phase. TS 2-4 gradually decrease in thickness along

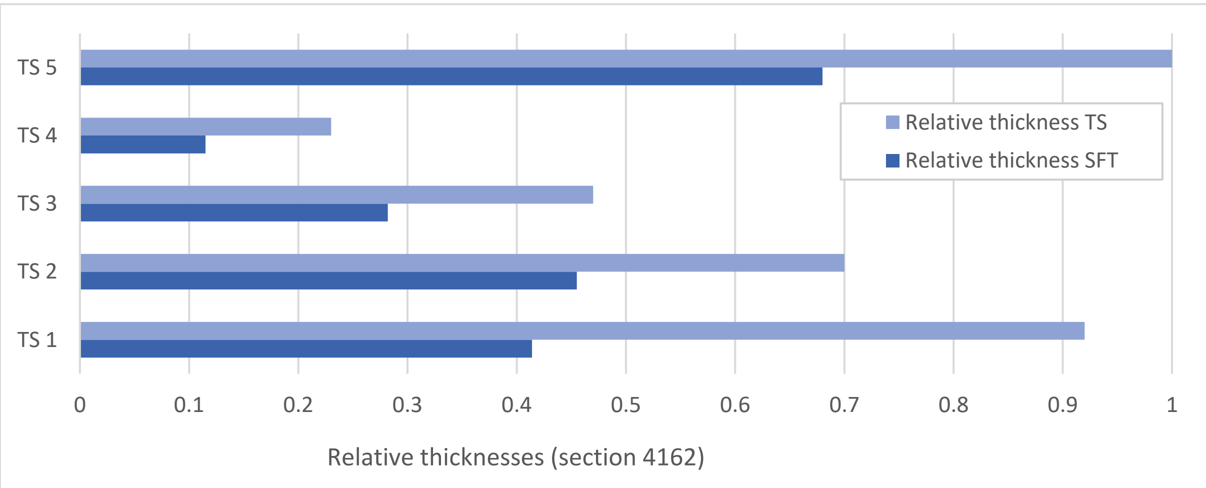


Figure 31: Graph of relative thicknesses of tectonic successions. This subdivision is based on setting the thickest succession (TS 5) as 100 percent (thus 1) and shows the relative thickness variations of SFTs and therefore amount of tectonic activity per tectonic succession.

with a slight eastward shift, which reflects a subsidence decrease, most likely due to relatively less strong offset faulting along fault F2 (figure 5, 6). TS 5 is significantly thicker than underlying TS in section 4162 (figure 25), and roughly the same thickness as TS 1 in section A (figure 24). This reflects a stronger subsidence pattern southward, which is in line with findings by Remmelts, 1995; however, this is only observed in the fifth tectonic succession. The changes are quantified in figure 30.

The fifth tectonic succession therefore constrains the additional subsidence to this event of tectonic activity, and should not be ascribed to the entire rift sequence of TMS-1. The predominantly marine Scruff Group was found to contain 1 and 2 additional tectonic successions respectively; these cycles are influenced by eustasy rather than by tectonics. The successions are overstepping basin margins, and are dominated by mostly NW-SE trending normal faults. This strengthens the hypothesis that the TMS-2 rift climax of the Kimmeridge Clay is reflected in the Early Kimmeridgian deposition, as such behavior was ascribed to TMS-2 (Verreussel et al., 2018). This would place the timing of TMS-2 for this section up to 3 Ma earlier than defined by Verreussel et al. (2018). This phase also coincides with the strongest subsidence, reflected in thicknesses of TS 6 and TS 6-7 in section 4162 (figure 25) and section A (figure 24) respectively.

8.3 Depositional environment linked to tectonics

When comparing the subtle variation and associated depositional environments of well log F03-06 (figure 22), F05-03 (figure 18) and F06-01-S1 (figure 19), it is clear that there are small lateral variations in facies distribution in the center of the basin. Due to local forcing of an additional salt tear intrusion, the thickness of successions in well log F05-03 are significantly thinner than observed in the other well logs. Furthermore, the facies of the basin wells differ only slightly from well log F05-01 (figure 21), located along the basin margin. When looking at the depositional environments in all described well logs, there is a gradual development from fluvio-deltaic to lacustrine/lagoonal, and later to open marine. No abrupt changes in this development show that sudden large offset faulting does not occur (Rajchl et al., 2008). Therefore, gradual subsidence must have occurred in the half-graben, and downwards stepping has not occurred; subsidence is enhanced by salt movement along fault planes. The topography changes are relatively gentle, observed in generally similar facies and lateral diminishable variety. This is in line with salt-driven rift-deformation in other areas (Rojo et al., 2020). These gentle topography changes are reflected in a coupled tectonic and salt redistribution depositional model within the Late Callovian – Late Oxfordian sediments (figure 28).

Linking these gradual changes back to the depositional model of figure 29, we find the following: in stage 1 large scale faulting results in subsidence and therefore regressive type sediments reflected in the sourceward migrating facies tracts. As described, the facies coarsen towards the margin due to a gradual retreat, and shows onlap geometries along these margins. In the second stage tectonic quiescence results in the sediments overstepping margins, as the sediment supply outpaces the subsidence rate. The resulting basinward migrating facies shows downlap and clinoformal geometries, as well as aggradation along the margins.

9. Conclusions

Our research has demonstrated that three tectonic phases have contributed to the basin development of the Dutch Central Graben, readily observed in the first-order interpretation. The thick Upper Jurassic sediments (Late Callovian - Late Oxfordian) were deposited in a syn-rift sequence with a depocenter located in the center of the graben. Accommodation is controlled by salt movement upwards from rim synclines combined with the subsequent Late Cretaceous inversion. From the Kimmeridgian onwards, deposition overstepped the previous basin margins due to migration upwards along rim synclines. Coincidentally, the Late Jurassic basin axis eroded due to this subsequent uplift, eventually resulting in the formation of a turtle anticline. The last event, the Cretaceous inversion phase, is reflected in further uplift, and apparent onlap of younger formations onto the Kimmeridge Clay, as well as angular truncation of Chalk Group strata.

The Upper Jurassic sediments were further investigated by combining this first-order interpretation with stratigraphic well log data into a well log facies model. This model allowed for subdivision in tectonic successions comprised of basinward and sourceward migrating facies tracts, and therefore a more in depth understanding of periods of tectonic quiescence and tectonic activity. The sedimentary cycles observed in well logs and therefore tectonic successions have a duration of 2 – 5 Ma, however further seismic control resulted in a duration of 2 – 3 Ma. These age constraints therefore rule out both 2nd and 3rd order sea-level interference on the sequences. An exception is the deposition of the tectonic cycles observed in the Kimmeridge Clay deposits, as the cycles closely resemble 3rd order sea-level fluctuations, during tectonic quiescence. The lithological trends and corresponding depositional environments show a gradual change in facies development, not influenced by large offset faulting as is found in classic fault-bounded half-grabens. This strengthens the first-order observation that the salt decoupled the Permian basement from overburden, and confirms that facies gradually change as opposed to rapid changes in fault-bounded basins lacking salt influence as the thick-skinned salt creates a shallow syn-depositional topography.

The subdivision in tectonic successions resulted in 5 sequences in the Late Callovian – Late Oxfordian Schieland Group, and 1-2 more in the Early Kimmeridgian Scruff Group. The geometries of the first five tectonic successions coincide with TMS-1, whereas the latter coincide with TMS-2 as proposed in the stratigraphic framework of Verreussel et al. (2018). Therefore, the subdivision enables a more in depth alternation of tectonic pulses and their intensity, in part represented by the shifts in tectonic activity and quiescence. By building onto this high-resolution subdivision further understanding of Late Jurassic can be achieved, providing a strengthened ability to locate sourceward and basinward facies tracts and the properties thereof. The alternation is controlled by large scale faulting in the Permian underburden, which enhances salt withdrawal from the basin center into the basin bounding salt diapirs. This observation demonstrates that the amount of subsidence in the Upper Jurassic tectonic successions of the Schieland Group is mostly defined by fault-controlled salt movement, which induces and facilitates halokinesis. The subdivision contributes to more in depth interpretation of structural configurations and controlling factors. It also leads to the understanding that the main controlling factors of the basin can be subdivided into two events, as the primary salt basin stage was proven to be influenced by more sub-salt faulting and associated salt movement than the peripheral salt basin stage. The expression of the successions into a turtle anticline is indicative for coeval salt migration upwards from rim synclines: reflecting a change from a basin axis phase to a peripheral basin phase when combining with compressional forces of the Late Cretaceous Inversion.

Lastly, slight differences in basin development were observed in the different interpreted sections, as the northernmost section seems to be less influenced by strong halokinesis and related subsalt faulting. The southernmost section was influenced by a local salt intrusion in the basin center, resulting in less sedimentary cycles. A collapse structure on top of this diapir most likely resulted in a more consistent alternation of BFT and SFT thicknesses in section B. Therefore, local forcing significantly altered the basin development, we proposed possibly contributing mechanisms causing these differences.

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Appendix A

Figure 32: Velocity driven time-depth conversion of section A, scale 1:1. In blue and baby-pink the defined faults of the section. Different formations from the Triassic to the Early Cretaceous were defined in color schemes as defined in table 1.