New insights into salt tectonics in the northern Dutch offshore: a framework for hydrocarbon exploration

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Abstract: The northern Dutch offshore is an area that has seen less hydrocarbon exploration activity than other areas of The Netherlands. Acquisition of a new regional 3D seismic dataset allowed further testing and re-evaluation of established geological concepts in this area. It is recognized that the presence and movement of Upper Permian Zechstein evaporites had a major impact on depositional patterns in Mesozoic sediments, structural development and hydrocarbon migration. As such, this study looks specifically at the role of salt tectonics in tectonosedimentary development. To assess this salt tectonic evolution within its structural context, a restoration of the Step Graben and Dutch Central Graben was performed. It follows that depositional patterns are closely linked to the nature of salt structure movement and the timing of regional tectonism. For example, during Late Triassic rifting, salt pillows developed and sedimentation focused away from salt structures into depocentres along regional fault trends. Restoration results show that this interplay between salt movement and tectonism is needed to accommodate the sedimentation patterns associated with the formation of the Step Graben and Central Graben during the Triassic and Jurassic, and later during Late Cretaceous and Cenozoic inversion tectonics.

During the Late Permian, hundreds of metres of Zechstein evaporites, including salt, were deposited in the northern Dutch offshore (Ziegler 1990; Geluk 2005). Subsequent halokinesis played an important role in the geological development of the area (e.g. Van Wijhe 1987; Ziegler 1990; Scheck-Wenderoth *et al.* 2008; Ten Veen *et al.* 2012). The formation of salt diapirs, salt walls and salt pillows led to the development of a range of hydrocarbon trap types. These include four-way dip closures in strata above diapirs and pillows, as well as three-way dip closures on the flanks of salt structures (Hodgson *et al.* 1992; Wride 1995; Davison *et al.* 2000*a*, *b*; Stewart 2007; de Jager 2012). Halokinesis also had a potential impact on Jurassic source rock distribution, burial depths and maturity (Grassmann *et al.* 2005; Verweij *et al.* 2009; Abdul Fattah *et al.* 2012), as well as on hydrocarbon migration paths and intra-reservoir facies distributions (e.g. Farmer & Barkved 1999; Van der Molen *et al.* 2005; Magri *et al.* 2008; Hampton *et al.* 2010; Back *et al.* 2011). As such, in order to conduct an effective play evaluation in the Dutch Central Graben and Step Graben, it is crucial to understand the timing of salt movement episodes.

The primary aim of this study is to better constrain when the main periods of salt movement occurred and how the geometries of salt structures developed through geological time. A thorough understanding of the development of the Dutch Central Graben and Step Graben systems and their later restructuration through inversion tectonics is also required to accurately describe the relationship between regional structuration and salt tectonics. In this study, a transect through the Dutch Central Graben and Step Graben is structurally restored. This restoration integrates a regional inventory of salt structure interpretations in the northern Dutch offshore, in which salt structures are systematically listed and characterized according to a range of salt structure characteristics (see Table 1). Using this method, it is possible to test the role of Zechstein halokinesis in influencing adjacent stratigraphic geometries and to visualize how the different deformation stages evolved. This approach gives a framework for the analysis of the role of salt tectonics in hydrocarbon play definition and the tectonostratigraphic development within the Dutch Central Graben and Step Graben.

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Table 1. *A selection of interpreted stratigraphic relationships around salt walls and salt diapirs in the study area, based on observations from regional 3D seismic data (Spectrum DEFAB 2010 survey)*

	Salt structure	Location (Schill Grund and Elbow Spit Platform, Step Graben, Central Graben)	Salt structure type	Youngest affected horizon	Oldest affected interval	Intervals thinning towards the salt structure	Intervals thickening towards the salt structure	Pre-salt fault orientation
1	A18-NORTH1	SG	Diapir	Base North Sea Supergroup	Upper Germanic Trias Group (RN)	RB, CK	RN, SL	North–south
2	B16F01-WEST1	SG	Wall	Middle Miocene	Upper Germanic Trias Group (RN)	RN, KN, CK, NS	AT	North–south
3	B16F01-EAST1	SG	Wall	Middle Miocene	Lower Germanic Trias Group (RB)	RN, CK, NS	RB	North–south
4	B17-SOUTH1	CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	AT, SL	RN, CK, NS	North–south
5	F02-NORTH1	SG	Wall	Base Quarternary	Upper Germanic Trias Group (RN)	CK, NS	RN, KN	North–south; ESE–WNW
6	F02-NORTH2	CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	AT, SL, CK, NS	RN	?
7	F03-EAST1	CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	RN, SL, KN, CK, NS	SL	North–south
8	F03-EAST2	SGP/CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	RN, AT, SL, KN	CK, NS	?
9	F05-EAST1	CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	RN, CK, NS	AT, SL	NNE–SSW
10	F05-WEST1	SG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	RN, AT, SL, CK	None	North–south
11	F05F08-WEST1	SG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	AT, SL, CK, NS	RN	North–south
12	F06b-EAST1	CG	Diapir	Middle Miocene	Upper Germanic Trias Group (RN)	RB, SL	RN, AT, NS	North–south
13	F06b-EAST2	SGP/CG	Wall	Middle Miocene	Lower Germanic Trias Group (RB)	RB, AT, SL, CK	RN, NS	North–south
14	F07F08-NORTH1	SG	Wall	Middle Miocene	Upper Germanic Trias Group (RN)	CK	RN, NS	NNE–SSW
15	F07F08-SOUTH1	SG	Diapir	Base Quarternary	Lower Germanic Trias Group (RB)	RN, AT, SL, CK, NS	RB,	North–south; NE–SW
16	F09-WEST1	CG	Diapir	Base Quarternary	Upper Germanic Trias Group (RN)	RN, CK, NS	AT, SL, KN	North–south
17	F09-EAST1	SGP/CG	Wall	Middle Miocene	Upper Germanic Trias Group (RN)	AT, SL, CK	RN, NS, KN	NNE–SSW
18	F10-EAST1	SG	Wall	Middle Miocene	Upper Germanic Trias Group (RN)	RN, KN, CK, NS	None	North–south; east–west; NW–SE

See Figure 2 for an overview of the interpreted diapirs and walls, and Figure 3 for a definition of the stratigraphic intervals.

Regional geology

Tectonic development

The study area, within the A, B, D, E and F blocks of the northern Dutch Central Graben and Step Graben, is located in the Southern North Sea, on the northern fringe of the Southern Permian Basin (Figs 1 & 2). The development of the wider Southern Permian Basin area was affected by three major periods of plate tectonics: (1) assembly of the Pangea supercontinent; (2) break-up of the Pangea supercontinent; and (3) distal inversion effects of the Alpine Orogeny (Nøttvedt *et al.* 1995; de Jager 2007; Breitkreuz *et al.* 2008; Krawczyk *et al.* 2008; Voigt *et al.* 2008; Pharaoh *et al.* 2010).

The assembly of Pangea is characterized by two major collisional events, resulting in the Caledonian and Variscan fold and thrust belts. The Caledonian collision occurred in the Early–Middle Paleozic between the continents of Laurentia and Baltica (Krawczyk *et al.* 2008). This resulted in the closure of the Tornquist Sea (Pharaoh *et al.* 2010) along the NW–SE-running Tornquist Suture Zone (Berthelsen 1998; Cocks & Torsvik 2006; Pharaoh *et al.* 2010). Subsequently, the microcontinent of Avalonia collided from the south, which closed the Iapetus Ocean along the NW–SE- to north–south-running Iapetus suture (Krawczyk *et al.* 2008; Pharaoh *et al.* 2010). This created a triple junction of plate boundaries just to the NW of the study area (Ziegler 1982, 1990; de Jager 2007). Generally, this junction is linked to the location of Mesozoic basins such as the Central Graben in the UK and The Netherlands (Ziegler 1990). A subsequent collision of the resulting continent (Laurussia) with the Gondwanan continent resulted in the Variscan Orogeny (Kroner *et al.* 2008). The Variscan thrust front associated with this collision moved northwards throughout the Carboniferous, with its final position trending east–west through present-day Belgium and to the NE into Germany (Fig. 1) (Ziegler 1990; Kroner *et al.* 2008; Pharaoh *et al.* 2010). Late Variscan tectonic activity (Wilson *et al.* 2004; Timmerman *et al.* 2009; Breitkreuz *et al.* 2008) induced widespread erosion in the Late Carboniferous (Geluk 2005). A phase of dextral translation of northern Africa relative to Europe then led to the onset of orogenic collapse and basin formation in NW Europe during the Late Carboniferous–Early Permian (Ziegler 1990; Geluk 2005; Pharaoh *et al.* 2010). In this period, an arid, desert-like area developed north of the Variscan front, where Lower Permian Rotliegend sediments accumulated (Stollhofen *et al.* 2008; Gast *et al.* 2010; Mijnlieff & Geluk 2011). Rotliegend isopach maps show subtle early structuration in the underlying basement, where several separate depocentres can be distinguished, including the large east–west-running Northern and Southern Permian basins (Geluk 2005; Gast *et al.* 2010). Continued isostatic subsidence (van den Belt & de Boer 2007) induced periodic flooding, resulting in the cyclic deposition of the Zechstein Group (Geluk 2005; Peryt *et al.* 2010). Rifting commenced during the Early Triassic in the Northern Atlantic domain (Ziegler 1990; Zanella & Coward 2003; Feist-Burkhardt *et al.* 2008; Stollhofen *et al.* 2008), which induced several phases of extension from the Triassic to the Early Cretaceous across the study area, although no continental break-up subsequently occurred (Ziegler 1990; Zanella & Coward 2003; Feist-Burkhardt *et al.* 2008; Stollhofen *et al.* 2008). In The Netherlands, a regional east–west orientation of extension is typically assumed, although basins like the Broad Fourteens Basin and the West Netherlands Basin follow a persistent NW–SE fault trend (Van Wijhe 1987), possibly due to older, reactivated basement fault trends (Ziegler 1990). Due to these extensional events, Triassic thermal subsidence was interrupted by periods of active faulting during the deposition of the Buntsandstein and Keuper formations (Geluk 2005). Subsequent development of a Mid North Sea thermal dome (Ziegler 1992; Underhill & Partington 1993), during the Middle Jurassic, induced deep erosion of Triassic–Jurassic sediments on platform and marginal areas, while deposition was limited to fault-bounded rift basins, such as the Central Graben (Husmo *et al.* 2002; Pieńkowski *et al.* 2008; Lott *et al.* 2010). Here, subsidence continued and a complete Jurassic sequence is typically present (Ziegler 1992; Bouroullec *et al.*, this volume, in press; Verreussel *et al.*, this volume, in press). Active rifting ceased in the Early Cretaceous and rift basins were filled with Lower Cretaceous sediments (Bouroullec *et al.*, this volume, in press; Verreussel *et al.*, this volume, in press). In the Mid-Cretaceous, continental break-up occurred in the Mid-Atlantic domain (Ziegler 1988, 1990). This caused extensional stresses to focus towards the Arctic and away from the Southern North Sea domain (e.g. Ziegler 1990; Scheck-Wenderoth *et al.* 2008). As such, background regional subsidence persisted in most of the Southern North Sea area throughout the Middle Cretaceous (Van Wijhe 1987; Littke *et al.* 2008). In southern Europe, the closure of the Tethys Ocean initiated in the Late Cretaceous with the collision of the African, Indian and Cimmerian plates from the south with the Eurasian continent in the north, resulting in the Alpine Orogeny (e.g. Reicherter *et al.* 2008; Pharaoh *et al.* 2010). Distal effects of this event significantly affected the Southern North Sea area, inducing several pulses of inversion within the Dutch Central Graben and the Broad Fourteens Basin (Van Wijhe 1987; Surlyk *et al.* 2003; de Jager 2003, 2007; Worum & Michon 2005). For the former, the most significant of these

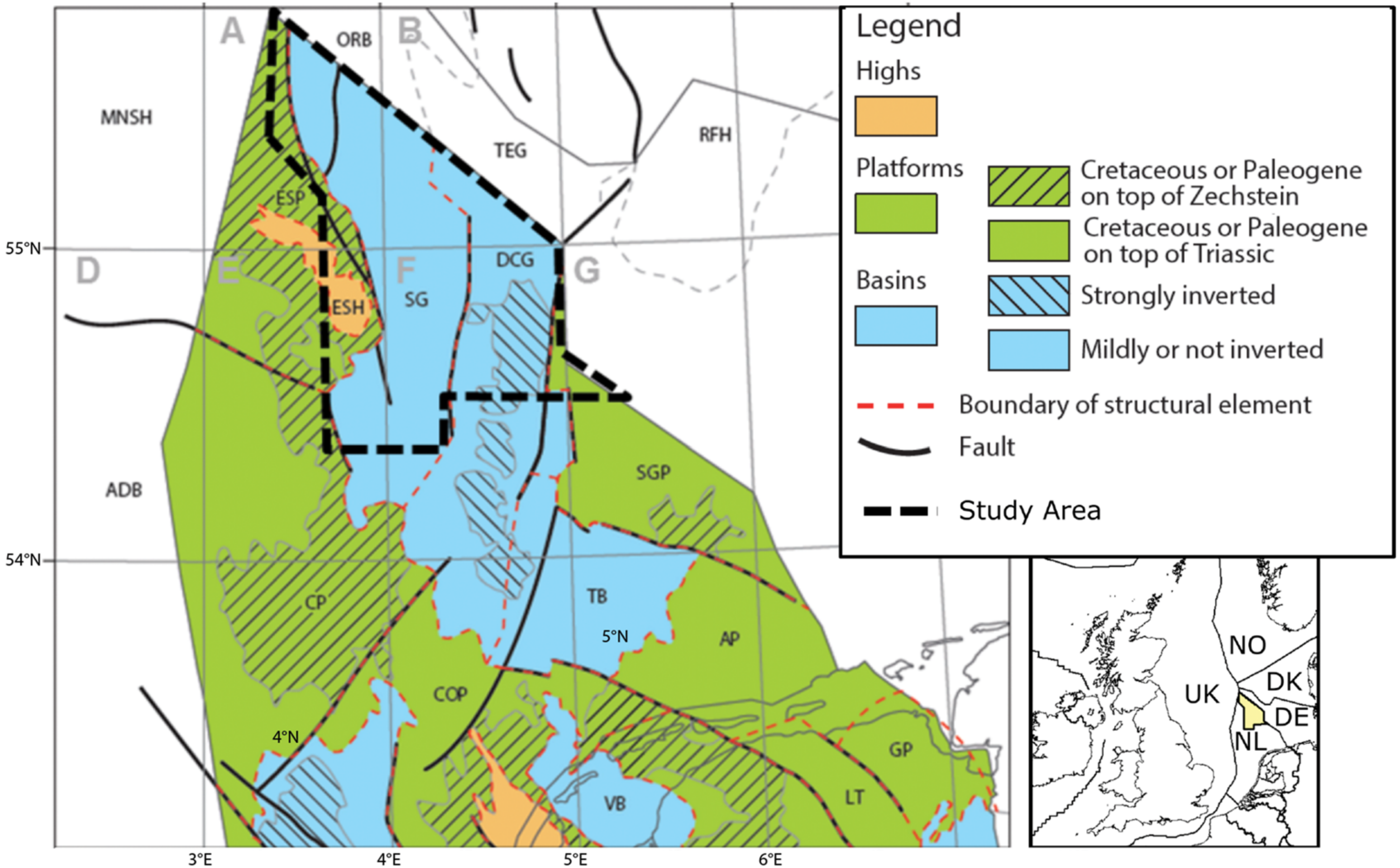

Fig. 1. Location of the study area (black outline) illustrating the main structural elements in the northern Dutch offshore (after Kombrink *et al.* 2012). ESP, Elbow Spit Platform; ESH, Elbow Spit High; SGP, Schill Grund Platform; DCG, Dutch Central Graben; SG, Step Graben; CP, Cleaverbank Platform.

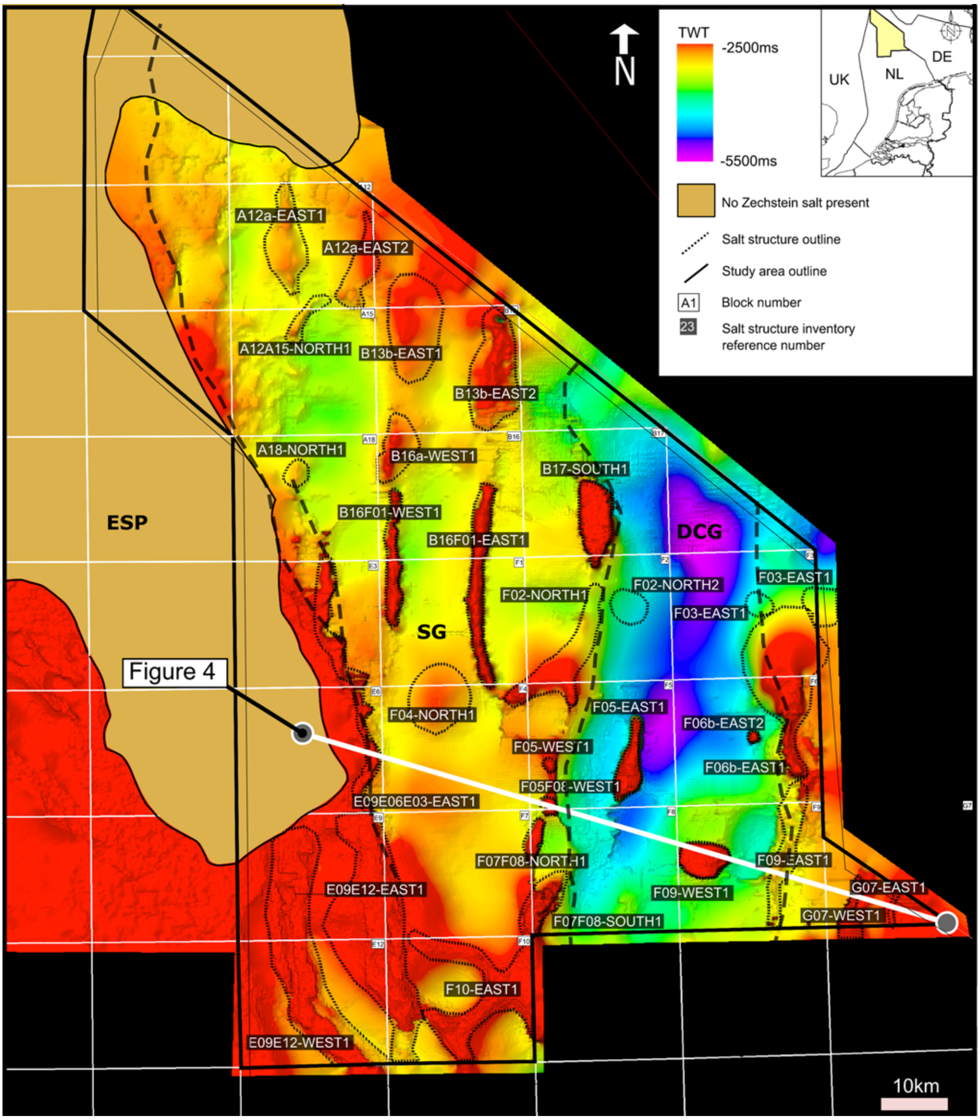

Fig. 2. Two-way time (TWT) map of the top Zechstein Group, based on the interpretation of regional 3D seismic data (Spectrum DEFAB 2010 survey). All 30 interpreted salt structures are indicated (dotted black lines); dashed black lines define the structural domain edges. All salt structures are listed in Table 1.

pulses occurred during the Campanian, Paleocene and Eocene (de Jager 2003, 2007; Surlyk *et al.* 2003; Van der Molen *et al.* 2005; Esmerode *et al.* 2008). While these inversions typically induced uplift of basin centres, most platform areas subsided (Littke *et al.* 2008; Pharaoh *et al.* 2010).

Structural and stratigraphic framework

The main structural elements in the study area are the Dutch Central Graben (DCG), the Step Graben (SG), and the margins of the Schill Grund Platform (SGP) and Elbow Spit Platform (ESP) (Duin *et al.* 2006). The Dutch Central Graben is the deepest section of the study area, and continues as the German Central Graben and the Tail End Graben to the north (Wride 1995). Most of the halite in this area is associated with the basinal Zechstein Group, which consists of evaporites, carbonates and clastics (Van Adrichem Boogaert & Kouwe 1994; Taylor 1998; Geluk 2005; Peryt *et al.* 2010). The Zechstein depositional cycles in this area are defined as Z1 (oldest)–Z5 (youngest), where the Z2 and Z3 members typically contain the thickest halite intervals (Ten Veen *et al.* 2012). Carbonate members are subdivided into shelf, slope and basinal facies (Van der Baan 1990; Tolsma 2014). Occurrences of slope-facies carbonates in the Zechstein Group are an indication of the location of the margins of the Southern Permian Basin and give an approximation of the extent of Z2 and Z3 halite deposition (Van der Baan 1990; Geluk 2005; Jenyon & Taylor 2005; Słowakiewicz *et al.* 2013). In general, halite thickness increases from west to east towards the basinal part of the Southern Permian Basin (Ten Veen *et al.* 2012), where the Zechstein Group sediments reaches an estimated initial thickness of 1500–2000 m (Ziegler 1990; Ten Veen *et al.* 2012; Hernandez *et al.*, this volume, in press).

The post-Permian stratigraphy in the study area is described using the nomenclature of Kombrink *et al.* (2012) with the key stratigraphic intervals shown in Figure 3.

Concepts of salt tectonics

In basins with a sufficiently thick, and therefore potentially mobile, salt sequence, depositional patterns and geometries are often controlled by halokinesis. This can typically be directly related to four distinct stages of salt movement (cf. Vendeville 2002):

- Layered salt stage: the salt layer is in its initial, depositional configuration.
- Pillowing stage: lateral salt movement within the salt layer leads to the development of a primary rim-syncline basin, away from the salt structure. Stratigraphic thinning occurs on top of, and adjacent to, the pillow.
- Piercing stage: salt moves vertically, piercing through younger stratigraphic layers. This stage is typically accompanied by withdrawal of the surrounding salt towards the piercing structure. This leads to the development of a secondary rim syncline where additional accommodation space is created. This results in a thickening of sediments towards the salt structure and into the rim syncline.
- Diapir rejuvenation stage: reactivation phase of the salt structure growth, typically associated with a third stage of rim-syncline development, where strata thickens away from the salt structure (Trusheim 1960; Vendeville 2002).

All four stages can be observed in the study area, as illustrated in Figure 3 for salt diapir F09-WEST1. Note that the model of Trusheim (1960), with only buoyancy being responsible for the creation of salt diapirs, is no longer considered appropriate with the generally accepted concept involving active faulting (Vendeville 2002). Furthermore, the depositional thickness of the salt is considered to have a major control on the style of subsequent faulting (the varying thickness of the salt results in variable degrees of decoupling between the basement and cover structures) and the distribution of synrift sediments (Stewart 2007; Ten Veen *et al.* 2012; Duffy *et al.* 2013).

Regional salt tectonic development

Based on the assessment of stratigraphic relationships around salt structures, described in the aforementioned salt structure inventory and supported by published material (see Table 1; Fig. 2), a first-order interpretation of salt tectonic development is presented with the aim of giving the reader a framework for understanding subsequent reconstructions.

The Early Triassic appears to have been a period of relative tectonic quiescence, although some syndepositional tectonics is suggested by the observation of variable thicknesses in the Lower Triassic of the northern Step Graben and the Dutch Central Graben (see also Dronkert *et al.* 1989; Ziegler 1990; Bachmann *et al.* 2010; Peryt *et al.* 2010; van Winden 2015). Middle and Late Triassic deposits show large thickness variations throughout the study area (Ziegler 1988, 1990; Remmelts 1995; Geluk 2005; Bachmann *et al.* 2010; van Winden 2015). Frequently observed thinning of the Upper Germanic Trias Group interval towards salt structures indicates a widespread salt-pillowing stage, interpreted as the first regional onset of halokinesis (Dronkert *et al.* 1989; Remmelts 1995; Geluk 2005; Bachmann *et al.* 2010; van Winden 2015). These salt movements are likely to be linked to the onset of the Early Cimmerian rifting phase, which allowed the formation of elongated pillows and locally detached faults above the salt layer (de Jager 2003, 2007, 2012; Ten Veen *et al.* 2012; Kombrink *et al.* 2012). In turn, this led to the development of depocentres in areas of salt withdrawal (Davison *et al.* 2000*a*, *b*; Ten Veen *et al.* 2012; Matthews *et al.* 2007).

The climax of the salt tectonics is observed to have occurred in the Jurassic period (see also Remmelts 1995; van Winden 2015). The presence of prominent rim synclines suggests the dominance of a piercing stage for many salt structures (Remmelts 1995; Lott *et al.* 2010; van Winden 2015; Vendeville 2002). In the Late Jurassic, rifting-related subsidence of the Dutch Central Graben was accompanied by widespread salt withdrawal, focusing deposition of sediments into the subsequent mini-basins (Lott *et al.* 2010). Because of the presence of thick Zechstein salt, Late Jurassic east–west rifting did not induce visible faults in the Upper Jurassic succession (Fig. 4) (Wijker 2014; van Winden 2015), although it is recognized that the main bounding

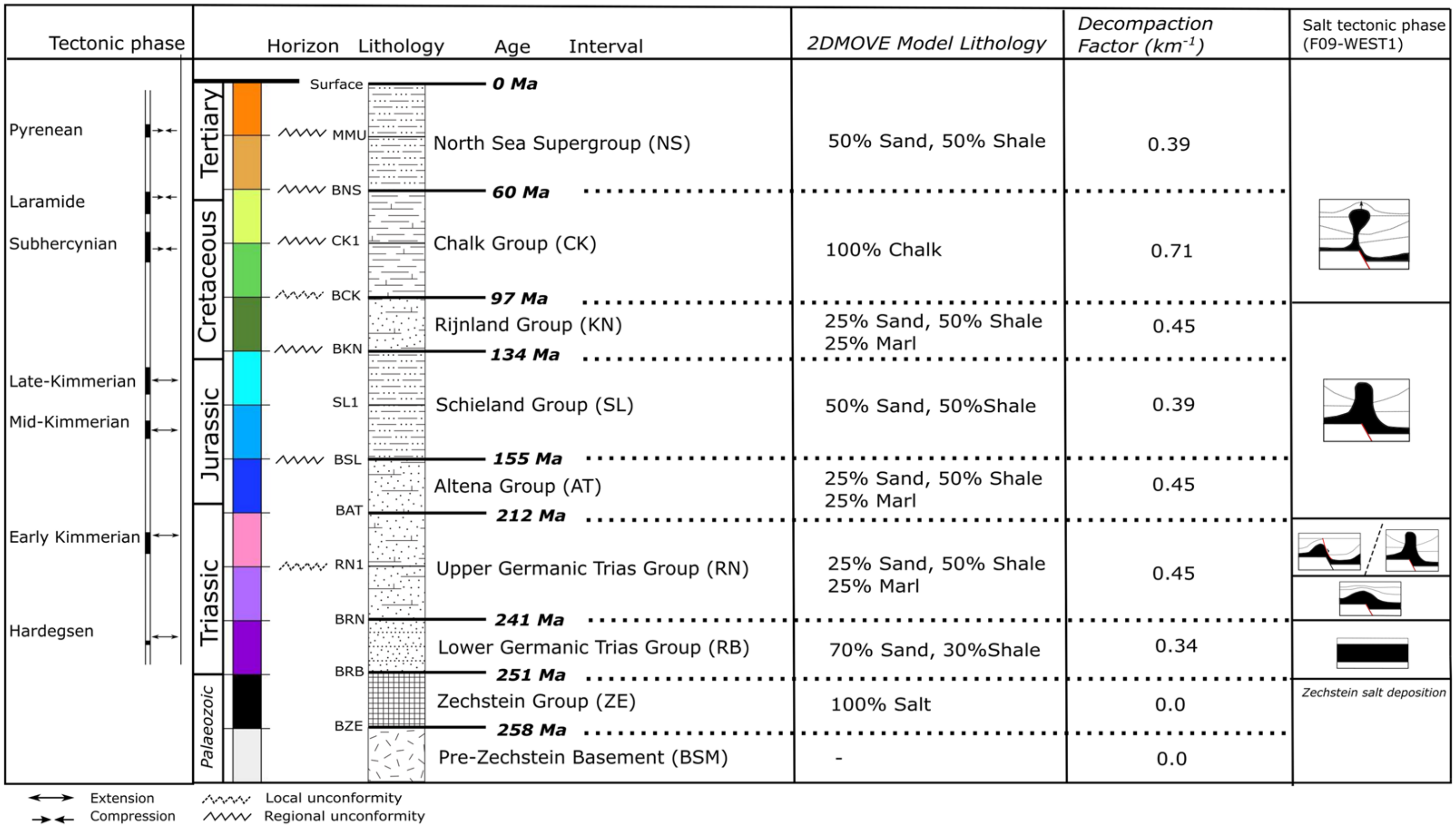

Fig. 3. Main tectonic events and restoration model stratigraphy, including lithological compositions and decompaction factors (after Verweij *et al.* 2009). Additionally, the interpreted salt tectonic phase of salt structure F09-WEST1 is plotted through time.

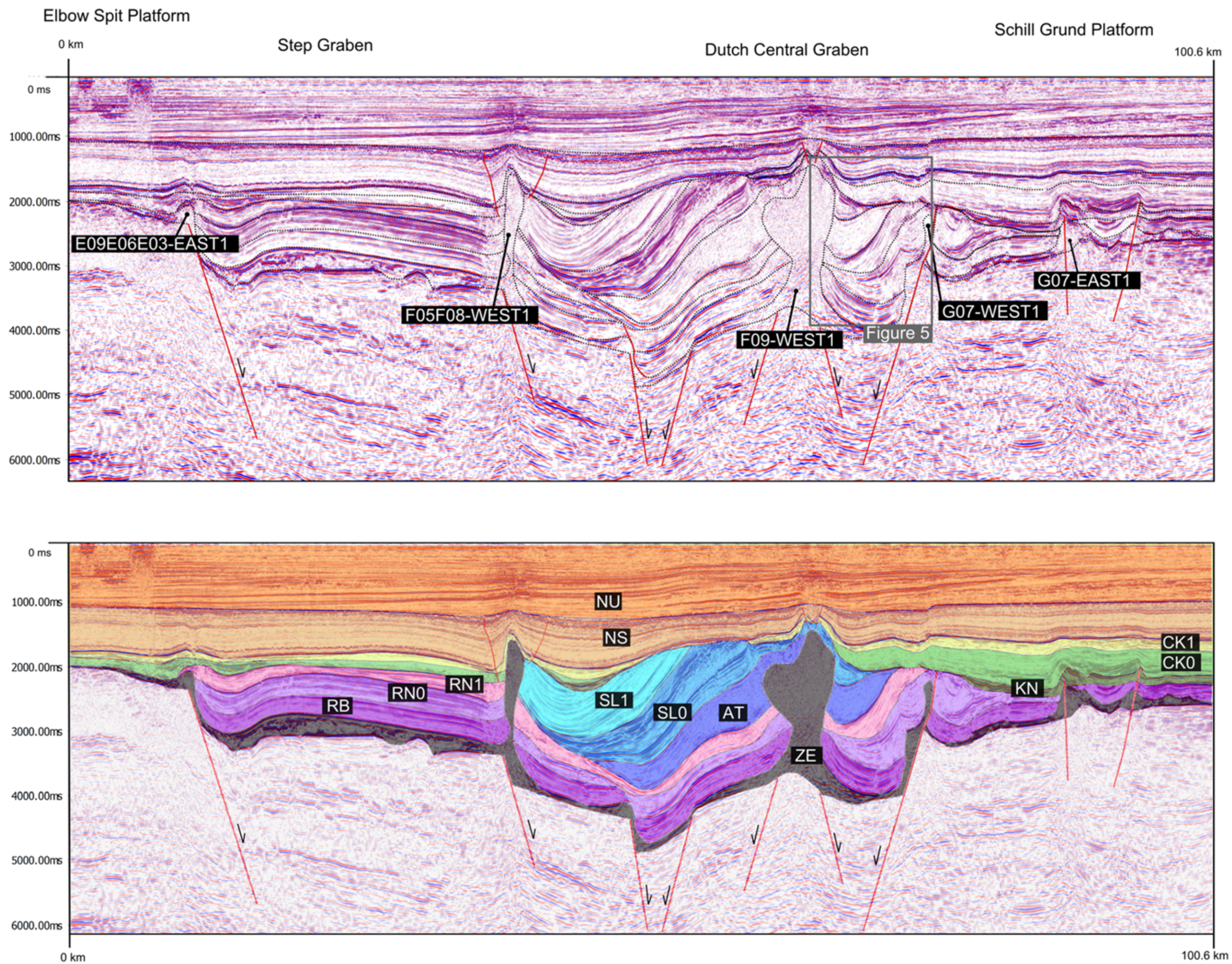

Fig. 4. Interpreted regional seismic section used for restoration (Fig. 6), from regional 3D seismic data (Spectrum DEFAB 2010 survey). For the location of the section see Figure 2. The abbreviations of stratigraphic intervals refer to Figure 3. The part of the section shown in Figure 5 is indicated on the seismic section (grey box).

faults of the Dutch Central Graben are overlain by salt walls, concealing much of the seismically definable subsalt structural detail (Fig. 4). However, subsalt basement faulting, through increased subsidence in the Dutch Central Graben, may have been responsible for a westwards shift of the Dutch Central Graben depocentre in Late Jurassic times (Wijker 2014; van Winden 2015). Thinning and local absence of Upper Cretaceous and Cenozoic strata over salt structures provides evidence for renewed salt movement during the Late Cretaceous and Cenozoic (Remmelts 1995; Van der Molen *et al.* 2005, Goffey *et al.* 2016).

The timing and development of salt structures, their interaction with faults and the effects on depositional patterns are not consistent throughout the entire study area, but vary depending on their location within the graben system. In order to better understand the implications of all post-Permian major structural deformation events on salt movement, a structural (palinspastic) restoration was performed.

Methods

A regional east–west seismic cross-section from the Spectrum DEFAB 2010 survey, through the Dutch Central Graben and Step Graben, was selected for a structural restoration with the aim of illustrating and testing hypotheses for the main stages of halokinesis and associated deformation. This particular section was chosen as it transects five key salt structures and all main structural domains (see Fig. 2). Additionally, this line trends perpendicular to the regional structural grain (NNE–SSW). Figure 4 illustrates this section with key stratigraphic intervals (listed in Fig. 3) and faults indicated (detailed section is shown in Fig. 5). Interpretations of horizons and

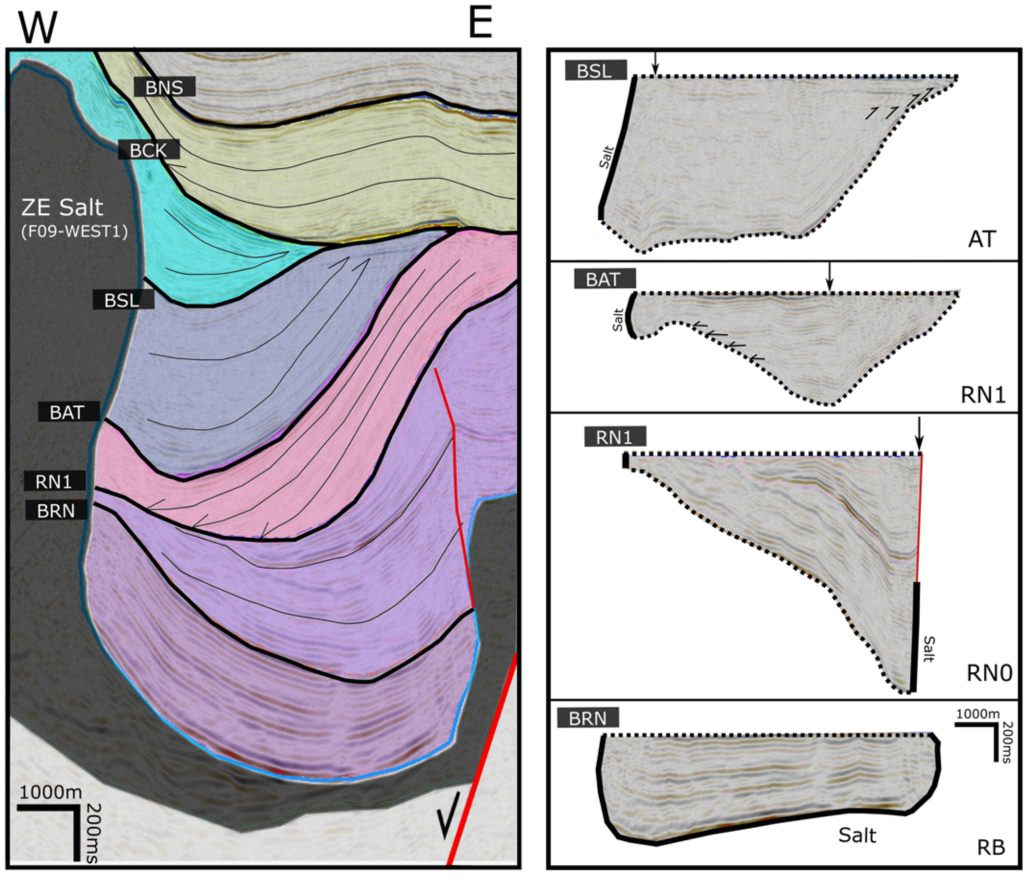

Fig. 5. Detailed interpretation on 3D seismic data (Spectrum DEFAB 2010 survey) of the Figure 4 seismic section, showing salt structure F09-WEST1 and adjacent intervals to the east. Four intervals are shown flattened on the corresponding top horizon: Lower Germanic Trias Group (RB), Upper Germanic Trias Group (RN0 and RN1) and the Altena Group (AT). The location of the palaeo-depocentre is interpreted (indicated by the black arrows).

Table 2. *The assumptions made for initial porosity, decompaction factors and densities of lithologies in the northern Dutch offshore (after Verweij* et al. *2009)*

Lithology	Initial porosity	Decompaction factor (km^{-1})	Density ($kg\ m^{-3}$)
Sandstone	0.49	0.27	2650
Shale	0.63	0.51	2720
Chalk	0.70	0.71	2200
Salt (halite)	0.00	0.00	2200
Marl	0.50	0.50	2700

faults were performed in time and subsequently depth-converted. The time–depth conversion was performed using a regional time–depth conversion model (Velmod v2.0: van Dalfsen *et al.* 2006). For all post-Permian intervals, a $V = V_0k$ function, where V = instantaneous velocity, V_0 = reference velocity and k = velocity gradient, was applied and Zechstein velocities were assumed to be constant. In order to appropriately model deformation and decompaction, rock properties were assigned to all 11 intervals of the model. For these intervals, the following properties were defined: (1) initial porosity; (2) decompaction factor; (3) compaction curve; and (4) bulk rock density (Table 2). These parameters were based on lithological information from the Terschelling Basin to the south of the study area (Verweij *et al.* 2009) and the Cleaverbank Platform to the SW of the study area (Abdul Fattah *et al.* 2012) (see Fig. 3). The Zechstein salt layer is treated as an incompressible layer. Vertical simple shear was applied in the restoration of faults and in unfolding. It is accepted that this may be unrealistic for restoration around salt structures, where strata dip steeply and a bed-length restoration algorithm may be more appropriate (Rowan & Ratliff 2012).

Several uncertainties are inherent to the structural restoration of salt sections. First, salt may have flowed in and out of the 2D section plane which would change the total area of the Zechstein salt layer, as represented in the 2D section. Secondly, dissolution and/or erosion of salt may have occurred, especially since models from this study suggest that salt was near, or even at, the surface in several locations and different moments in time (see also Hernandez *et al.*, this volume, in press). In this study, restoration of salt volumes and estimates of the total original thickness are further constrained by stratigraphic and structural geometries and by comparison to previous studies (e.g. Hossack 1995; Ten Veen *et al.* 2012).

Results

Figure 6a–h presents the results of the structural restoration of the regional transect shown in Figure 4. Eight restoration steps were performed in order to present a possible Early Triassic structural configuration. A chronological description of the resulting models is given below.

Early Triassic

The Lower Germanic Trias Group (RB) was deposited on top of the Zechstein Group (ZE) evaporites. Although the original thickness distribution of the ZE interval in the restored section is uncertain, it is likely that thinning of the interval occurred towards the edges of the Zechstein salt basin to the west of salt structure E09E06E03-EAST1 (Fig. 4), as is modelled in the restored section shown in Figure 6a. The location of this basin edge in this area is based on the occurrence of slope facies carbonates (Tolsma 2014). Towards the east of salt structure F05F08-WEST1 (Fig. 4), the original salt thickness may have reached up to 1500–2000 m (based on 50% salt dissolution and restored current-day salt thicknesses of up to 900 m: Ten Veen *et al.* 2012). The relatively constant thickness of the Lower Triassic sediments observed in this section suggests that the ZE salt was mostly unstructured at this time and is modelled as an interval with layered geometry. The RB interval is offset by younger faults, including the Dutch Central Graben boundary faults, at several locations. However, it is modelled that in this section the RB interval itself was deposited with a mostly homogeneous thickness (Fig. 6a). There are no indications that, during the deposition of the RB interval, active tectonism occurred in this part of the basin, even though in the north of the Step Graben (A and B blocks) there are local indications of active Early Triassic rifting (van Winden 2015). As such, it is expected RB was deposited without much palaeorelief present in the modelled part of the basin. The model includes some structuration in the pre-Zechstein basement, which may have controlled the location of the Southern Permian Basin margins and the Central Graben boundary faults, which show similar trends (north–south). This interpretation is speculative and based on seismic observations of a pre-Zechstein graben structure following the trend of the present-day Dutch Central Graben.

Late Triassic

Clear thickness variations near salt structures (mainly thinning: e.g. salt structure F09-WEST1) and thickening towards the eastern boundary fault of the Dutch Central Graben is observed in the lower part of the Upper Germanic Triassic Group (RN0) in this section. As the ZE salt had a significant thickness and was less deformed at this time, suprasalt faults were likely to be detached from pre-salt faults. This is consistent with the observed

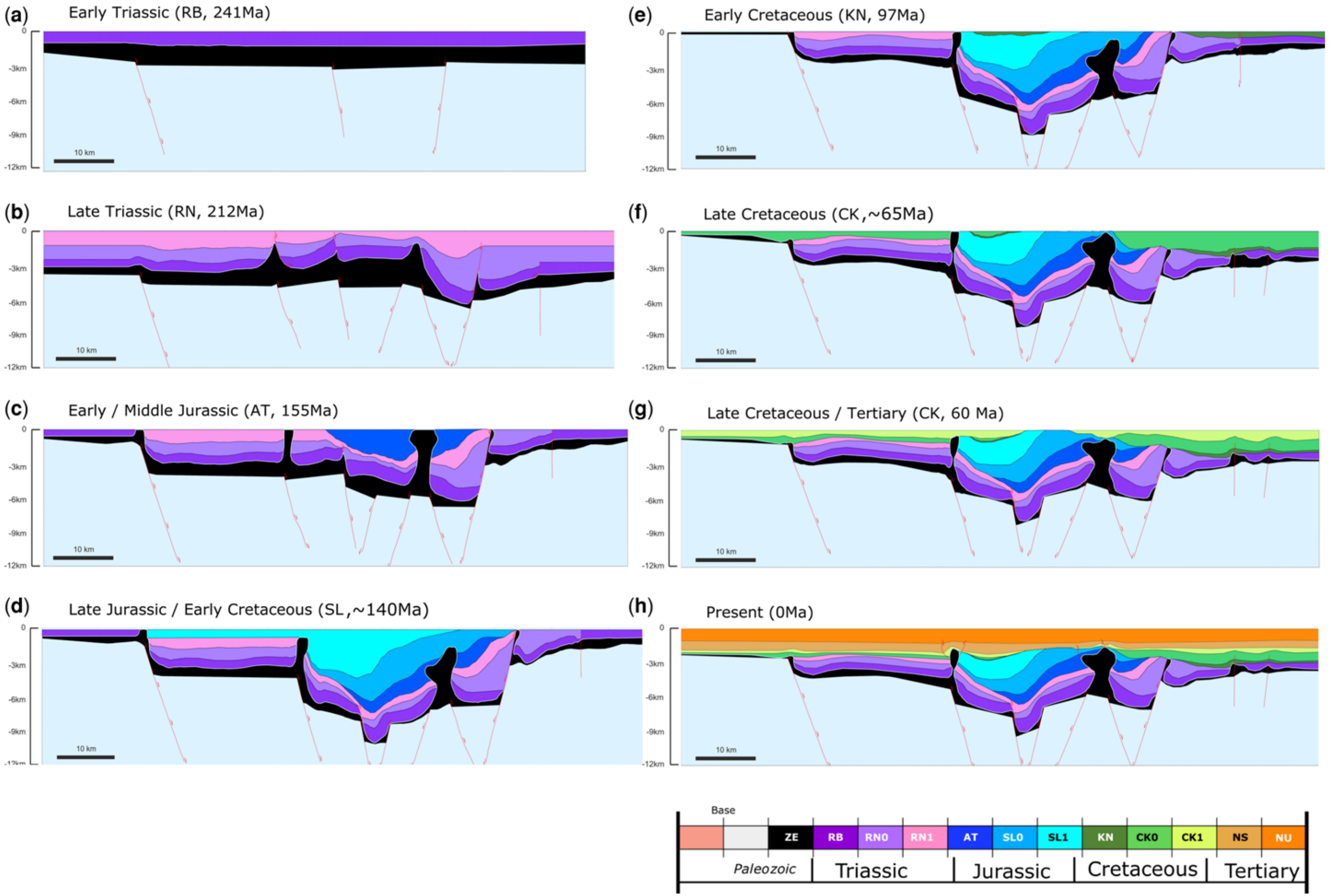

Fig. 6. Resulting cross-sections at various times in the structural restoration model (×2 vertical exaggeration) showing: (**a**) the estimated depositional salt thickness in the Early Triassic; (**b**) the initiation of salt tectonics in the Late Triassic; (**c**) & (**d**) the salt tectonic climax in the Jurassic; (**e**) & (**g**) Cretaceous erosion; and renewed salt movement in (**f**) the Late Cretaceous and (**h**) the present day.

stratigraphic geometries in the RN0 interval (e.g. Fig. 5). It is interpreted that most faulting throughout the Late Triassic was detached from basement faulting and the depositional pattern was controlled by non-linked or soft-linked faults above salt pillows. This is based both on the stratigraphic geometries throughout the RN interval (Fig. 5) and on the idea that the Zechstein salt layer probably had a greater, more homogenous thickness at the time of initiation of faulting. The RN0 interval shows clear stratigraphic thinning towards salt structure F09-WEST1. This geometry can be explained by the development of a depocentre away from a Zechstein salt pillow during deposition. A similar geometry, where strata thicken into a fault plane on one side of a salt structure and thins on the other side, can be observed to the west of salt structure F09-WEST1.

In this section, sediments of the RN0 interval within the Step Graben appear to have been deposited relatively undisturbed, as reflectors are parallel and continuous (Fig. 4). Some internal truncation can be observed near the western Step Graben boundary fault, which suggests minor syndepositional fault activity. On the Elbow Spit Platform, no Triassic strata can be observed today, but it is assumed the interval was deposited homogenously across the platform area and eroded at a later stage. This is based on the continuous nature of Triassic stratigraphy near the western Step Graben boundary fault (see also the palaeogeographical reconstructions of Doornenbal *et al.* 2010; after Ziegler 1990). From the Dutch Central Graben onto the Schill Grund Platform, the RN0 interval in this section shows stratigraphic thinning and is absent further to the east (Fig. 4). The restoration assumes relatively thin deposits, although it is uncertain how much Triassic was originally deposited on the stable Schill Grund Platform. The interval thickens rapidly into the Dutch Central Graben towards the west, resulting from subsidence of this area with respect to the adjacent platform areas and the Step Graben (Geluk 2005; de Jager 2007).

Fault activity gradually slowed during the later part of the Late Triassic. Stratigraphic thickness variations within the RN1 interval in the restored section shows a shift of depocentres at several locations within the Dutch Central Graben, in particular to the east of salt structure F09-WEST1 near the eastern graben boundary fault (Figs 5 & 6b). The depocentre of the RN1 interval is observed to shift from close to this boundary westwards towards salt structure F09-WEST1. This indicates an increased control of salt movement on the deposition of sediments. Reflectors of the RN1 interval downlap onto the top of the RN0 interval (Figs 4 & 5), illustrating the development of an eastwards-dipping slope during deposition of RN1. The flattened sections shown in Figure 5 confirm this westwards shift. This shift and associated downlapping sediments indicate the withdrawal of salt towards the west and an increase in salt thickness at the location of salt structure F09-WEST1, as modelled in Figure 6b. Away from the graben, RN1 is mostly absent at the present day, but is interpreted to have been deposited relatively undisturbed and homogenously (Ziegler 1992).

Jurassic

The Lower Jurassic Altena Group (AT) thickens towards the centre of the Dutch Central Graben in this section (Fig. 6c), where a secondary rim-syncline geometry is observed adjacent to salt structure F09-WEST1 (see Fig. 5). This implies that the salt structure pierced the overburden at this time. Towards the Dutch Central Graben boundary faults, the AT interval is truncated and absent on the platform areas and in the Step Graben. The AT interval is assumed to have been deposited regionally (in an open-marine setting: Doornenbal *et al.* 2010; after Ziegler 1990) and eroded from platform highs only at a later stage.

This erosion is believed to have been caused by uplift in the area of the restored section related to thermal doming in the Middle Jurassic (*c.* 155 Ma: Kombrink *et al.* 2012) which induced deep erosion (including of Middle–Upper Triassic deposits) on the platform areas and minor erosion within the Step Graben. During the same period, the Dutch Central Graben continued to subside and is, therefore, mostly unaffected by erosion, forming a restricted marine embayment (Ziegler 1990; Cope *et al.* 1992; Ineson & Surlyk 2003; Feldman-Olszewska 2006). Salt structures F05F08-WEST1 and E09E06E03-EAST1 were at, or near, the surface during this period (Fig. 6c), exposing Zechstein salt to erosion and dissolution. This is incorporated in the model as significant reduction in salt volume (up to 40%) throughout the Jurassic (Fig. 6c, d).

During deposition of the Upper Jurassic SL0 interval, a secondary rim-syncline geometry adjacent to salt structure F09-WEST1 persists (Fig. 6d), although a gradual shift of the depocentre occurs towards the west (Fig. 4). The shift of depocentre is accommodated in the restored model by fault-controlled subsidence (related to active accelerated rifting), combined with an increased withdrawal of salt in the west of the Dutch Central Graben. However, the true relative influence of these factors is uncertain.

A regional unconformity between SL1 and SL0 (Fig. 4) represents a major westwards shift of the depocentre, which starts during the deposition of the SL1 interval (Fig. 6d). As fault activity continued, deposition of both SL0 and SL1 remained restricted to the subsiding graben structures. To the north, Upper Jurassic sediments locally occur in rim synclines adjacent to salt structures within the Step Graben. This indicates that some Upper Jurassic deposition occurred in the Step Graben. The SL1 interval is interpreted to have been widely deposited and subsequently eroded in this area (Fig. 6d).

Cretaceous and Cenozoic

In the Early Cretaceous, erosion of almost all Jurassic strata outside of the Dutch Central Graben occurred, represented by the Base Cretaceous Unconformity (Fig. 6d) (Copestake *et al.* 2003; Pharaoh *et al.* 2010). On the Elbow Spit Platform, erosion removed all sediments overlying the Zechstein salt and is likely to have significantly eroded Zechstein sediments themselves, leading to a reduction in salt volume (Fig. 6e). Some erosion of Upper Triassic sediments occurred on the Schill Grund Platform and possibly within the Step Graben (Fig. 6e). The Rijnland Group (KN) was deposited during the Early Cretaceous, and was eroded from most of the Dutch Central Graben and Step Graben areas during the Late Cretaceous (Fig. 6f).

Within the Upper Cretaceous Chalk Group (CK), the Late Campanian Unconformity is interpreted to separate the Chalk Group into two intervals (CK0 and CK1: Fig. 3) (Van der Molen *et al.* 2005; Scheck-Wenderoth *et al.* 2008). This boundary is chosen as it is represents a significant Late Campanian inversion event, which can be identified as an unconformity in seismic (Fig. 3), and in CK0 and CK1 depositional trends. The CK0 interval onlaps towards the west on the eastern side of the Dutch Central Graben. On top of the Dutch Central Graben almost no CK0 is present, as the Late Campanian Subhercynian phase of uplift caused erosion down to the Base Cretaceous Unconformity (Figs 4 & 5) (Farmer & Barkved 1999; Van der Molen *et al.* 2005; Hampton *et al.* 2010). Subsequently, the post-Campanian sediments of the CK1 interval were deposited during the later part of the Late Cretaceous (Fig. 6g), which represents the preserved Chalk sediments of the Dutch Central Graben. After deposition of CK1, the central part of the Dutch Central Graben was inverted once more during the Laramide inversion pulse (Ziegler 1990; Ziegler & Dèzes 2007), causing local erosion of CK1. These inversions were not instantaneous and the deposition of sediments will have continued, as is suggested by the observed thinning of the CK0 and CK1 intervals towards the axis of main inversion.

The phases of inversion also induced renewed halokinesis, causing deformation of CK strata above salt structures. This resulted, for example, in an anticlinal geometry at the CK1 level above salt structures F05F08-WEST1 and F09-WEST1 (Fig. 4), and to a lesser extent above salt structures E09E06E03-EAST1, G07-WEST and G07-EAST (van Winden 2015). Faults on the Schill Grund Platform were also reactivated in a reverse sense, evidence of which is shown by locally thrusted CK0 strata to the east of salt structure G07-EAST1 (Fig. 4) and mass-flow deposits (e.g. near the eastern Central Graben boundary fault in Fig. 4 and above salt structure G07-EAST1: see also Arfai *et al.* 2016). Upper Cretaceous strata on top of the Late Campanian Unconformity appear less deformed, suggesting that no further significant inversion events occurred during the Cretaceous in this particular area of the Dutch Central Graben.

In the Cenozoic North Sea Group (NS), further vertical growth of salt structures F05F08-WEST1 and F09-WEST1 (Fig. 6h) is noted, indicated by a general thinning of the NS interval towards the axis of the Dutch Central Graben and above these salt structures (Fig. 4). Thinning of the pre-Miocene Lower North Sea Group sediments in this section also indicates another phase of inversion. Late Miocene–Pleistocene sediments exhibit stratigraphic thinning in anticline salt structures F05F08-WEST1 and F09-WEST1, suggesting a more recent reactivation of vertical salt structure growth.

Discussion

Considerations of the presented restoration models are discussed in this section, including inherent assumptions related to this restoration method and the limitations of the input data. Additionally, the main uncertainties and shortcomings of this model, related to the local geology and modelling approach, are highlighted.

Restoration model considerations

Whilst there are some indications of Early Triassic active tectonism towards the northern Step Graben (e.g. near salt structure A12-EAST2) and along the eastern Dutch Central Graben boundary fault, there are no clear indications of active rifting and associated salt movement in this period across the majority the study area. Faults, although mostly detached, can typically be correlated with active deeper basement faults. For example, major fault movements are suggested at the eastern Dutch Central Graben boundary fault (Figs 4 & 5). At the present day, this fault is observed to link from basement into the overburden through the salt cover, but it is unclear if this was the case in Late Triassic times. The restoration model assumes a consistent structural style across the Triassic basin and, therefore, models the fault as detached. It is likely that, at this stage, the location of salt structures was already determined and these Late Triassic salt pillows have a generic relationship to the salt structures present within the Dutch Central Graben today.

Zechstein salt thickness through time is interpolated between two end members: estimated thickness during the Early Triassic (1500–2000 m: Ten Veen *et al.* 2012) and present-day salt thickness. A reduction in salt volume is assumed to have been most intense in periods during which Zechstein salt was exposed to the surface (Early Jurassic and Cretaceous: Fig. 6c, e, f) and in periods during which most salt movement out of the plane of section is expected (Early Jurassic–Early Cretaceous: Fig. 6c, d, e).

The development of a secondary rim syncline during deposition of the Altena interval is interpreted as the piercing stage of the F09-WEST1 diapir (Fig. 6d). However, this creation of accommodation space can also be attributed to tectonic subsidence. The restoration model associates AT sediment accommodation with salt withdrawal which is supported by active salt movement during this period (transition from Triassic pillowing to a fully pierced salt structure in the Late Jurassic). Other, tectonic subsidence models could be investigated to understand how these processes interact. Note that this study interpreted a gradual thickening of the Altena Group into the Dutch Central Graben in contrast to published concepts of homogeneous deposition (Doornenbal *et al.* 2010; after Ziegler 1990), based on its interpreted thickness in 3D seismic data (Figs 4 & 5) (Wijker 2014; van Winden 2015).

The observation that the Altena Group is only preserved within the Dutch Central Graben is explained in the restoration model by continued subsidence subsequent to deposition. The accommodation space for the overlying SL0 and SL1 intervals can, again, be attributed to either salt withdrawal or tectonic subsidence. In this case, tectonic subsidence is used in the model because of known regional Late Jurassic rift acceleration (Ziegler 1990; amongst others), and a continuous thick (>6 km: Fig. 4) pile of SL0 and SL1 sediments. Some salt withdrawal is, nevertheless, likely and is incorporated locally into the restoration model. As such, the model assumes that accommodation was generated by salt withdrawal in the Altena interval, with tectonic subsidence more dominant in the SL0 and SL1 intervals.

In the restoration model, platform areas are deeply eroded below the Base Cretaceous Unconformity. The precise depositional area of KN is uncertain, here it is assumed that the interval had an approximately constant thickness, but with localized thickening onto the Schill Grund Platform and within the Dutch Central Graben. This variability is based on the palaeogeographical maps of Ziegler (1982), which suggest a transition from paralic to deep-marine deposition from platform to graben (see also Zwaan 2018).

The restoration of CK0 involves an estimate of the amount of eroded Jurassic and Cretaceous strata associated with the Late Campanian inversion. The restored geometry and thickness of these intervals is important, since this affects every older restoration step. The decision on how much strata to restore is based on the most realistic geometry in the context of local geology and extrapolation of truncated reflectors above the Late Campanian Unconformity (by flattening seismic data at this level). This interpretation suggests a maximum erosion of 900 m in the centre of the Dutch Central Graben. Basin modelling, constrained by vitrinite reflectance data, indicates this amount of uplift and erosion is in a realistic range (700 m: de Jager 2003). Alternative models with a thicker missing section would increase the compaction of underlying strata in the preceding restoration steps, which would, in turn, increase depositional thickness estimates of Jurassic and Triassic strata.

The role of Triassic evaporite intervals (e.g. Röt evaporites) and their interaction (e.g. co-mobilization or intermingling) with Zechstein evaporites (Niebuhr *et al.* 1999; Maystrenko *et al.* 2006; Pharaoh *et al.* 2010) was not within the scope of this study. Dedicated modelling work is suggested to investigate a possible relationship between the timing of Triassic evaporite deposition and the presence of Zechstein evaporites at or near the surface. This could include investigation of a potential correlation between the formation of lateral Zechstein salt intrusions and the presence of Röt evaporites (see also Pharaoh *et al.* 2010).

Uncertainties and assumptions of the restoration model

It is acknowledged that all restoration models have inherent uncertainties and assumptions. The main limitation for this study is the use of 2D sections that do not take into account salt and tectonic movements outside or at an angle to the section of the plane. Additionally, strike-slip components have not been taken into account, even though oblique components are documented in the tectonic phases (most notably Late Cretaceous and Cenozoic inversion: e.g. Van Wijhe 1987; Dronkers & Mrozek 1991; Nalpas *et al.* 1995; de Jager 2007; Pharaoh *et al.* 2010).

The authors acknowledge that it is likely that salt moved in and out of the plane of the restored 2D section (e.g. F05F08-WEST1 and F09-WEST1). At the same time, the main depocentres in the restored section (e.g. on both sides of the F09-WEST1 structure) were probably affected by very significant salt withdrawal to areas out of the section plane. Further work could be considered to build 3D restorations of such structures.

The presented model is based on a depth-converted seismic interpretation but, nevertheless, shows simplified geometries. Due to limited deep well control, the time-to-depth conversion is poorly constrained for the oldest intervals and for the top of the pre-salt. As such, the depth of the base Zechstein in the deepest part of the graben (up to 9 km in the restoration model; see also Geluk 2005) is associated with considerable uncertainty (at least 500 m). Lithologies, and associated decompaction factors, assigned to the deeper intervals also carry uncertainty due to limited or no well control.

Impact of models on hydrocarbon play definition

The model presented in this study, for the timing and nature of salt movement, can give insight into various aspects of the petroleum system of the northern Dutch offshore. For example, this model could be applied to define the depositional and preserved extent of Jurassic (Posidonia/Kimmeridge) source rocks, to investigate the timing of subsequent hydrocarbon charge though salt windows or to understand the distribution of shallow gas occurrences above salt diapirs. Understanding rim-syncline development can also help with the definition of reservoir distribution in Upper Triassic, Jurassic and Cretaceous strata (see also Bouroullec, this volume, in press; Verreussel, this volume, in press; Zwaan 2018). Zechstein salt movement also impacts other plays in this area, including the Triassic Volpriehausen play (charge through salt windows from Carboniferous source rocks, salt-controlled traps and lateral seals, and the risk of halite reservoir cementation: e.g. Fontaine *et al.* 1993; Purvis & Okkerman 1996), the Chalk play (Jurassic source rock maturation, reservoir facies distribution and fracturing, and diaper-controlled four-way dip closure traps: e.g. Van der Molen *et al.* 2005; Grassmann *et al.* 2005; Verweij *et al.* 2009; van Lochem, this volume, in press) and Upper Jurassic plays (local source rock and reservoir burial in salt-withdrawal basins, reservoir sand distribution and trap formation: Abbink *et al.* 2006; Grassmann *et al.* 2005). To further understand the impact of salt tectonics on Mesozoic hydrocarbon systems and reservoirs, a similar restoration study on a local scale is suggested. This would, for example, allow a more detailed analysis of the local effects of salt tectonics on Jurassic source rocks (e.g. around salt structure F09-WEST1 and F05F08-WEST1). Additionally, it could give more insight into the impact of late stages of salt structure growth on Chalk Group sediment facies and fracturing. The integration of further well data and the development of a more detailed regional velocity model will reduce the uncertainties of structural restoration in future studies, which would allow for better constrained assumptions on lithological properties and time-to-depth conversion.

Conclusions

This paper describes a detailed structural restoration of a regional seismic section through the Step Graben and the Dutch Central Graben. Combined with a regional analysis of salt structures and depositional patterns, this allowed the development of a new model, based on recent 3D seismic data, for the interaction between salt movement, tectonic activity and sedimentation at different stages in the post-Permian history of the northern Dutch offshore.

It is observed that periods of salt tectonic development are closely linked to regional tectonic events. It follows that depositional patterns are controlled by an interplay between salt movement and active faulting. This is exhibited during widespread Late Triassic rifting, which induced detached faulting above a layer of Zechstein evaporites. Deposition of Upper Triassic sediments occurred in fault-bounded depocentres along these soft-linked faults, while salt pillows formed simultaneously along the regional structural grain (NNE–SSW). This resulted in elongated depocentres away from salt structures and the thinning of sediments over the salt pillow crests. Early Jurassic deposition of thick Altena Group sediments resulted in continued halokinesis and the subsequent localized formation of diapirs. Middle Jurassic thermal doming eroded much of the sediment on the higher platform areas, which is likely to include a significant volume of Zechstein salt. Tectonic subsidence related to a Late Jurassic rifting phase provided the primary mechanism for the creation of accommodation space in the Step Graben and Dutch Central Graben. Acceleration of salt withdrawal into isolated salt diapirs and salt walls provided a secondary mechanism to accommodate the thick Upper Jurassic Schieland Group sediments filling the graben during Late Jurassic. Distal effects of Late Campanian (Subhercynian) and Early Cenozoic (Laramide) inversion phases led to regional uplift in the Dutch Central Graben, and local vertical salt movement in salt diapirs and pillows. This had a direct effect on the depositional characteristics and structural geometry of the Upper Cretaceous Chalk Group sediments above salt diapirs.

This study demonstrates that an analysis with a strong focus on halokinetic development can provide new insights into the local effects of structuration, which has implications for the position of local depocentres and for hydrocarbon play elements such as source rock and reservoir deposition or preservation.

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