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Salt tectonics

Renaud Bouroullec & Johan H. ten Veen*

*Corresponding author: renaud.bouroullec@tno.nl

ABSTRACT

Salt tectonics refers to structural deformation involving bodies composed of evaporite minerals. The Dutch subsurface is characterized by a thick sequence of Zechstein salt deposited during the Late Permian. Its deformation in response to several tectonic phases had a pronounced influence on Meso-Cenozoic tectonostratigraphic and depositional evolution. Salt layers of the Zechstein Group are the most prominent and regionally significant intervals that were affected by salt tectonics in the Netherlands. Other salt layers in the middle to early late Permian Silverpit Formation and of Triassic age (e.g. Main Röt Evaporite Member) were affected by more local and less extensive salt tectonics than the Zechstein and are of secondary importance. The main salt tectonic structures observed in the Dutch sector are due to large volumes of Zechstein salt that were mobilized laterally or vertically, feeding large salt bodies and allowing basins to form in response to a combination of salt withdrawal, extensional- and contractional tectonic forces. These growth basins include mini basins, sub-basins, rim synclines, rollover anticlines and collapse grabens. Successive crustal-scale tectonic events induced the salt tectonics in the Netherlands, localizing salt movements, enhancing salt migration, and deforming pre-existing salt bodies (e.g. through diapir squeeze). In this chapter we discuss the main salt tectonic processes, the original Zechstein salt thickness and the five types of salt structures observed in the Dutch subsurface (salt pillows, diapirs, walls, rollers, and sheets), including their geometry, their geographic distribution, their kinematics and their effects on associated structures such as growth fault/raft systems, crestal faults, turtle structures, caprock and collapse grabens. The Meso-Cenozoic sediment pathways, sediment distribution/preservation and the overall basin architecture were also affected by accommodation changes resulting from salt withdrawal and migration.

In the Netherlands, limited syn-depositional faulting during the Tubantian I phase (Geluk, 1999) caused local thickness variations within the Zechstein Group. The actual movement of Zechstein salt started as early as the Early Triassic but most of the significant salt tectonics occurred between the Middle Triassic and the Paleogene in response to a combination of gravitational forces (halokinetics) and tectonic events. Since the Paleogene, salt tectonic intensity has diminished but salt bodies and their crestal faults affect several processes in the shallow overburden up until the Quaternary.

<< Rhythmic millimetre-scale calcite (brown) and gypsum-bearing (white) laminites interpreted as seasonal varves formed from hemipelagic settling and correlatable over a hundred kilometres. Photo: Zoltan Sylvester.

Introduction

Knowledge about salt tectonics in the Dutch subsurface has grown rapidly since the seminal work of Heybroek (1975). The work carried out by the oil and gas industry as well as academic research on salt basins worldwide, including those of the North Sea Basin has provided the framework for salt tectonics analysis in the Netherlands (Clark-Lowes et al., 1987; Wong et al., 1989; Nalpas et al., 1995; Remmelts, 1995, 1996; Nalpas, 1996; Geluk, 2005; De Jager, 2012; Nelskamp et al., 2012; Ten Veen et al., 2012; Bouroullec et al., 2016, 2017, 2018; Peeters, 2016; Van Winden et al., 2018). The Zechstein salt in the Dutch subsurface displays a wide variety of salt body types and associated structures. ‘Salt body’ is a general term referring to any individual salt feature. In the Dutch sector the main salt body types are salt pillows, salt diapirs and salt walls but locally salt rollers and -sheets are observed as well (Fig. 12.1). Salt bodies and structures formed during multiple periods and their distribution depends on a combination of factors, including 1) the depositional thickness and lithology of the original (mother) salt layer, 2) the burial depth of the salt, 3) the topography of the subsalt strata (e.g. faulted pre-salt), 4) the sediment loading rate and direction, 5) the structural evolution of basins, platforms and highs (e.g. rifting, inversion), 6) the presence of pre-existing salt bodies formed during previous tectonic or basin fill phases and 7) the occurrence and amount of erosion. All these factors will be described in this chapter.

Rheology and geomechanics of evaporites

Rheology is the study of deformation of matter and in geology deals with the flow of solid rock visible only over geological time. The rheological behaviour of evaporites and particularly rock salt (halite, NaCl) plays a major role in how salt basins develop. Geomechanics, i.e. the mechanics of rocks, is a broader term that describes the brittle behaviour of rocks and tackles the formation of faults and fractures. Both rheology and geomechanics play a role in salt tectonics, especially in the case of Zechstein salt deformation (Bouroullec & Geel, 2025, this volume). Halite layers are the weakest, while anhydrites, carbonates and siliciclastics are stronger. Such mechanical layering plays an important role in the way the internal deformation of salt layers and bodies occurs (Rowan et al., 2019). Salt weakness is extremely variable and many concepts and quantifications based on studies in the Netherlands are now used worldwide (Urai, 1983; Urai et al., 1986, 2008; Schlöder & Urai, 2005). A thorough summary in Hudec and Jackson (2007) testifies to the current understanding of salt behaviour at multiple scales.

Halite behaves in a ductile fashion when deformed or when mixed with higher-pressured fluids. The short-term fracture strength of halite is as high as that of concrete.

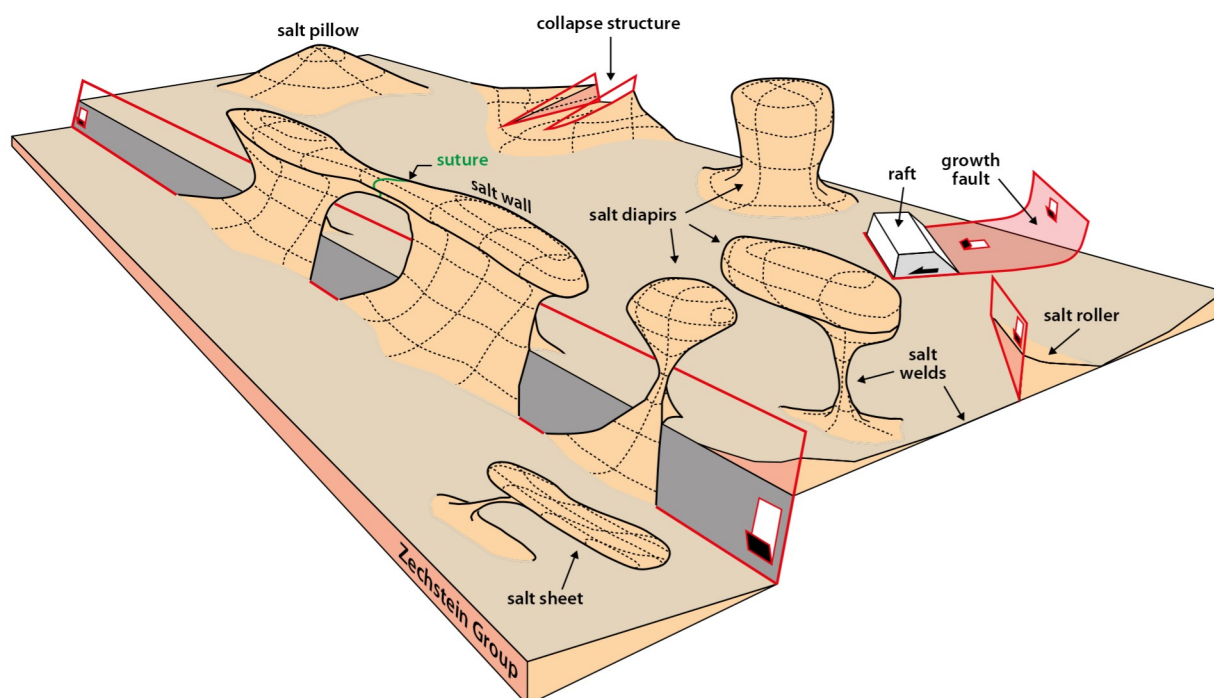


Figure 12.1. The main salt body types in the Dutch subsurface. See text for explanation.

However, the yield strength for long-term creep of halite is near zero, which means that salt will creep plastically even if shear stress is very low. Various processes such as dislocation glide, dislocation creep, solution-precipitation creep and water-assisted dynamic recrystallization play a role in the microstructural deformation of halite (Urai et al., 1986, 2008). Grain size (typically around 10 mm in diapiric halite), impurities, stress paths, temperature and fluid chemistry also play a role (Rowan et al., 2019). Differential stress in naturally deforming halite generally ranges between 0.5 and 2 MPa but can be as high as 5 MPa at shallow levels (Spiers & Carter, 1998; Schlöder & Urai, 2005). Anhydrite (CaSO_4) is stronger than halite but weakens rapidly when burial temperatures reach 100° to 200°C. Deformation is aided by low effective stress caused by highly pressurized pore fluids sealed within encasing rock salt (Van Gent et al., 2011). Therefore, anhydrite is weaker than most rock types and forms effective décollements. For example, in the Dutch subsurface many faults are detached onto the Triassic Keuper evaporites. Thick anhydrite layers can also form stringers (see below for definition) when embedded in thick halite layers. If shortened, anhydrite stringers are folded, while they may be subject to boudinage while extended. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is not as weak as halite but is still a ductile rock type and can also act as an effective detachment. However, the rates of pressure solution in compacting gypsum are typically three to four orders of magnitude lower than in halite under similar conditions (Spiers et al., 1990). Carnallite (hydrated potassium-magnesium chloride) and Bischofite (hydrated magnesium chloride) are much weaker than halite and are often referred to as squeezing salts by drilling engineers. These salts have much lower viscosities than halite and flow 100–1000 times faster under a given differential stress (Urai, 1983; Urai et al., 1986). For example, at 60°C, carnallite has a viscosity as much as 10^6 times lower than that of halite (Van Keken et al., 1993). For a differential stress of 10 MPa at a temperature of 60°C, carnallite creeps about 100 times faster than halite; and bischofite creeps about 10,000 times faster than halite (Urai et al., 1986).

Interbeds of various lithologies within halite layers will deform in specific manners when salt flows, depending on their own lithology, degree of cementation, overpressure, thickness, and burial. For example, in the Dutch sector, the “Z3 stringers” composed of anhydrite, carbonates and clay, are locally well imaged on seismic data since they are relatively thick (40–50 m in average and up to 150 m). These stringers are often folded or deformed as boudin structures and locally have perturbed salt flow (Van Gent et al., 2011). The mechanical behaviour of both carbonate and anhydrite is different from rock salt. Under conditions relevant for deformation of stringers, rock salt tends

to become ductile while carbonates and anhydrites tend to be relatively more competent with folding being common; hence the stringer does not deform in a fully brittle fashion (Van Gent et al., 2011). This basically means the depth or confining pressure for the transition between brittle and ductile deformation is larger for carbonates and anhydrite than for rock salt. It also means that at greater depths, the rate of ductile deformation is lower for carbonate and anhydrite than for rock salt at similar flow stress.

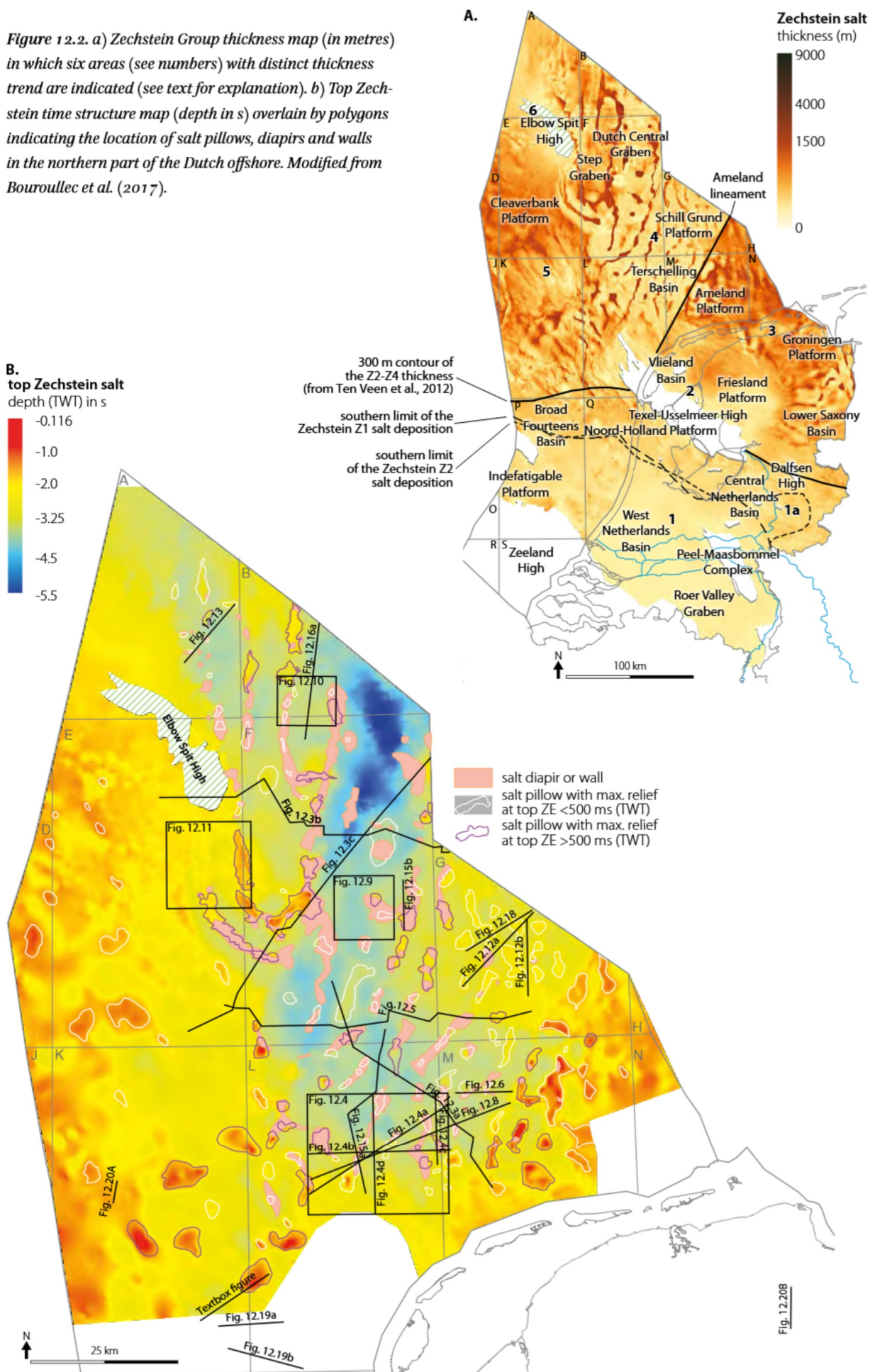
Salt tectonics processes

Current understanding of salt tectonic processes has significantly benefited from technical progress made during the decades of hydrocarbon exploration. Access to 3D seismic data and improvement of seismic imaging and analysis techniques allows for better seismic and structural interpretation and has changed the view on how salt diapirs behave within the main extensional grabens in NW Europe (e.g. Mohr et al., 2005).

There is consensus that the main reason salt mobilizes and migrates in the subsurface over geological time scales is because of its mechanical weakness. However, since the 1930s the ideas on salt flow triggering mechanism(s), rheology, timing and modes of salt structure formation have changed. The movement of salt under the influence of gravity is referred to as halokinesis (Trusheim, 1957). One of the oldest ideas was that low-density salt penetrates higher-density overburden sediments solely due to differential loading (salt piercement model of Trusheim, 1957), and that salt buoyancy (lava lamp-like deformation) was the main process involved in salt tectonics. After the 1980s, the buoyancy process fell out of favour as an explanation for salt tectonics and the now-established – and still evolving concepts – consider the combination of a brittle and competent overburden and differential loading as the main process driving salt flow.

After reaching as little as 200–300 m of burial depth, the confining pressure and diagenetic processes affecting siliciclastic sediments increases to the point that they become mechanically stronger than salt layers. With further compaction the sedimentary overburden lithifies, increasing further the strength of the supra-salt sediments (sediments located above the salt layer or body). Contrastingly, the salt weakens only slightly with increasing burial and temperature. With continued burial, the salt layers become the weakest rock and, at a geological time scale, will tend to flow and deform under gravitational displacement and thermal loading forces (Hudec & Jackson, 2007). Active tectonics increases the likelihood of salt structure formation as it triggers differential loading (e.g. Vendeville &

Figure 12.2. a) Zechstein Group thickness map (in metres) in which six areas (see numbers) with distinct thickness trend are indicated (see text for explanation). b) Top Zechstein time structure map (depth in s) overlain by polygons indicating the location of salt pillows, diapirs and walls in the northern part of the Dutch offshore. Modified from Bouroullec et al. (2017).



Jackson, 1992; Vendeville, 2002) and associated lateral salt flow (migration). The term halotectonics or salt tectonics covers all salt mobilization processes where tectonic forces are also involved and is more appropriate for the Netherlands given its long and complex tectonic history. All these processes allow the salt to migrate, forming salt bodies (salt pillows and/or diapirs) and ridges (salt walls) separated by depressions where thicker sedimentary successions could accumulate (Fig. 12.1). Continued sedimentation in these depressions increases differential loading, further favouring salt flow until salt supply from the source layer is cut off, due either to the salt volume running out or the creation of a physical barrier (e.g. fault, or collapse of the salt body feeder).

In the Dutch sector only a small number of salt bodies are allochthonous, meaning that they were emplaced as sub-horizontal or moderately dipping sheet-like salt diapirs, at a stratigraphic level above the autochthonous (mother-salt) layer (Zechstein).

The salt bodies can often reach shallow depth and even extrude at the seafloor or free surface, forming salt sheets or salt glaciers such as those that can be seen at present in the Zagros Mountains of Iran. Zechstein salt glaciers that extruded during the Late Triassic have been recognized in Germany (Mohr et al., 2007). In the Netherlands, most salt bodies are buried under a thick Cenozoic sequence and show little signs of deformation post-dating the Alpine orogeny. Differential subsidence around salt bodies may have led to formation of crestal faults that play an important role in hydrocarbon migration (e.g. shallow gas).

Zechstein salt distribution in the Netherlands

The combined effects of burial, temperature and (for the Dutch subsurface) external forces such as differential loading, extension and compression, ensure that thick salt flows in various fashions to form salt bodies that have various sizes and geometries. As pointed out by Geluk (2007a) for the Netherlands it is extremely important to differentiate between areas with thick salt and those without salt (Fig. 12.2a), since the structural styles of these areas are completely different during phases of extensional or compressional tectonics (De Jager, 2007). Salt flow was more intense during periods that coincide with known tectonic phases, but the intensity differs considerably between structural element types (e.g. Ten Veen et al., 2012).

The partitioning of the Southern Permian Basin into several basins and highs during the Triassic and Jurassic was accentuated by intense salt tectonics, located primarily along fault-bounded basin margins (Heybroek, 1975; Clark-Lowes et al., 1987; Wong, 2007). No evidence of Per-

mian-age salt tectonics has been described in the Netherlands. Salt tectonics is dominant in rift basins such as the Dutch Central Graben, the Step Graben, the Terschelling and Broad Fourteens basins and their associated platforms (Fig. 12.2a). These basins have a horst and graben configuration and are bounded by large syn-sedimentary faults and salt diapirs or salt walls that were repeatedly reactivated during Mesozoic and Cenozoic rift and inversion events and in response to differential loading and erosional events. Basin compartmentalization and sub-basin formation were focused predominantly in the Dutch Central Graben, Step Graben and Terschelling Platform, where salt withdrawal involved thick salt layers. In the Broad Fourteens Basin compartmentalization occurred to a lesser extent since the original salt layer was thinner, as discussed below. Salt tectonics also took place in the Lower Saxony Basin, Groningen Platform, Friesland platform and around the Lauwerszee Trough (Strozyk et al., 2014).

The present-day thickness of the Zechstein Group increases from less than 50 m in the southern part of the Netherlands to more than 1200 m in the northern offshore (Geluk, 2007a). It is composed of five evaporite cycles (Z1-Z5), which may comprise fringe sandstone, carbonates, anhydrites, halite or claystone (for detail, see Bouroullec & Geel, 2025, this volume). The thickest halite layers are the Stassfurt Halite (Z2) and Leine Halite members, up to 600 m and 300 m thick, respectively. Locally, movements can result in salt bodies that can reach heights of 8 km. The main Zechstein unit deforming into salt bodies is the Stassfurt Halite (Z2), which has the highest overall percentage of halite (>95%) and forms the most important top seal for the Upper Rotliegend gas reservoirs (Geluk, 2007a; Ten Veen et al., 2012). The depositional Zechstein salt geometry was of a horizontal nature with possibly some local thickening on the downthrown sides of pre-existing faults. Based on numerical restoration Ten Veen et al. (2012) estimated that the original depositional thickness of the main Zechstein salt ranged from a few hundred metres in the southern part of the Dutch on- and offshore to an average of 500-700 m in the northern half of the offshore, reaching a maximum thickness of 900 m in the northern part of the present-day Dutch Central Graben and on the northeastern part of the Step Graben and thickening toward the German offshore sector.

It should be considered, however, that the amount of salt observed in many Dutch basins is only a portion of the originally deposited salt since it can be subject to intense dissolution and/or withdrawal and may have been eroded during local or regional basin evolution. Since the Jurassic, erosional events have occurred frequently in the Dutch sector. For instance, during the Middle Jurassic Mid-Cimmerian erosional phase (Ziegler, 1990; Underhill & Partington, 1993; Surlyk & Ineson, 2003; Bouroullec et

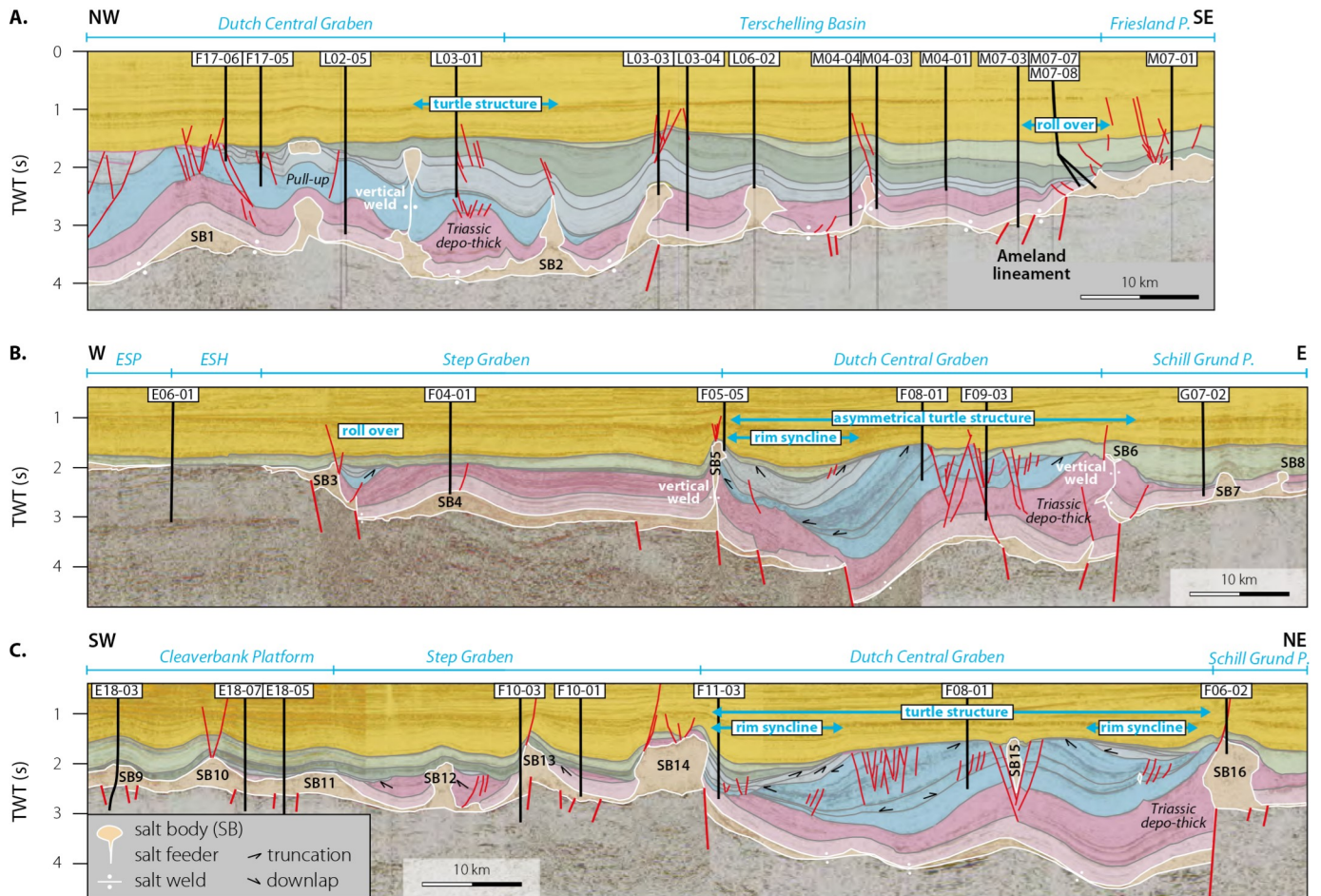


Figure 12.3. Interpreted seismic time sections across the northern part of the Dutch offshore highlighting the type of salt bodies (pink polygons) observed. Each panel is a composite from various 2D and 3D seismic datasets, selected such that key wells are intercepted. The pre-Zechstein interval is not interpreted. a) NW-SE trending panel from the southern part of the Dutch Central Graben to the Friesland Platform through the Terschelling Basin. b) W-E trending panel from the western part of the Elbow Spit Platform to the Schill Grund Platform across the Elbow Spit High, the Step Graben and the Dutch Central Graben. c) SW-NE-trending panel from the Cleaverbank Platform to the Dutch Central Graben through the Step Graben. See text for further explanation and Fig. 12.2b for location of the seismic sections. Modified from Bouroulec et al. (2016, 2019). ESP = Elbow Spit Platform; ESH = Elbow Spit High.

al., 2018; Verreussel et al., 2018) shallow salt bodies located along the flanks and within the Jurassic rift system were significantly eroded (see Verreussel et al., 2025, this volume). Throughout parts of the Dutch sector, there is evidence that during continued flow salt bodies at one time may have reached shallow depths or even the paleo-free surface, forming glaciers, as observed in Germany (Mohr et al., 2007). The presence of cap rocks at the top of salt bodies (see discussion on cap rock below) also indicates that salt dissolution was likely a common phenomenon. Cartwright et al. (2001) indicated that lateral dissolution of salt bodies could have taken place in the North Sea basins resulting in the removal of as much as 40% of the original Zechstein volumes. These dissolution phenomena and erosional events complicate attempts to reconcile the present-day volume of Zechstein salt preserved in the

subsurface with salt-related stratigraphic and basinal geometry observed throughout the Dutch subsurface. Often, a considerable volume of salt needs to have been lost in order to explain the extreme basinal geometries observed in the northeastern part of the Dutch sector. In this area, at least 1000 m of salt must have been deposited and as much as 1300 m or more if significant dissolution occurred. These values exceed the earlier 900 m estimate of Ten Veen et al. (2012).

Present-day salt thickness can be approximated by looking at the variations of the overall Zechstein Group thickness (Fig. 12.2a) which, to a large extent, is related to migration of Zechstein Z₂ salt. The salt migrated and withdrew in multiple directions, forming different types of salt bodies and associated basins and sub-basins (see below). At the

present-day six Zechstein Group thickness areas can be differentiated in the Netherlands:

1. The first area (Area 1 in Fig. 12.2a) extends NE to SW across the southern Dutch on- and offshore. This area is located north of the Zeeland High and includes the Indefatigable Platform, the West Netherlands Basin, the Roer Valley Graben, the Peel-Maasbommel Complex and the southern part of the Central Netherlands Platform. This area shows little to no thickness change and no salt bodies have been identified. The area is located south of the approximate southern limit of Zechstein halite deposition (Fig. 12.2a) and is devoid of salt tectonic features. A small area in the eastern part of the Central Netherlands Basin (Area 1a, Fig. 12.2a) shows some thickness variations that are likely related to Z₁ salt movement since the southern depositional limit of Z₂ halite is farther to the north.
2. The Zechstein Group is very thin or absent in the area to the north (Area 2 in Fig. 12.2a). This area is in the vicinity of the Texel-IJsselmeer High and includes the northern part of the Central Netherlands Platform, Friesland Platform, the Vlieland Basin and the Noord-Holland Platform. The Texel-IJsselmeer High was a high during the deposition of the Zechstein Group and the limited thickness of the salt (mainly Z₂ and limited Z₁) allows for minor movement into small salt pillows only. In the area located between the southern depositional limits of Z₂ and Z₁ salt (Fig. 12.2a) and the original 300 m Z₂-Z₄ thickness (from Ten Veen et al., 2012) the salt is considered to be too thin to have been subject to significant diapirism and this is shown by the lack of salt bodies. Rather, this area was subject to minor salt migration and salt-induced differential subsidence.
3. The third area (Area 3 in Fig. 12.2a) is in the central eastern part of the Netherlands, spanning from the on-shore Lower Saxony Basin via the offshore Ameland Platform to the eastern part of the Schill Grund Platform. Strozyk et al. (2014) illustrated the salt tectonic style of this region and highlighted the presence of Z₃ stringers (see below for description of stringers). Overall, this area consists of a relatively thick (700 to 1400 m) Zechstein Group with a predominance of large salt pillows and salt diapirs. The transition in thickness between Area 2 and 3 is smooth, in contrast to the distinct and linear transition between the third and fourth areas (referred to as the Ameland lineament; Fig. 12.2a). This feature was likely an inherited pre-Zechstein fault that affected the depositional thickness of the salt as well as the later deposition and preservation of the Triassic sequence (see Fig. 12.3a, in particular around wells Mo7-07 and Mo7-08).
4. The fourth area (Area 4 in Fig. 12.2a) is in the central part of the Dutch offshore and comprises the Terschell-

ing Basin, the western part of the Schill Grund Platform, the Dutch Central Graben and the Step Graben. This area shows by far the most extreme post-depositional Zechstein Group thickness variation with large zones where the salt withdrew and migrated toward preferential locations forming large and numerous salt diapirs and salt walls above or in the vicinity of rift bounding faults (Fig. 12.3; Strozyk et al., 2012). This is one of the few areas that contains disconnected salt stocks, i.e. salt bulbs with salt welds beneath them. Note that this is not the norm in the Netherlands since most salt pillows and diapirs have relatively thick bases or stems. The resulting growth basins and sub-basins were formed during Middle Triassic to Early Cretaceous rifting phases and comprise turtle back structures with rim synclines, roll-over anticlines and intra-rift sub-basins. Some of the salt diapirs located in this area were squeezed and became disconnected during the Middle to Late Triassic in response to thin-skin extension around the paleo basin margin (see below for additional information).

5. The fifth area (Area 5 in Fig. 12.2a) is located west of areas two and four and extends from the Broad Fourteens Basin in the south to the Cleaverbank Platform (see Fig. 12.3c). This southern part of the area is dominated by Alpine compressional features such as large folds, inverted pre-existing normal faults and thrusts that are occasionally salt-cored (Nalpas & Brun, 1993). Prior to compression, the original Mesozoic geometries of these salt bodies were likely to have been similar to the ones found in Area four and they show a predominance of rift-related salt withdrawal and migration into salt diapirs and walls. The central part of Area five is dominated by a relatively thick salt layer composed of numerous salt pillows and some rare salt bodies. The eastward transition between Area five and four is rather smooth and is demarcated by an increasing number of salt diapirs and collapsed salt bodies (see below). The northern part of Area 5 transitions smoothly into Area 6 with a decreasing Zechstein thickness towards the Elbow Spit Platform and High.
6. Area 6 is in the northwestern part of the Dutch offshore around the Elbow Spit High (Figs 12.2a, 12.3b). In this area the Zechstein Group is very thin or absent. A few small isolated Early to Middle Triassic mini basins (pods) exist in the eastern part of this area, similar to those in the UK offshore sector (Penge et al., 1999; Stewart & Clark, 1999). Mini basins are small intra-salt basins largely surrounded by and subsiding into relatively thick salt areas (e.g. deep in the Gulf of Mexico; Pilcher et al., 2011; Bouroullec & Weimer, 2017). Such mini basins are not clearly observed elsewhere in the Dutch sector except for some areas located between salt pillows on the Groningen Platform (Raith et al., 2016).

Salt bodies, associated structures and phenomena in the Netherlands

More than 230 salt bodies primarily consisting of Zechstein salt pillows, salt diapirs and salt walls (Figs 12.1 and 12.2b; Groenenberg et al., 2025, this volume, their Figure

16.4) have been recognized in the Netherlands. For the Dutch onshore, the term “dome” has been historically widely used as a synonym for salt diapir or -wall in the hydrocarbon industry as well as in the salt mining and -production industry. Other salt body types observed in the Dutch subsurface include salt rollers, i.e. overthickened

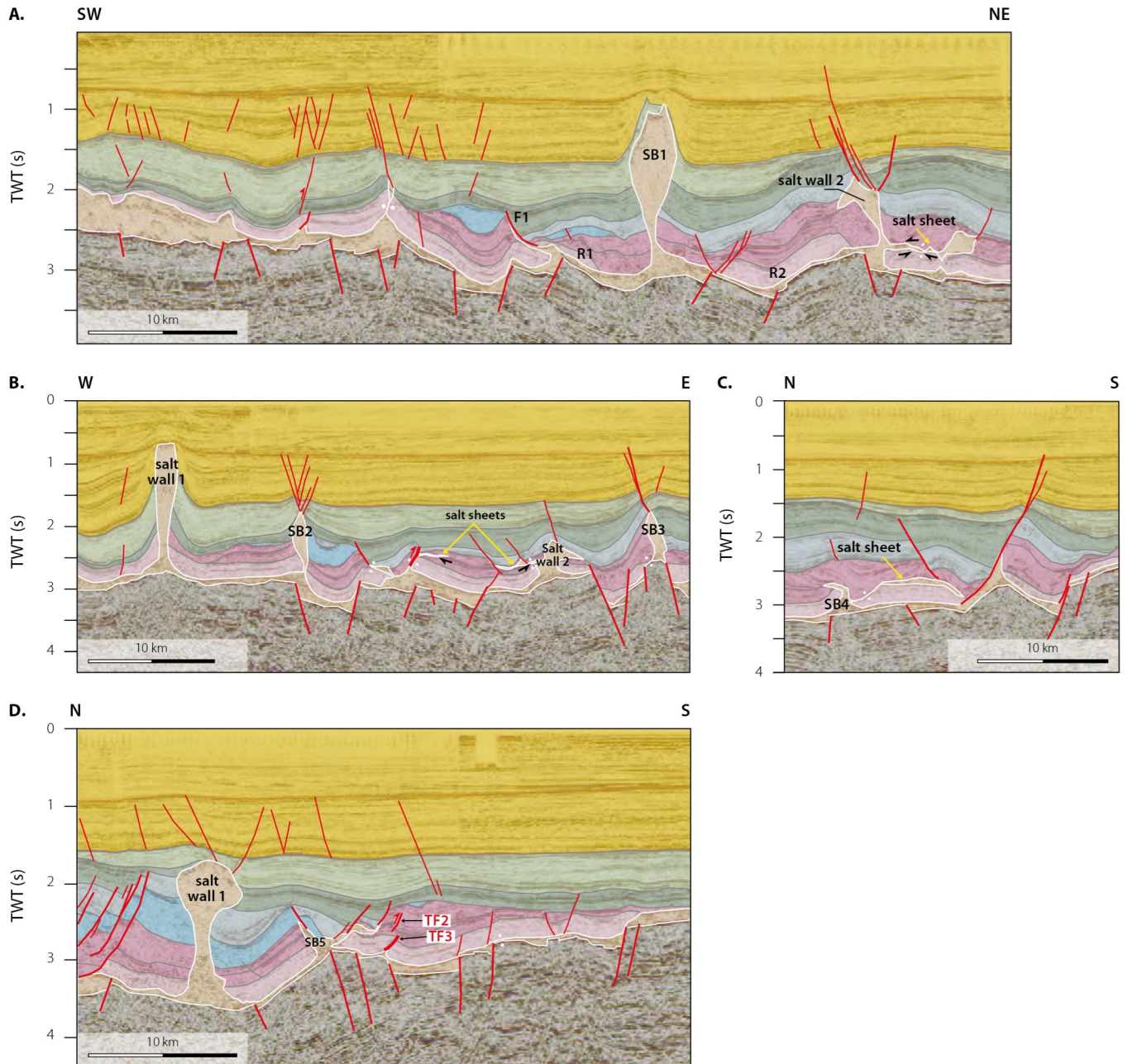


Figure 12.4. Interpreted seismic time sections located in the southern part of the Terschelling Basin and the northern part of the Friesland Platform. Zechstein salt is shown as pink polygons, faults as red lines. Note the series of loaded salt sheets in sections (a), (b), and (c) as well as collapsed diapirs in section (a), (b), and (d). Section A shows a zone around salt body 1 (SB1) where the Lower Triassic is absent, likely due to rafting. Note the rugose nature of the base Zechstein Group with its large number of normal faults and a large flexure that demarcates the Hantum Fault Zone that strikes SE-NW from the southern part of the Lauwerszee Trough to the southern part of the Terschelling Basin. See Fig. 12.2b for location of the seismic sections and Fig. 12.3c for explanation of salt symbology. Modified from Bouroullec et al. (2017).

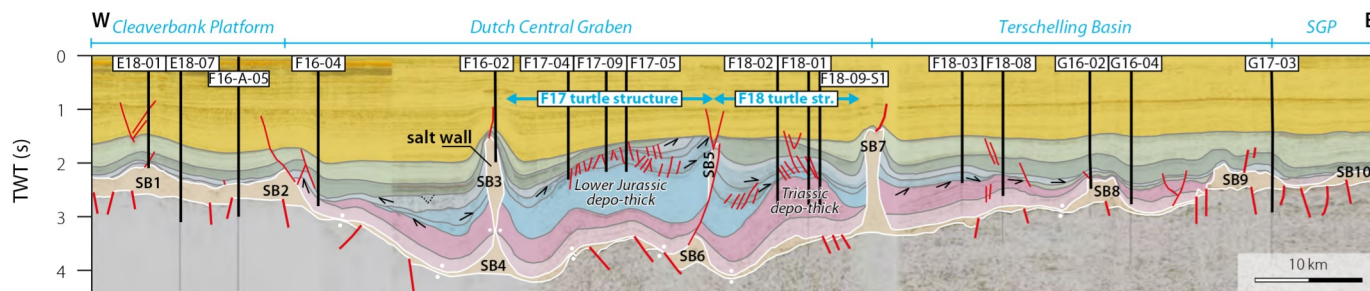


Figure 12.5. Interpreted composite seismic time section across the Dutch Central Graben showing turtle structures and associated salt bodies. The F17 and F18 turtle structures are located in the central and eastern part of the rift basin and are separated by a squeezed salt wall. See Fig. 12.2b for location and Fig. 12.3c for explanation of salt symbology. Modified from Bouroullec et al. (2017).

asymmetric pyramid-shaped salt bodies on the footwall side of syn-depositional faults (SB3 in Figs 12.1, 12.3b) and small loaded salt sheets that are most likely loaded paleo-salt glaciers (Figs 12.1, 12.4a-c). Figures 12.2b and 12.3 highlights the omnipresence of salt pillows and diapirs in the northern part of the Dutch offshore. The salt pillows are present across most of this part of the Dutch sector but the highest relief pillows (more than ~500 m of relief) are predominantly related to Mesozoic rift structures around the Step Graben, the Dutch Central Graben and the Terschelling Basin (Fig. 12.3b,c). Salt diapirs and salt walls are also predominantly organized along Mesozoic rift trends and their formation is closely related to the tectonostratigraphic evolution of the same basins. The exact geometry of the salt bodies is difficult to interpret using time seismic data since salt velocities are much higher than those of the surrounding sediments. Since high-velocity salt absorbs a lot of the acoustic energy, good quality seismic imaging below salt bodies is often difficult to obtain. In the past few decades radical improvements in subsalt seismic data imaging technologies have helped exploration in salt basins such as the Gulf of Mexico and the South Atlantic margins. Most seismic surveys acquired in the Netherlands, however, only provide limited illumination below salt diapirs such that the exact geometry and width of salt stems/feeders is often open to debate. Because of the high salt velocities, velocity pull-up structures below thick salt bodies are commonly seen on Dutch time seismic data or sub-optimally migrated depth data. Sub-salt geometries are therefore unrealistically represented as can be seen for the salt bodies between wells F17-05 and L02-05 in Figure 12.3a.

Zechstein salt migration also triggered the formation of several associated structures such as syn-sedimentary faults, crestal faults, salt welds, salt stems, salt feeders, growth fault/raft systems, salt sheets, mini basins, rim synclines, turtle structures, collapse graben and collapse diapirs that are described in more detail below.

Salt pillows

A salt pillow (Fig. 12.1) is a subcircular upwelling of salt that has a concordant overburden (Trusheim, 1960) and a low-amplitude reflection at the upper surface of the salt layer. Dutch salt pillows (e.g. SB1, 2 and 7-11 in Fig. 12.3; salt bodies SB1, 2, 5, 6, 8-10 in Fig. 12.5) are primarily observed on the platforms such as the Schill Grund- (Fig. 12.3b), Cleaverbank- (Fig. 12.3b), Friesland-, Groningen- and Ameland platforms (Fig. 12.3a). Here the amount of differential sediment loading was limited compared to the Mesozoic rift basins. The salt pillows vary in shape from circular to elongated in map view, are up to 15 km in diameter or length and vary from gentle dome-like structures with a few tens of metres of relief to concave upward or A-shape salt bodies with up to 1200 m of relief. Within the pillows, the overall thickness of the Zechstein salt can reach 1500 m (Ten Veen et al., 2012). In cross-sectional view the salt pillows are often asymmetric due differential loading and later deformation related to rifting and compression. The base Zechstein can be faulted below the salt pillows, which often played a role in localizing the flow of salt into those salt bodies. Such relationships between salt bodies and faulting in pre-salt strata (commonly referred to as 'basement' in salt tectonic terms) is common in many salt basins such as the Gulf of Mexico (Bouroullec & Weimer, 2017) or Angola (Jackson & Hudec, 2005). See also the basement section below.

Salt diapirs

A salt diapir (Fig. 12.1) is a mass of salt that has flowed in a ductile manner and appears to have discordantly pierced or intruded into the overburden. The term was first coined in 1907 by the Romanian geologist Ludovic Mrazek to describe a salt formation that intrudes due to the rise of lighter rocks into denser rocks. Diapirs commonly start to rise vertically, driven by buoyancy contrasts between the relatively low-density salt and the denser overburden rocks (Bouroullec & Weimer, 2017; Jackson

& Hudec, 2017). In extensional settings the overburden commonly thins and fractures, allowing the mobile salt to rise further. As the diapir becomes taller the driving force can be taken-up by differential loading. Halokinetic sequences around the deforming salt diapirs develop with a wide range of stratigraphic geometries, architectures and deposits that depend on the syn-tectonic depositional environments, sedimentary flux in relation to the salt deformation rate and preservation potential. The map view geometry of the diapir bodies in the Dutch subsurface can greatly vary, from circular to elongated (Fig. 12.2b). The diameter (or main axis) of salt diapirs ranges from 1 to 15 km and their height from 2 to 8 km. With a planform aspect ratio of 2 or more the salt diapirs are commonly referred to as salt walls (see below). The cross-sectional view of many salt diapirs in the Dutch sector is often difficult to evaluate due to seismic data imaging challenges. However, well data and depth-domain seismic data from the North Sea, the Gulf of Mexico and the African West Coast show that narrowing of the salt diapirs' core (feeder or stem) is common. A salt stem refers to the narrow part of the salt body connecting the source salt to the shallower salt body. Most salt bodies in the Dutch sector have a salt stem, though with variable narrowing ratios (Figs 12.4b,e; 12.3a, c; 12.5). The width of the stems is difficult to estimate but vertical separation (welding; see definition below) of both sides of salt bodies can locally be observed (Figs 12.3a,b; 12.4b; 12.13). In general, most salt diapirs in the Netherlands did not intrude into sediments above the Cretaceous interval and are buried by Cenozoic strata. Occasionally,

however, the North Sea Group was intruded or affected (Figs 12.3b; 12.4a,b; 12.5; 12.19) especially in the eastern part of the Dutch onshore, where many salt diapirs reach shallow depths and are being solution mined (Groenenberg et al., 2025, this volume). The shapes of salt diapirs in the Netherlands are often related to the interplay of tectonic deformation (rifting and compression) and halokinetic deformation. Hence many diapirs have complex geometries due to multiple phases of deformation, with evidence of diapiric rise, fall (collapse), squeezing/shortening, strike slip deformation and erosion (see Evolution of salt tectonics section below).

Salt walls

A salt wall (Fig. 12.1) is an elongate upwelling of diapiric salt that forms parallel sinuous rows (Trusheim, 1960). In the Dutch subsurface, less than twenty structures can be referred to as salt walls. They are predominantly located within and along rift basin faults (Figs 12.2, 12.5). In their short axis they have a similar cross-sectional view as in salt diapirs but can extend up to 65 km in length. Salt wall systems are often organized along regional trends and are often seen above the main rift bounding fault systems (see Fig. 12.3b). Most salt walls were formed along the newly formed rift system from the amalgamation of salt diapirs that formed during the Triassic as individual salt bodies, but which later collided and merged into elongated salt walls (Fig. 12.5). The identification of sutures (zone of collision between different salt bodies) within Dutch salt walls has not been successful due the subsequent defor-

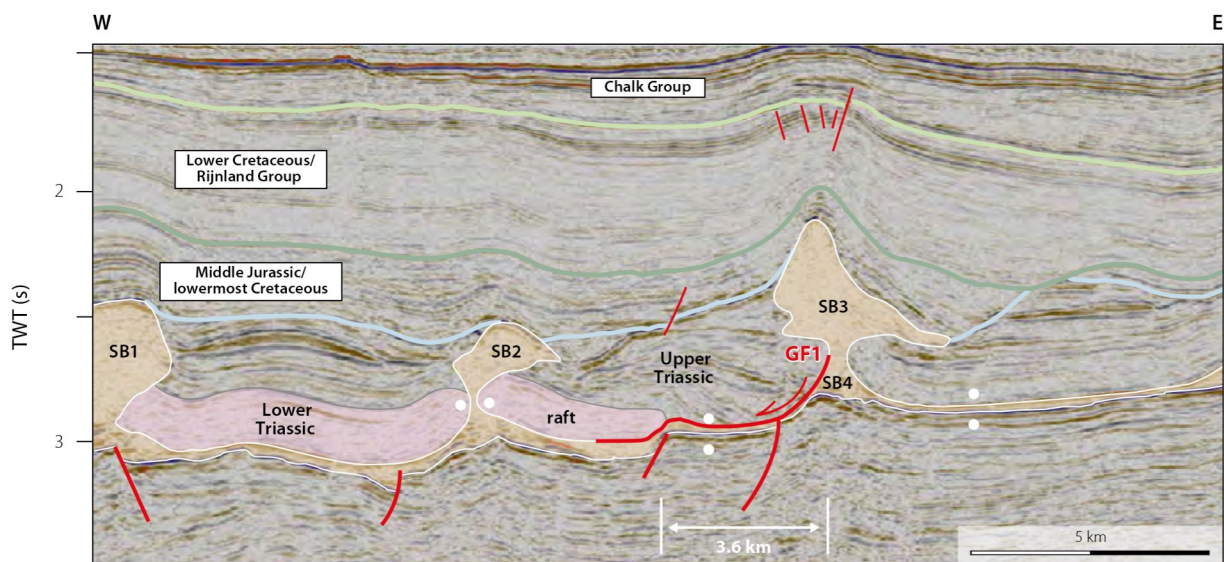


Figure 12.6. Interpreted seismic time section from a 3D seismic survey in the eastern part of the Terschelling Basin showing a growth fault/raft system that was active during the Middle-Late Triassic as shown by the rollover on the downthrown side of the growth fault GF1 (modified from Bouroullec et al., 2017). The Lower Triassic raft translated westward on top of the mother salt over a distance of 3.6 km. Three salt bodies (SB1–3) were squeezed during the deposition of the Upper Cretaceous and SB2 was also shortened during the Late Triassic in response to the upward extension during gravitational gliding. See Fig. 12.2b for location.

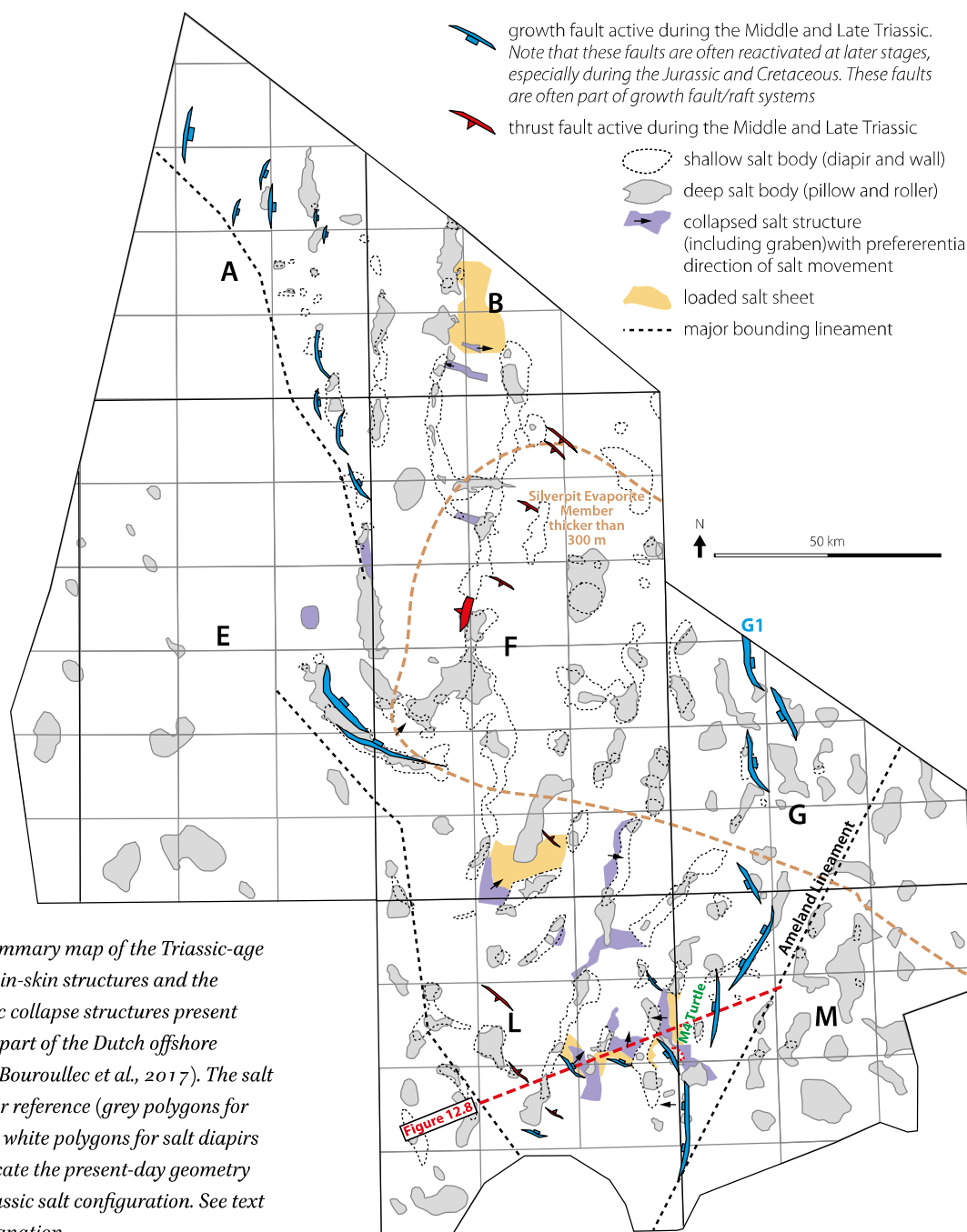


Figure 12.7. Summary map of the Triassic-age gravitational thin-skin structures and the Triassic-Jurassic collapse structures present in the northern part of the Dutch offshore (modified from Bouroullec et al., 2017). The salt bodies shown for reference (grey polygons for salt pillows and white polygons for salt diapirs and walls) indicate the present-day geometry and not the Triassic salt configuration. See text for further explanation.

mation that has blurred the picture, and seismic imaging challenges. Especially during the Alpine contractional phases many salt bodies in the Netherlands were shortened and squeezed.

Salt rollers

A salt roller (Fig. 12.1) is a low-amplitude, asymmetric salt structure composed of two flanks, a gently dipping flank with a conformable stratigraphic contact with the overburden, and a steeply dipping flank with a normal-faulted contact with the overburden (Bally, 1981). Many large faults detaching on the Zechstein salt have a salt roller on

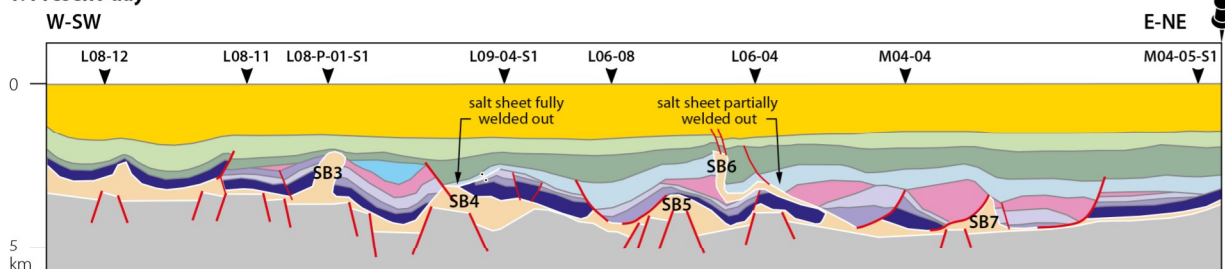
their footwall side (see SB3 in Fig. 12.3; SB2 in Fig. 12.5; SB4 in Fig. 12.12; SB1 and SB2 in Fig. 12.18) and are often present on the footwall side of growth faults (Rouby et al., 2003; Jackson & Lewis, 2012) as is the case for salt body SB4 in Figure 12.6.

Salt sheets

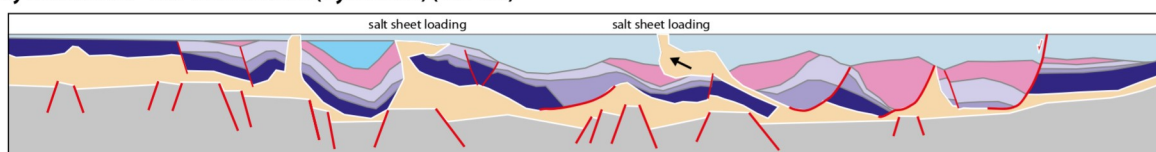
A salt sheet (Fig. 12.1) is a sub-horizontal salt body that originated by salt expansion from a salt-diapir configuration at or near the seafloor. Salt sheets can amalgamate and form salt canopies. These salt body types have become better understood since the 1980s, when improvements



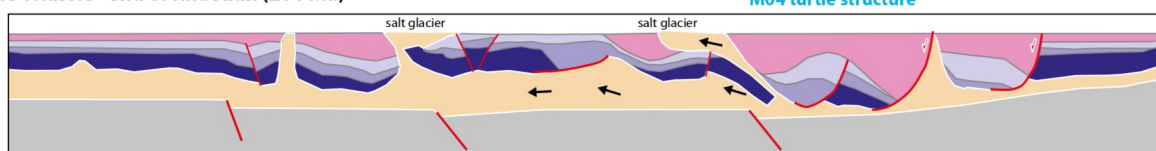
1. Present-day



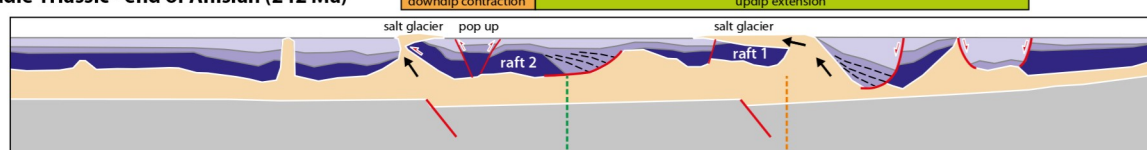
2. Early Cretaceous - end of Berriasian (Ryazanian) (141 Ma)



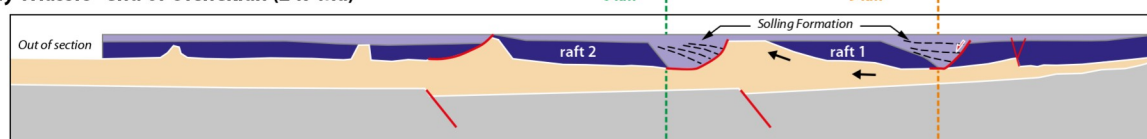
3. Late Triassic - end of Rhaetian (201 Ma)



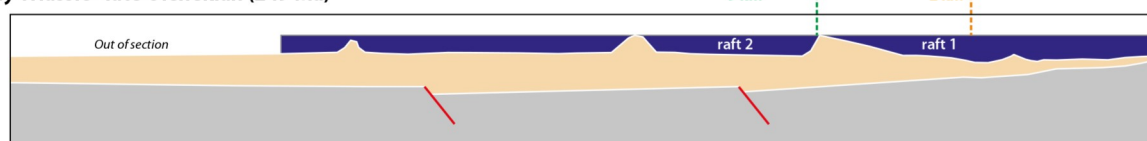
4. Middle Triassic - end of Anisian (242 Ma)



5. Early Triassic - end of Olenekian (247 Ma)



6. Early Triassic - late Olenekian (249 Ma)



7. Late Permian - end of Lopingian (252 Ma)

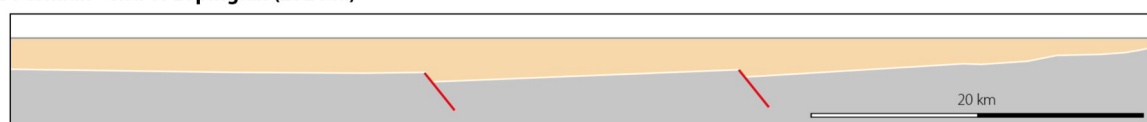


Figure 12.8. 2D palinspastic restoration of a SW-NE trending section from the Friesland Platform to the Ameland Platform through the southern part of the Terschelling Basin. The section intercepts blocks Lo8, Lo9, Lo6 and Mo4 and was constructed from 2D and 3D time seismic data that was depth converted and restored using 2D Move software (Petroleum Experts Ltd). Most of the wells displayed are located on the section, but wells Lo8-12, Lo8-11, Lo9-04-S1 and Lo6-08 were projected from 2-4 km distance. See text for further explanation and Fig. 12.7 for location. Modified from Bouroullec et al. (2017).

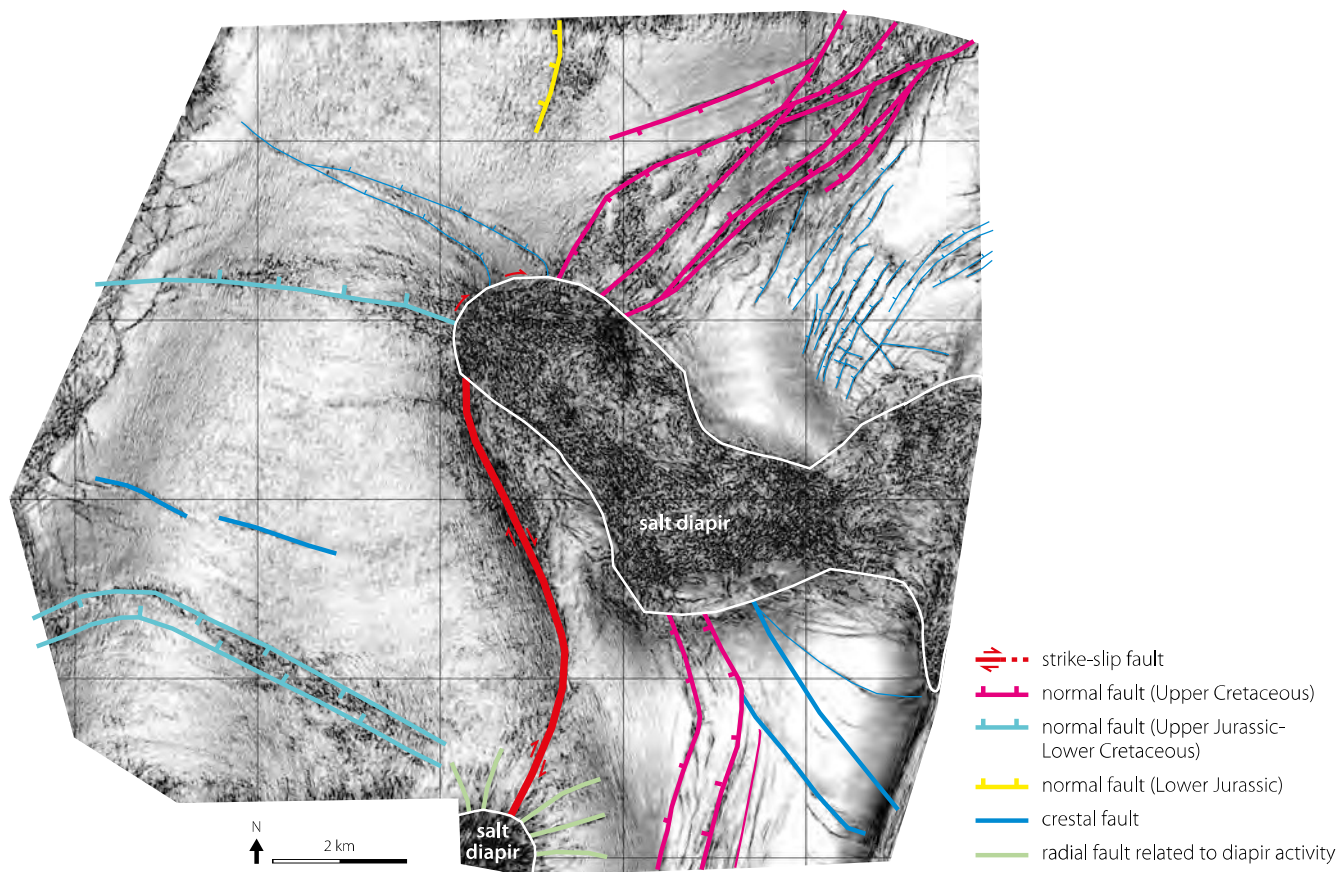


Figure 12.9. Similarity attribute map of the base Altena Group in block F11. Note the deflection of the Cretaceous-age strike slip systems around the central salt body. See Fig. 12.2b for location. Modified from Peeters (2016).

in drilling and seismic technologies led to a surge of interest in allochthonous salt on deep-water passive margins. In the past thirty years, thousands of salt sheets in more than thirty-five basins have been recognized worldwide. Recently, several small sheets have also been interpreted in the Dutch sector (Bouroullec et al., 2017), mainly in the southern part of the offshore L quadrant along the southern margin of the Terschelling Basin (Fig. 12.4a-c). These salt sheets are located down-dip of growth fault/raft systems and were mainly loaded by Middle to Late Triassic strata. They are interpreted as resulting from excessive shortening of pre-existing salt diapirs. During gravitational gliding (see section on growth fault/raft systems below) the up-dip thin-skinned extension was mainly balanced by shortening of pre-existing (Early to Middle Triassic) salt diapirs instead of reverse faulting. This explains why only a few Triassic-age reverse faults are observed in the Dutch sector (see below). Instead, diapirs were horizontally squeezed and salt migrated upward, occasionally extruding at the free surface to form exposed salt masses (glaciers, see Mohr et al., 2007) that were later either completely or partially eroded and/or dissolved. Occasionally the remaining parts of these salt sheets were loaded by

Triassic or Jurassic sediments and were deformed again to accommodate the resulting differential subsidence (Fig. 12.16). The remaining salt was loaded by Middle to Upper Triassic deposits and migrated into peripheral salt bodies or was partially to entirely welded out. The presence of salt welds related to such loaded salt sheets is often difficult to distinguish from stratigraphic geometry. In Germany Zechstein salt can form wings when salt is remobilized laterally from a diapir into adjacent stratigraphic positions, protruding itself into weak Triassic strata such as the Main Röt Evaporite Member (Hudec & Jackson, 2006; Pharaoh et al., 2010). Such salt wings have not been recognized yet in the Dutch sector. As lateral intrusions require salt to compete with gravity, they are mechanically more likely to occur with the help of external (compressional or extensional) forces. One way to distinguish between intruded (salt wing or salt-wing intrusion) or extruded (loaded salt sheet) salt systems is to analyse the sub- and supra-salt stratigraphy, with intrusion favouring concordant geometry while extrusion favours angular unconformities. For more information regarding loaded salt sheets see the section below on the evolution of salt tectonics.

Salt welds

A salt weld (Fig. 12.1) is a thin or narrow salt interval that forms when a salt layer becomes very thin due to salt movement, dissolution, or removal by faulting such that the overburden and the underlying sub-salt strata become effectively welded together (Jackson & Cramez, 1989). Salt welds may also develop vertically when the squeezing is horizontal, bringing the sides of salt diapirs in contact with each other. Horizontal salt welds have been interpreted in the Dutch sector of the North Sea where, especially in the central parts of the rift basins, where most or all the available mobile mother salt has withdrawn laterally (see Figs 12.3-12.6). Locally, such as in the southern part of the Terschelling Basin, a combination of salt welds and growth fault/raft systems places the Middle or Upper Triassic strata directly above Rotliegend strata, without erosional processes being involved (see Fig. 12.3a, between wells Lo6-02 and Mo4-04; around SB1 in Fig. 12.4a; Figs 12.6,

12.8). Salt welding in the Dutch subsurface may often be incomplete, meaning that some tens of metres of (probably) deformed and fractured Zechstein strata (likely the mechanically stronger lithologies such as the carbonates and caprocks) may remain on the weld surface after most of the ductile salt has migrated away. This situation differs from the relatively clean salt welds found in other basins (e.g. Gulf of Mexico; Bouroullec & Weimer, 2017). If such welds become faulted later, they may provide important zones for hydrocarbon migration. It is difficult to determine ahead of drilling whether an apparent salt weld contains any evaporites or non-evaporitic residue (Jackson & Hudec, 2017).

Growth fault/raft systems

A growth fault/raft system (Fig. 12.1) is an association of 1) an extensional listric fault that detaches on a sub-horizontal salt layer (here the Zechstein Group) and 2) one or

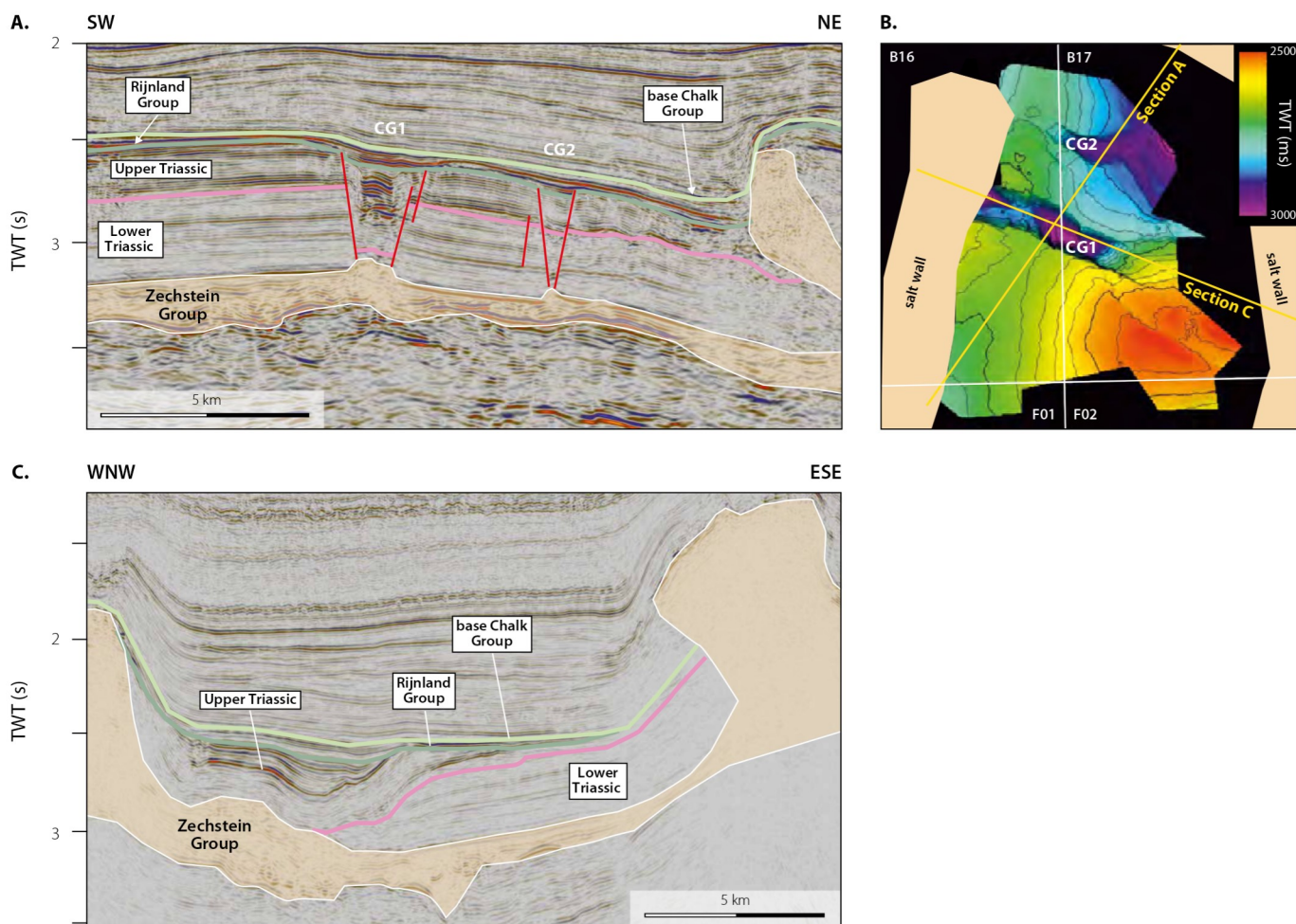


Figure 12.10. Two WNW-SSE trending collapse grabens (CG 1 and CG2) are present spanning the B16 and B17 blocks. a) Interpreted time seismic section showing a strike view across the collapse grabens (see (b) for location). b) Time structure map of the top Lower Triassic horizon (see Fig. 12.2b for location). c) Interpreted time seismic section showing a dip view along the axis of the collapse graben CG1 (See (b) for location). Note that the western part of the graben is filled with Upper Triassic strata which is indicative of salt withdrawal that fed a shallow salt body located toward the WNW in block B16. Modified from Bouroullec et al. (2017).

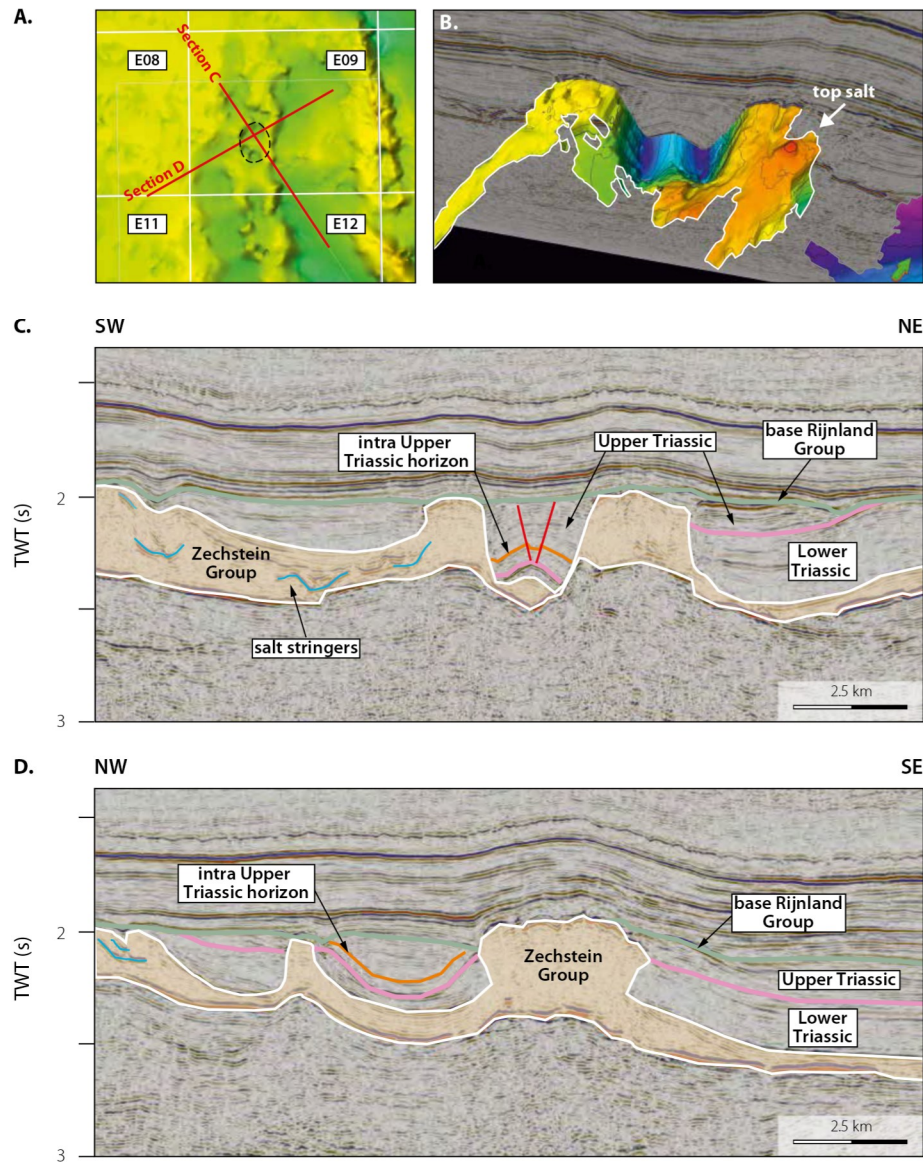


Figure 12.11. Collapsed salt body on the Cleaverbank Platform in block E09. a) Location map (see Fig. 12.2b for location). The position of the mini basin that formed on a collapsed salt body is encircled with a black dashed line. b) Perspective view, looking towards the NW of the E09 collapse mini basin and showing the top Zechstein salt surface with a reference strike seismic line. c) SW-NE seismic section showing the narrow mini basin configuration with Upper Triassic growth wedges along the margins. Blue lines highlight salt stringers. d) NW-SE seismic section showing the Upper Triassic depocentre in the central part of the mini basin. Modified from Bouroullec et al. (2017).

a series of stratal blocks referred to as rafts (here blocks containing Lower Triassic rocks). A growth fault is a listric syn-sedimentary fault that detaches on a ductile layer (in this case mainly autochthonous but occasionally allochthonous salt layers) and allows for a large growth stratigraphic wedge (roll-over) to form on its hanging wall side. A raft is fault-block located below or downdip of the main stratigraphic wedge and is formed by extreme extension over a horizontal to gently dipping detachment. These rafts can be separated from their footwall stratal equivalent by distances up to 16 km, as can be seen on the Con-

go-Cabinda continental margin (Rouby et al., 2002, 2003). Note that the usage of the term raft differs in the above case from that commonly used to describe salt stringers, which are blocks of non-halite rock within a salt structure. The growth fault and the rafts within this system are separated by trough-like depocentres of younger syn-kinematic strata (Burllet, 1975; Rouby et al., 2002, 2003).

Several growth fault/raft systems that were active during the Middle to Late Triassic as shown by the age of growth strata have been recently identified in the Dutch sector (Bouroullec et al., 2017). They have been identified in

the Schill Grund Platform, the eastern and southern part of the Terschelling Basin and along the western flank of the Step Graben (Figs 12.6-12.8). The amount of extension was limited in the western part of the Dutch offshore (Step Graben) and was at its maximum in the Terschelling Basin where up to 12 km of raft gliding/translation have been deduced from palinspastic restoration (Fig. 12.8). This amount is comparable to the horizontal translation observed in classical raft tectonics in west Africa (14 km in Rouby et al., 2002) or the Gulf of Mexico (11 km in Bouroullec & Weimer, 2017; 8 km in Jackson & Hudec,

2017). Lower Triassic rafts were transported westward by gravitational gliding toward the paleo-basin centre located at that time in the eastern part of the offshore F quadrant. Several eastward-directed gravitational slides on the eastern part of the Schill Grund Platform indicate that gravitational gliding occurred at the western margin of the paleobasin, i.e. heading towards the German sector of the North Sea as well. De Jager (2012) showed a similar salt-tectonic geometry associated with the Triassic Fat Sand Play (Solling Formation) which is now interpreted as being part of a growth fault/raft system.

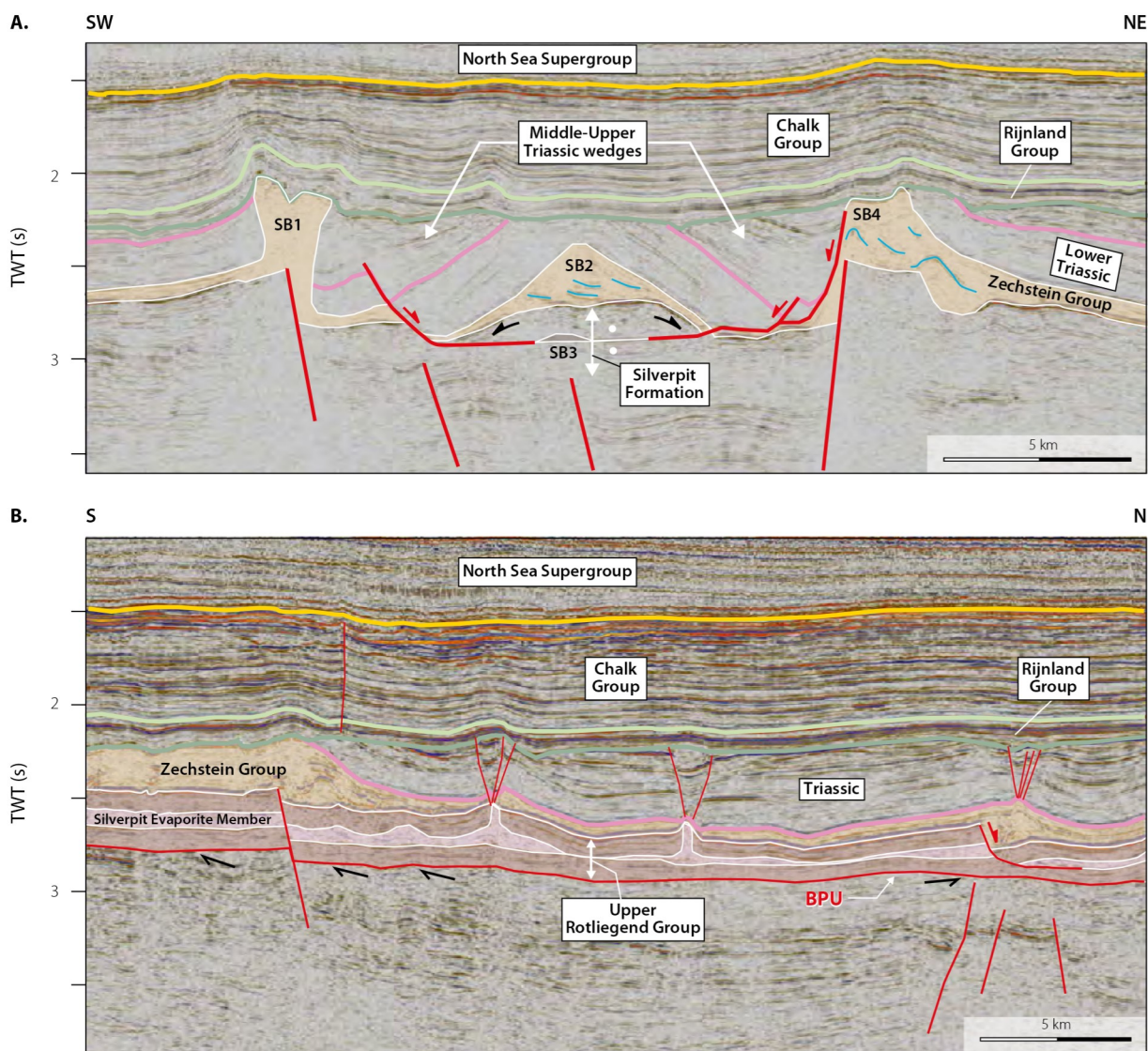


Figure 12.12. Interpreted time seismic sections on the Schill Grund Platform illustrating salt tectonic features associated with Rotliegend-age salt layers of the Silverpit Evaporite Member (see Fig. 12.2b for location). a) Two Upper Triassic growth faults (thick red lines) are detached on the thick halite layers of the Silverpit Formation (Rotliegend Group), i.e. on a deeper stratigraphic level than the Zechstein Group. Blue lines highlight salt stringers. Modified from Bouroullec et al. (2017). b) Salt pillows and diapirs formed in the Silverpit Evaporite Member. Based on the formation of collapse grabens above these diapirs, the salt movement and formation of the deep salt diapirs is likely Triassic in age. Note the growth fault on the northern side of the section showing Zechstein-age syn-sedimentary fault activity detaching onto the Silverpit Evaporite Member of the Upper Rotliegend Group. Modified from Peeters (2016). BPU = Base Permian Unconformity.

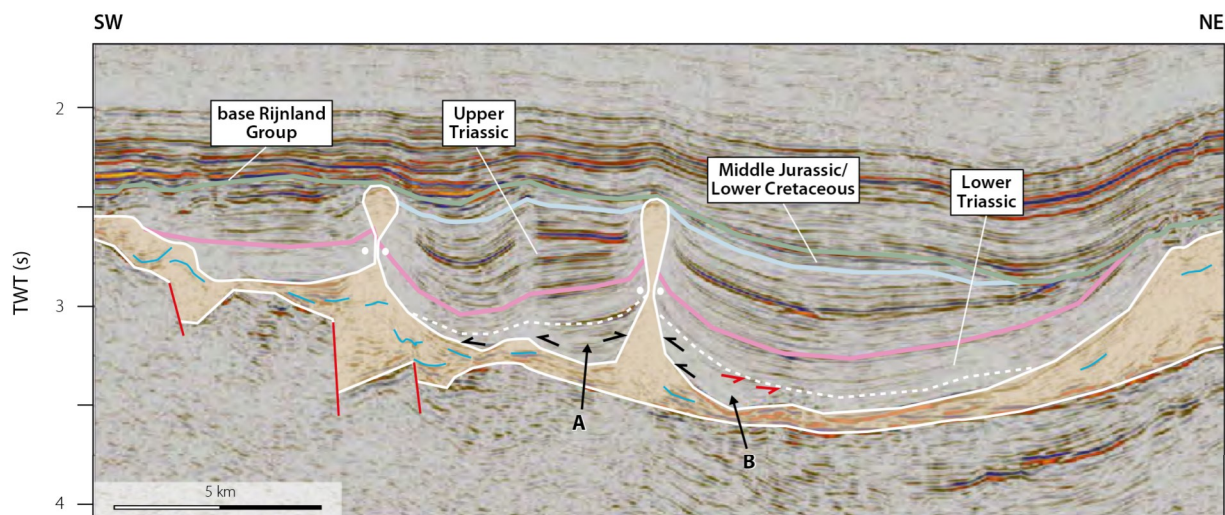


Figure 12.13. Interpreted 2D time seismic sections showing salt-related Early Triassic mini basins (A and B). Basal and internal onlaps (black arrows) and truncations (red arrows) are only observed in the Lower Triassic within these mini basins. This line is crossing the northern parts of the A15 and A13 blocks. Blue lines highlight salt stringers. See Fig. 12.2b for location. Modified from Bouroullec et al. (2017).

Crestal faults

Crestal faulting often occurs above salt pillows, diapirs and walls in the areas defined as crests, which are the anticlines formed in the syn- or post-kinematic strata above salt bodies. These faults are mainly linear in cross section but can be organized radially or longitudinally in the case of circular or elongated salt bodies, respectively. The faults connect downward to the salt body's crest and the degree of upward penetration into shallow stratigraphic levels depends on the deformation of the salt, the rock properties of the suprasalt (e.g. chalk has more crestal faults above salt bodies), the burial history and the local and regional tectonics. Many salt bodies in the Dutch subsurface have crestal faults (Figs 12.3, 12.4, 12.5, 12.19) that range from low-displacement to large-displacement and are associated with supra-salt grabens that formed during salt body collapse (e.g. Salt wall 2 in Fig. 12.4a, Salt wall 2 and SB2, SB3 in Fig. 12.4b, Salt wall 1 in Fig. 12.4d; see section below on collapse salt bodies). Some salt bodies, for instance on the Cleaverbank Platform and the Schill Grund High (Figs 12.3b,c), where faults are mainly observed below major unconformities (e.g. Mid-Cimmerian Unconformity), as well as those on rift shoulders and platforms, are devoid of crestal faults. This suggests that most crestal faults were initiated during the early stages of extensional salt tectonics (in the Triassic and Jurassic). In later stages, salt bodies were often shortened during the Cenozoic Alpine compression and show reactivated, often rotated outward-directed faults or new associated crestal faults. Some shallow faults located above salt bodies can be wrongly interpreted as crestal faults in cross sectional view but appear to be related to large-scale strike slip systems when seen

on 3D seismic data (Fig. 12.10). Such flower structures, formed during Mesozoic or Cenozoic transpressional regimes, were accommodated by brittle deformation in the sub- and supra-salt section and by ductile movement within the salt bodies (Peeters, 2016). The presence of such multilayered detached deformation is the reason why the identification of even large strike slip systems in the Netherlands is challenging.

Turtle structures

Turtle structures (or turtle-structure anticlines) are mounded strata lying between salt diapirs, typically consisting of a flat base and a rounded crest. The structure may have a low salt pillow core above which a thick sedimentary sequence thins laterally. Turtle structures form between diapirs whose flanks have subsided because of regional extension or between salt structures whose withdrawal basins migrate and widen through time (Trusheim, 1960).

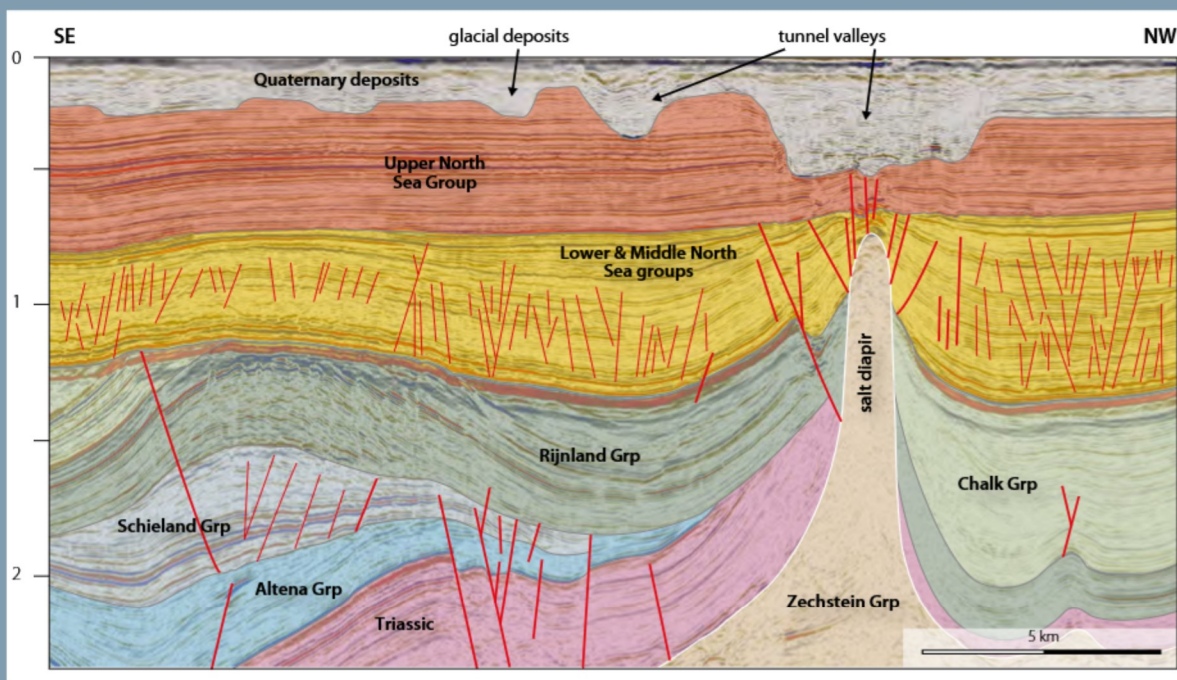
Several turtle structures are present in the Dutch offshore (Figs 12.3, 12.5, 12.8). They are often large and formed within the Mesozoic rifts in response to extension and outward salt migration towards the basin margins. All turtle structures have a unique kinematic setting formed by local parameters such as: 1) the amount and characteristics of original salt available, 2) the timing of sediment loading, and 3) the timing of Zechstein salt welding at the basin-centres. These parameters control the turtle structure inversion and lateral depocentre shift toward the basin flanks in later stages (see below 'Evolution of salt tectonics' for additional discussion). Depocentre shifts highlight the change of the main loci of subsidence and loading from the axial position of the turtle towards

Glacial tunnel valleys and salt domes

In a strip across the Broad Fourteens Basin, the northern part of the Netherlands onshore and northern Germany, Quaternary (Elsterian), glacial tunnel valleys appear to partly coincide with the location of salt diapirs and -walls, suggesting that at these sites increased and large-scale glacial erosion of pre-glacial sediments occurred. For the offshore Broad Fourteens Basin, Wenau & Alves (2020) showed that glacial valleys follow the strike of a Zechstein salt wall and its crestal faults. Changes in downstream tunnel valley orientation coincide with the strike direction of these salt-induced faults.

One possible explanation is that sediments affected by crestal faults above a salt diapir (see figure) offered less resistance to erosion, which facilitated the formation of Elsterian glacial tunnel valleys and the development of subglacial dewatering pathways during periods of ice sheet advance (Wenau & Alves, 2020). Renewed glacial erosion during subsequent ice ages is evidenced by the observation that Elsterian sediments are thinner above the salt domes of Anloo and Schoonlo (Bregman & Smit, 2012).

In an additional explanation, it is assumed that open fault systems are spots with higher heat flow, which could increase basal melting rates of the ice (Bregman & Smit, 2012). Ice streams may then be 'pulled towards' these favourable pathways since sliding will be facilitated by higher geothermal fluxes. Above the salt diapir, a higher salinity content of the subglacial groundwater may also have had an impact on the above-mentioned processes by lowering the freezing point of the ice. Although most of the salt diapirs are not shallow enough to have played a role in diverting tunnel valley courses, the presence of diapirs may have triggered forebulging in front of the advancing glaciers due to their relative rigidity compared to the surrounding unconsolidated sediments. This may have focused glacier surge to the less elevated areas above and around salt diapirs. Differential compaction and subsidence probably created some undulating surface relief of the pre-glacial landscape making the salt diapirs areas of preferential incision and erosion.



Relationship between salt body-related crestal faulting and glacial tunnel valleys in the offshore Broad Fourteens Basin (K quadrant, see Fig. 12.2b for location). The seismic interpretation of the tunnel valleys is modified from Wenau and Alves (2020).

4. Top Keuper Formation (base Rhaetian, 209 Ma). End of Upper Triassic Germanic Group (RN)

W or NW

E or SE

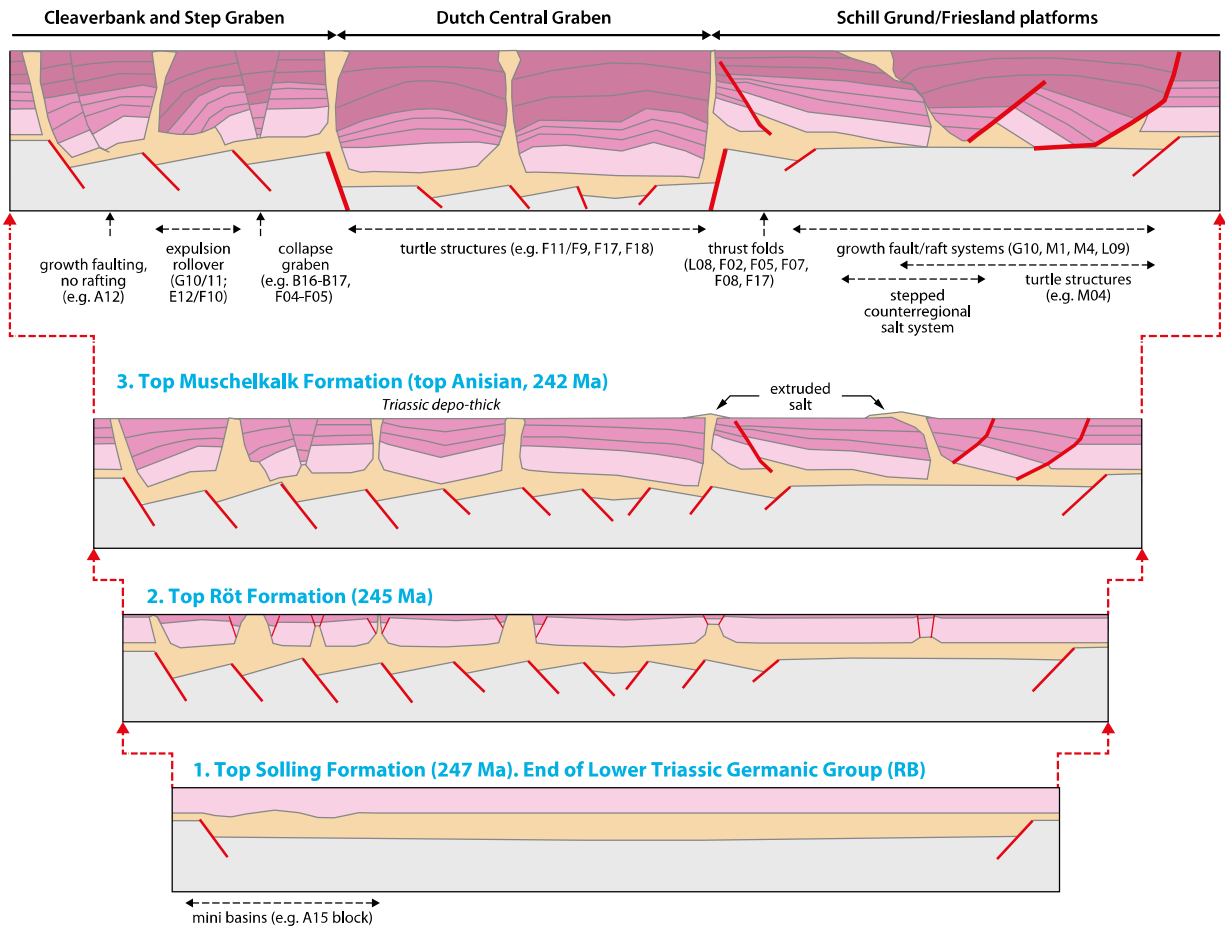


Figure 12.14. Conceptual kinematic model showing the structural evolution during stages of the Triassic, following the deposition of the Solling, Röt, Muschelkalk and Keuper formations in the vicinity of the Dutch Central Graben. This cross section summarizes the different types of salt tectonic structures observed in the area and at specific locations (see text for explanation). The approximate orientation of the sections is from W-E to NW-SE; the sections are not to scale. Modified from Bouroullec et al. (2017).

its margins, following the direction of salt migration. For illustration, Figure 12.8 shows a structural restoration of one of the turtle structures (Mo4 Turtle) located in the southern part of the Terschelling Basin.

Distinguishing between individual turtle structures in the Dutch offshore is not straightforward since many neighbouring turtle structures are genetically related to each other. Additionally, the salt migration that controls the formation of turtle structures is rarely unidirectional and may have changed direction during the formation of specific structures, for instance due to salt volume constraints during different phases of rifting. Such dynamics make Dutch turtle structures very complex and evaluation of observed structures and depositional trends requires full 3D structural restoration. To date, such a task has not been carried out and would likely be a challenge for years to come. Figure 12.3c shows a typical turtle structure geometry that comprises: 1) a Lower to Upper Jurassic TMS-1

basin-centered depo-thick that formed when the Zechstein salt evacuated from the axis of the Dutch Central Graben, and 2) marginal rim synclines with stratigraphic wedges of Upper Jurassic to Lower Cretaceous (TMS-2 and 3; Verreus-sel et al., 2025, this volume) deposits that formed when the salt migrated and fed two large salt diapirs at the rift edges (SB 4 in Fig. 12.3c). The period during which the depocentres shift from axis to margin is referred to as turtle structure inversion and indicates when the mother salt, located below the initially subsiding basin, runs out due to complete salt withdrawal. From this time onward, the salt can only migrate laterally and the turtle structure ‘inverts’. This creates an initial point of contact between sub- and supra-salt strata and forces the salt to further withdraw laterally, resulting in the downward and outward rotation of the flanks of the basin and in the formation of rim synclines.

Rim synclines (also referred to as peripheral sinks) are depressions that formed along or around a salt body when

salt migrated into that salt body. In this chapter, rim-synclines refer to sub-basins that form in the late stage of turtle structure development along the bounding salt diapirs or walls. They are the result of salt withdrawal along the flanks of a growing salt pillow, diapir of wall and consist of strata thinning or thickening toward the salt body. In the Dutch Central Graben, the initial inward rotation of pre-kinematic strata such as the Lower to Middle Triassic along the basin margins during the initial stages of turtle structure formation was so drastic that the later-developing rim synclines were eroded down to older Jurassic units and locally down to Lower Triassic (e.g. around the location of well F11-03 in Fig. 12.3). Such local salt-tectonically-controlled erosion permitted vast amounts of Mesozoic sediments to be eroded and redeposited within the rift basin. This occurred not only in the area above the salt bodies but in large zones surrounding the salt bodies.

Recent work by Bouroullec et al. (2018) showed that in extreme cases the central part of the Dutch Central Graben (e.g. Fig. 12.3b), which was the original depocentre, became a topographic high (island) and was likely a source area for cannibalization and rerouting of Jurassic sediments toward neighbouring Late Jurassic and Early Cretaceous rim synclines. The F17 and F18 turtles are noticeable structures in the southern part of the Dutch Central Graben (Fig. 12.5) and underlie several oil and gas fields. The Mo4 turtle structure, located in the Terschelling Basin, formed as a final stage of a growth fault/raft system which explains why Lower Triassic rocks are absent from its core due to earlier rafting toward the west (Fig. 12.8).

Caprocks

A caprock is a dissolution interval located at the crest of a salt body. If the top of a salt body reaches depths at or near the free surface halite will be dissolved leaving a residue of insoluble anhydrite that is later altered to gypsum, calcite, and sulfur. The cap rock may be intermixed with deformed and cemented rocks from the overlying strata transported upward with the migrating salt. As solution takes place in the circulating (shallow) water zone, it is likely that deeply buried domes with cap rock may have been located at shallow depth at some former time and subsequently buried, or else deeper fluid migration may have occurred to trigger the formation of caprock at the crest or along the shoulders of the salt bodies. In that context the Mid-Cimmerian Unconformity played a significant role in bringing the Zechstein salt into contact with Upper Jurassic and Lower Cretaceous reservoir rocks. Locally, the dissolution of vast amounts of halite led to the formation of depressions that controlled Late Jurassic sediment pathways. The formation of these depressions may also have been enhanced by salt body collapse (see below) which occurred during the same period. Verreussel et al. (2018) showed

that palynofloras occurring in the basal part of cap rock successions indicate a latest Callovian to earliest Oxfordian age and a marine depositional setting. This suggests that these diapirs were partly dissolved, collapsed, and subsequently flooded and filled in with TMS-1 age sediments (see Verreussel et al., 2025, this volume). In the Netherlands several Zechstein caprocks were drilled and a Scruff Group (Upper Jurassic-Lower Cretaceous) play on the Schill Grund Platform was proved to be economic (G16-A discovery).

Collapse structures

Collapse structures are circular, elongated or graben-like depocentres (Fig. 12.1) above a salt layer or diapir resulting from salt withdrawal or dissolution. Seventeen collapse structures have been identified by Bouroullec et al. (2017) in the central part of the Dutch offshore (notably in quadrants B, F, L). They range from 2 to 20 km in length and are filled with Triassic and Jurassic pre- and syn-kinematic strata relative to the timing of salt movement. For these collapse structures, deep salt withdrawal rather than dissolution is suggested as the most applicable mechanism. The geometry of the collapse structures is normal to the direction of salt migration, with unidirectional salt flow favouring elongated graben-like depressions (Fig. 12.10). Some of these grabens formed over salt pillows of the Silverpit Evaporite Member (Fig. 12.12b) rather than those of the Zechstein Group. These collapsed salt bodies provided new sediment pathways by turning the areas above salt bodies from topographic highs to topographic lows in a similar fashion to the fluvial systems of the Paradox Basin in Utah (Banham & Mountney, 2013). For example, in well A18-02-S1 sediments of the Noordsvaarder Member include Zechstein pebbles that are located directly above the salt. The area is interpreted as an incised valley that was flooded and filled with marine sandstones during the earliest Volgian (Bouroullec et al., 2016).

Mini basins

Mini basins are small intrasalt basins largely surrounded by and subsiding into relatively thick salt. Those in the Dutch subsurface can be grouped into three categories.

The Lower Triassic mini basins: supra-salt stratigraphy is primarily concordant with the upper surface of the Zechstein pillows, except in few locations such as the eastern part of the northern offshore (Fig. 12.13) and the Cleaverbank Platform (Fig. 12.20a), where several small thin ponded mini basins with Lower Triassic growth strata are observed. These mini basins formed directly above the autochthonous Zechstein.

The Middle to Upper Triassic mini basins: these basins also formed over autochthonous Zechstein salt on the rift platforms but distinguish themselves by their greater

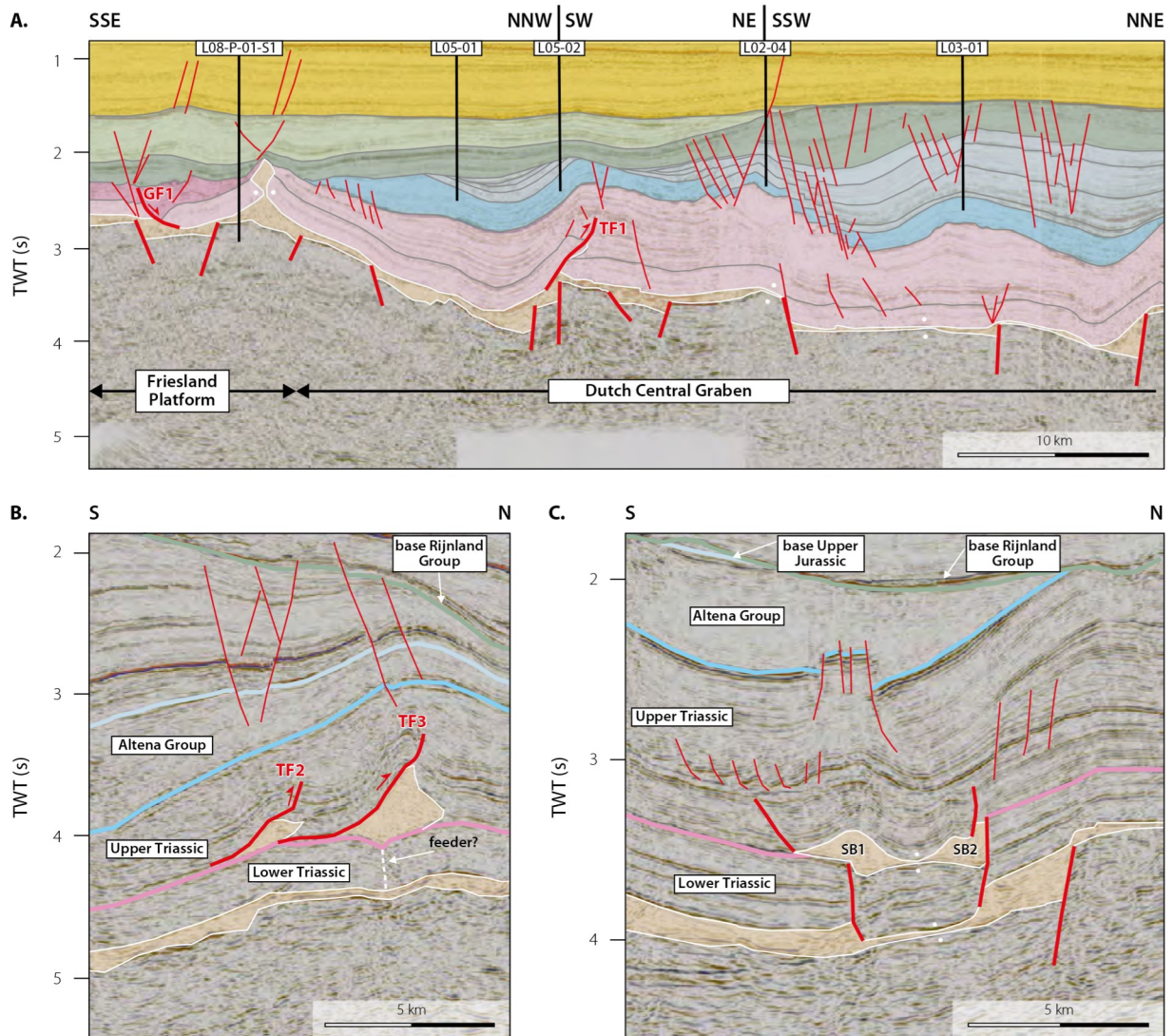


Figure 12.15. Features of Triassic shortening in the Dutch offshore. a) Interpreted seismic time section from the Friesland Platform to the southern part of the Dutch Central Graben. b) Upper Triassic contraction in the Fo2 Block. Two thrust faults (TF2 and TF3) are observed that contain a salt core (beige polygons). Either, the salt core contains remobilized Zechstein salt injected upward from its original position or, more likely, the salt represents structurally over-thickened Röt Evaporite that forms a shallow detachment, possibly connected to the Zechstein salt layer further towards the south (ramp and flat geometry). c) Intra Upper Triassic salt features in the Fo9 Block. This salt sheet has not been drilled and is composed of two salt bodies (SB1-2 indicated with beige polygons) that are located stratigraphically above the top of the Lower Triassic. In the northern part of the Dutch offshore, folding and thrusting during the Middle to Late Triassic is interpreted as downdip shortening, balancing some of the thin-skin extensional tectonics (growth fault/raft systems) that took place along the outer rims of the Triassic early rift basins. See Fig. 12.2b for location. Modified from Bouroullec et al. (2017).

thickness and circular shape (Fig. 12.11). They form over large salt pillows that collapsed during the early phase of rifting (Middle to Late Triassic). Similar mini basins (or pods) are observed in the UK North Sea sector (Penge et al., 1999; Stewart & Clark, 1999).

The Mid Triassic to Early Cretaceous mini basins: these basins formed over large allochthonous salt bodies (Fig. 12.16) that formed close to the free surface due to shortening of their stems resulting in increased diapiric rise during

the Middle to Late Triassic. These allochthonous salt bodies, which may have locally been extruded during the Mid Triassic, were then loaded to form intrasalt mini basins.

Salt stringers

Salt stringers are deformation features within a salt body and refer to layers or fragments of rock consisting mainly of minerals other than halite (e.g. anhydrite or carbonate) (Figs 12.20, 12.11, 12.12, 12.13, 12.16a). Most of

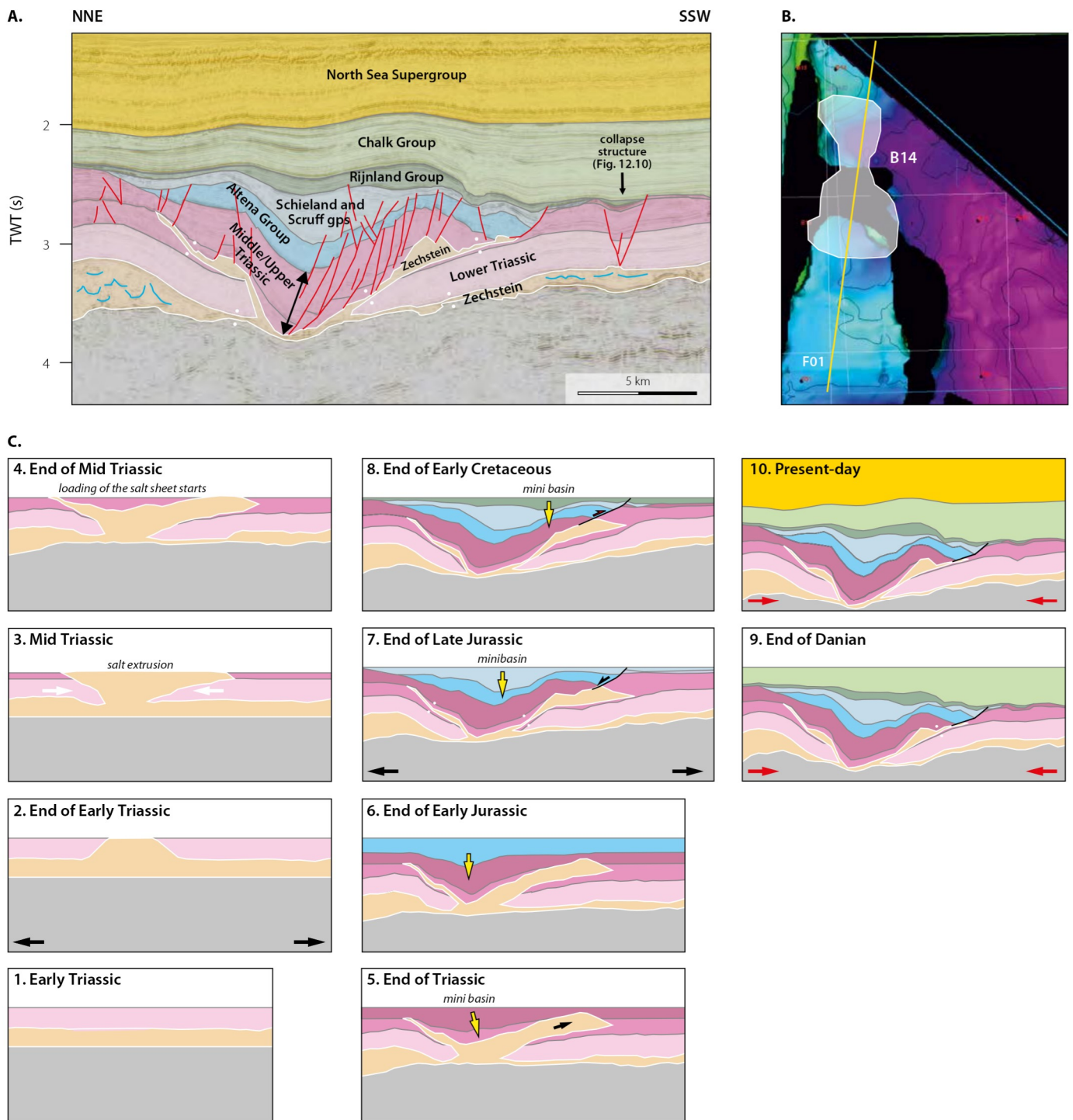


Figure 12.16. Squeezed and loaded salt diapir in the B14-B17 area in the northern part of the Dutch offshore. a) NNE-SSW interpreted seismic time section showing the morphology of a squeezed salt body. Part of the deformation is related to Cenozoic shortening but most of the intra-Triassic deformation is related to the shortening of a pre-existing salt body during the early part of the Middle Triassic. This salt body was later loaded by Upper Triassic and Jurassic sediments. Blue lines highlight salt stringers. See Fig. 12.3c for explanation of salt symbology and inset map (b) and Fig. 12.2b for location of the seismic section. b) Location map. The white polygon shows the extent of the squeezed and loaded salt body that stretches 20 km in N-S direction. c) Conceptual structural restoration of the section shown in (a). Not to scale and without major erosion or dynamic decompaction taken into account. Modified from Bouroullec et al. (2017).

the stringers identified within the Zechstein of the Dutch subsurface are Z₃ anhydrite-carbonate (Z₃AC) stringers (Geluk, 2007a; Van Gent et al., 2011; Strozyk, 2017). The Z₃AC lithologies are assumed to have formed as continuous layers across large parts of the Zechstein Basin, especially in the southern part of the Southern Permian Basin currently located in the subsurface of the onshore (Geluk, 2007a). Further north (basinward), the thickness of Z₃AC decreases. Stringers have been identified from the Cleaverbank Platform in the west as far as the Ameland Platform in the east and are well developed in the Waddenzee area (Strozyk et al., 2012; Strozyk, 2017). The apparent lack of stringers in other parts of the Dutch subsurface is likely due to the difficulty of imaging internal heterogeneities within the Zechstein Group. Stringers clearly stand out on seismic data because of their different acoustic properties and, where visible, the geometry of the stringers can give an indication of the severity of salt flow. They are found in many wells as well: Van Gent et al. (2011) showed that the Z₃AC stringers are on average 40–50 m thick and have a complex structure dominated by boudinage and folding (Fig. 12.3; Hoetz et al., 2011). They also indicated that these stringers form blocky thickness anomalies and may be up to 150 m thick. They are commonly broken into mappable fragments of varying sizes but are most likely still arranged along the deformed boundary between the Z₂ and Z₃ salt, generally following the shape of top Zechstein (Strozyk, 2017). In some areas the salt and the imbedded Z₃AC stringers are almost undeformed (for example at the Friesland Platform), while in other areas they are very fragmented (for example at the Vlieland Platform; Fig. 12.2a). Recent research (SODM, 2020) concluded that the internal heterogeneities and their effects on stress distribution within the salt are not understood well enough to allow salt solution mining (Groenenberg et al., 2025, this volume) and storage of liquids and gasses (such as hydrogen). For the energy transition in the coming decades, research will be needed to de-risk the presence and effects of salt stringers to ensure the safe development of storage of fuel-based energy carriers (natural gas, oil and likely hydrogen in the near future), feedstocks (nitrogen) and disposal of nuclear waste in salt domes.

Non-Zechstein salt tectonics

Besides the dominant Zechstein salt units other stratigraphic intervals were subject to and initiated salt-related deformation in the Netherlands. These include the Silverpit Formation of the Upper Rotliegend Group and evaporitic intervals in the Triassic, especially the thicker Main Röt Evaporite (see McKie & Kilhams, 2025, this volume).

The Silverpit lake depocentre contains the thickest hal-

ite units of the Silverpit Evaporite Member and was located in the eastern part of the Dutch sector around the quadrants F and G (see Fig. 12.7). In this area, several anomalously thick but small salt pillows and rollers have been identified (Peeters, 2016; Bouroullec et al., 2017). Locally these salt layers were used as detachment surfaces for Mesozoic growth faults (see SB₃ in Fig. 12.12) and they reach deeper than the ductile Zechstein layer, probably because at that time the Zechstein salt was welded out and was not able to act as a detachment.

Occasionally, Triassic salt layers can also form salt bodies and form detachment horizons for extensional and contractional faults. Figure 12.15b shows two salt-cored thrusts that were active during the Late Triassic. These thrusts are interpreted as the downdip compressional part of gravitational gliding systems that were active during the Triassic. Growth fault/raft systems were active around the basin margins while the basin centre was affected by thin-skin compressional structures that occasionally detached into shallower ductile layers (multilayer salt tectonics). Distinguishing between intruded Zechstein salt into Triassic weak layers (e.g. salt wing model), buried salt glaciers and deformed in-situ Triassic salt is not always easy and only detailed seismic and geochemical analysis may help.

Role of base salt geometry on salt tectonics

The geometry of pre-salt strata (referred to as 'basement' in salt tectonics) played an important role in the location and the way salt flows into preferential zones, influencing the location of diapirism. Many salt bodies are located close or above basement (sub-Zechstein) faults (Figs 12.3, 12.4, 12.5, 12.8 and 12.12). Either the basement faults were present prior to the deposition of the mother salt or formed during and/or after the deposition of the salt layer. Both scenarios have been described from the Dutch subsurface. Barabasch et al. (2019) interpreted disrupted Z₃ stringers above base salt faults in the Friesland Platform and the overthickening of the supra-stringer salt layers (Z₃ and Z₄) as evidence for syn-sedimentary tectonics during Zechstein deposition. These subtle structures are difficult to identify in many parts of the Netherlands because they have been overprinted by later salt tectonics. Geluk (2007a) described syn-rift salt fill of Permian half graben- and pull-apart basins that formed during the Tubantian extensional phase, which is seen as a relaxation phase of the Variscan orogeny. Where the depositional thickness of salt changes across fault zones it may have later controlled salt flow and differential loading and resulted in the localization of salt pillows in the vicinity of basement faults. Tectonic events post-dating the salt deposition also af-

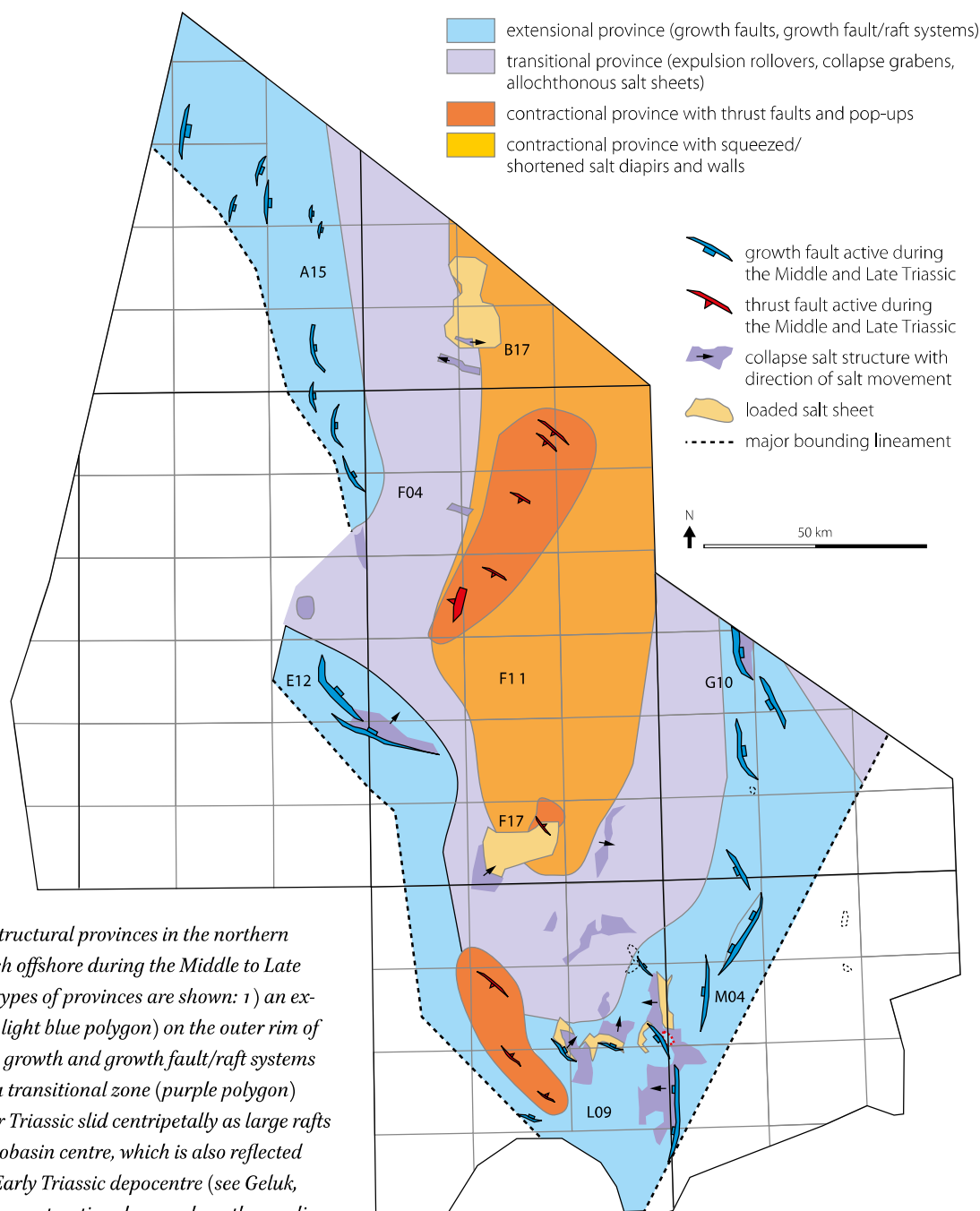


Figure 12.17. Structural provinces in the northern part of the Dutch offshore during the Middle to Late Triassic. Three types of provinces are shown: 1) an extensional zone (light blue polygon) on the outer rim of the basin where growth and growth fault/raft systems were active, 2) a transitional zone (purple polygon) where the Lower Triassic slid centripetally as large rafts toward the paleobasin centre, which is also reflected by the thickest Early Triassic depocentre (see Geluk, 2007b), and 3) a contractional zone where the up-dip extension was accommodated by pre-existing salt body shortening (light orange polygon) and minor thrusting (dark orange polygons). Some of the salt bodies were squeezed to the extent that salt extruded at the paleo-free surface and formed salt glaciers that were later loaded as salt sheets (pale orange polygons). Note the eastward dip of some of the faults in quadrant G, which form the base to eastward-slid stratal blocks. Also note the small area with thrusting in the middle part of quadrant L, which could be related to pre-existing base Zechstein topography ('basement' faults) that may have limited gravitational gliding over long distances and resulted in a small fold belt in this area. Modified from Bouroullec et al. (2017).

affected the preferential directions of salt flow around basement faults, the loci of differential accommodation and hence sediment loading, and deformation of salt bodies in the vicinity of basement faults.

Evolution of salt tectonics in the Dutch subsurface

In this section we discuss the main geological events and phenomena related to salt tectonics that took place in the Netherlands since the Permian. Much of the following is based on offshore studies and publications. Figure 12.21

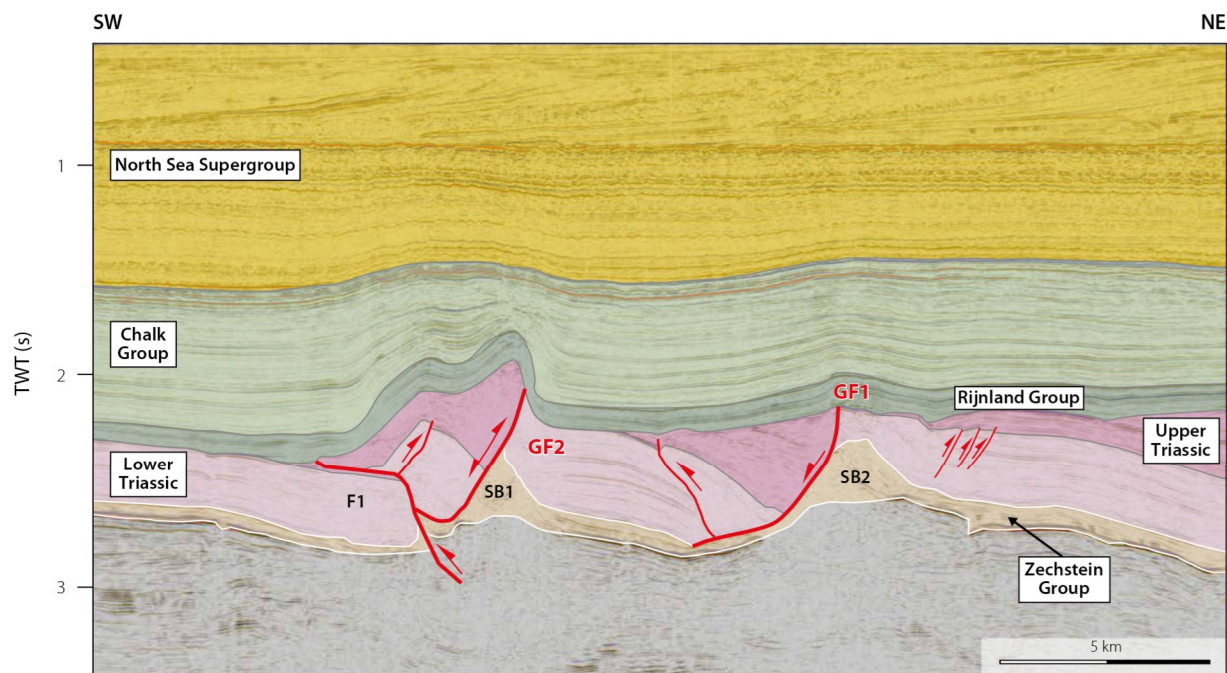


Figure 12.18. Interpreted seismic time section from a 3D survey showing an example of inversion of Triassic structures during Alpine compression. A pre-existing Triassic growth fault (GF2) was reversed during the depositional time of the Chalk and lower Cenozoic and forms one of the sides of a pop-up structure. Note the local blind thrusts in the core of the pop-up and on both sides of growth fault GF1. See Fig. 12.2b for location. Modified from Bouroullec et al. (2017).

summarizes most of the salt evolution described in the text below.

Permian

- I. The first significant event was the deposition of thick halites of the Silverpit Formation (Upper Rotliegend Group; see Fig. 4.2 of Bouroullec & Geel, 2025, this volume) during the Capitanian (middle Permian). These individual halite layers are up to 40 m thick in the central part of the basin (e.g. well G13-01).
- II. The Zechstein Group was deposited in a large part of the Netherlands during the Wuchiapingian and Changhsingian (late Permian). Its thick salt members, in particular the up to 1300 m thick Z2 halite (Fig. 12.2a), were deposited in the northern part of the on-shore and in most of the central and northern parts of the offshore. The original salt thickness was variable across the Dutch sector (see above; Ten Veen et al., 2012) and along pre-existing fault blocks (section 1 in Fig. 12.14).
- III. In contrast to the UK (Stewart, 2007), no evidence of Permian-age salt tectonics has been described for the Netherlands. It is however conceivable that some of the thick halite layers of the Silver Pit Formation may have been buried deeply enough to start flowing into salt pillows, but such observations have not been made so far.

Triassic

- IV. Overall, the Early Triassic is a period without salt tectonics in the Netherlands (Geluk, 2007b). Recent work by Bouroullec et al. (2017), however, shows that some small growth mini basins (pods) formed in the northwestern part of the Dutch sector in the A15 and A13 Blocks (Figs 12.13, 12.20a). In the rest of the Dutch offshore the Lower Triassic thickness is more uniform and reflects a homogeneous subsidence (mainly thermal in origin), with Buntsandstein reflectors unaffected by syn-depositional faulting (Ziegler, 1990; Hoffmann & Stiewe, 1994; Geluk, 2007b; Ten Veen et al., 2012). This makes the Lower Triassic a very useful pre-kinematic reference unit ('rail-track') across most of the Dutch salt province as is illustrated in Figures 12.3, 12.4 and 12.6.
- V. The Middle Triassic is a period of great importance for the Dutch salt tectonic history since it sets the stage for many other events that followed. Three notable events can be highlighted:
 - i. Thickening of the Solling Formation into listric faults (Fig. 12.8) suggests that locally gravitational sliding must have started to play a role already during the latest Olenekian. In the early Anisian (around 247 to 245 Ma), at the onset of rifting in the Dutch sector, small amounts of extension in the sedimentary basins allowed local faulting and

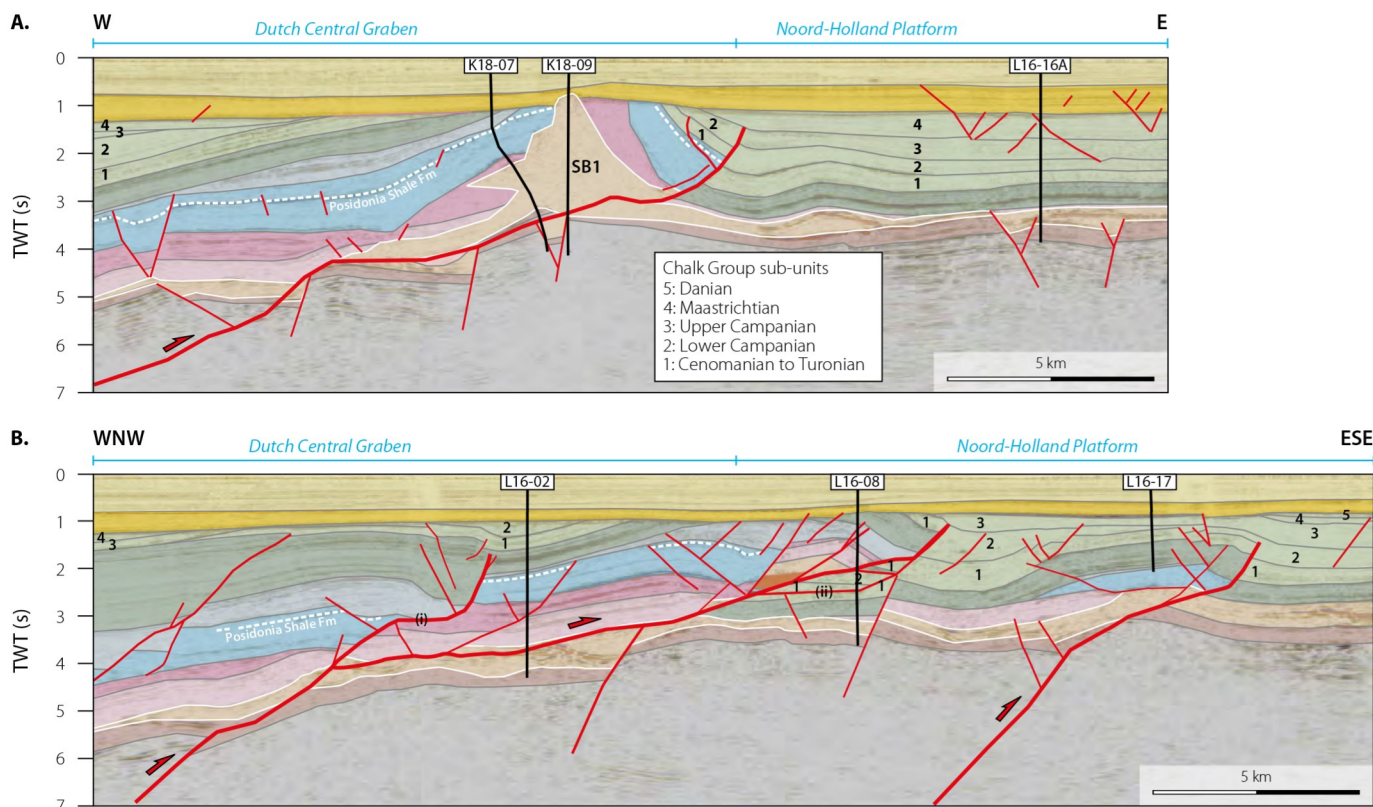


Figure 12.19. Interpreted seismic time sections in the southern part of the Dutch offshore (blocks K18-L16). a) W-E oriented section across a large thrust fault (thick red line). The core of the hanging wall is occupied by a large salt body (SB1). The presence of a Lower Jurassic stratigraphic wedge on the eastern side of the salt body indicates that the thrust occupied a normal fault that was originally associated with Jurassic rifting. This salt was located in the vicinity of the rift bounding fault on the eastern side of the Broad Fourteen Basin and was remobilized during reactivation in the Late Cretaceous. Unconformities between sub units of the Chalk Group attest to multiple periods of Late Cretaceous to early Cenozoic inversion. Note the repeated section of Carboniferous (Limburg Group) in well K18-07. b) Section just south of section (a) showing two thrust faults (thick red lines), one of which is interpreted as a duplex with multiple branches (thinner red lines). Note that the flat and ramp geometries of the larger thrust faults mainly detach in the Zechstein salt. The branches also use Middle-Upper Triassic mechanically weak layers (likely in-situ salt layers of the Main Röt Evaporite Member) or weak levels in the Texel Formation of the Chalk Group (likely the Plenus Marl Member). These detachments are indicated with (i) and (ii), respectively. See Fig. 12.2b for location of the lines. Modified from Peeters et al. (2021).

- extension within the suprasalt overburden to take place, locally breaking strata into blocks and allowing salt to flow into the newly formed grabens (sections 1 and 2 in Fig. 12.14). This is also well documented in the Gulf of Mexico and on the west African continental margins (Schultz-Ela, 1992; Jackson et al., 1994; Mauduit et al., 1998), allowing several salt pillows to form. The Middle Triassic shows more thickness variation than the lower Triassic but less than the Upper Triassic, which indicates that the intensity of salt tectonics was not yet at its peak during this period (Fig. 12.14).
- ii. During the Anisian two main Triassic salt-prone units were deposited, namely the Main Röt Evaporite and the Muschelkalk Evaporite members.

- iii. Gravitational sliding intensified at the end of the Anisian period with a predominance of extension on the outer-rim of the Triassic basin (eastern part of quadrant A, southwestern part of F; northern part of L, northwestern part of M and G) (Bouroulec et al., 2017; see Fig. 12.7). Growth fault/raft systems formed in the same regions during this period with a vergence toward the Permian and Lower Triassic paleo-basin axis that was located in the quadrant F (Figs 12.6, 12.7, 12.8, 12.12, 12.14) and continuing farther northeast towards Germany. Fault G1 in Figure 12.7 dips to the east and is indicative of eastward gravitational gliding. The best developed growth fault/raft systems are observed in the L and M quadrants and are associated with

salt sheets that represent squeezed and extruded salt from pre-existing salt diapirs that formed at the onset of the Middle Triassic (Fig. 12.8). With the predominance of extensional gravitational systems on the outer rim of the paleo-basin, one would expect a large concentration of reverse faults in the down-dip/basin axis area (quadrant F). However, only a few of that age have been observed (TF1-3 in Fig. 12.15). One example is seen in Figure 12.15a where up-dip extension during the Late Triassic (growth fault GF1) is balanced downdip by a thrust fault (TF1) located below well Lo5-02. TF1 detached onto the Zechstein salt and has a narrow salt body on its footwall side that is interpreted as a shortened and overthrust-ed pre-existing salt diapir that formed around the depositional time of the Röt Formation. Figure 12.15b shows examples of thrusts faults that detach on shallower (Triassic) salt units. Bouroullec et al. (2017) suggested that most of the balancing was accommodated by squeezing of pre-existing salt diapirs and -walls (SB6 in Fig. 12.3b; Salt wall 2, SB 4 and SB5 in Fig. 12.4; SB2 in Fig. 12.6; SB4 and SB6 in Fig. 12.8; Fig. 12.14; step 3 of Fig. 12.16). This increased the upward migration of the salt in those areas and locally allowed salt to extrude at the free surface (in a similar fashion as the salt glaciers in the Zagros Mountains in Iran). Such extruded salt bodies are represented by a few remaining (non-eroded) loaded salt sheets in the south of the paleo-basin (quadrant L) and in the north of the Dutch onshore in quadrant B (see Figs 12.4a-c, 12.7, 12.8 and step 3 of Fig. 12.14).

- VI. The Late Triassic was a period of intense salt tectonics that led to the large variation in stratigraphic thicknesses observed throughout the Dutch sector. Large stratigraphic wedges formed on top of rollover anticlines in growth faults/raft systems. Salt migrated toward rift bounding faults where it formed large salt diapirs and -walls. Concurrently, Triassic axial depocentres developed and evolved into turtle structures as salt withdrawal continued (e.g. Figs 12.3, 12.8, 12.14). Several salt sheets that were emplaced during the Middle Triassic became subsequently loaded by thick Upper Triassic (and younger) strata that locally accumulated in mini basins above the originally squeezed and extruded salt masses (Figs 12.4d, 12.16).
- VII. During the Early Jurassic salt tectonics declined and only minor and long wavelength salt-related thickening features are observed. The Altena Group is often thicker in the axis of the Dutch Central Graben, which is indicative for continued salt migration from

the basin axis toward its margins but this took place in a more homogeneous manner than during the Middle/Late Triassic or during the upcoming Middle Jurassic-Early Cretaceous phases (Figs 12.3c, 12.5, 12.16). This can be related to a relatively quiet phase in the Dutch rifting history and the decrease of accumulation rate that triggered less differential loading on pre-existing salt bodies.

- VIII. The Middle Jurassic is missing from most of the Dutch salt province due to the Mid-Cimmerian erosional phase which eroded large portions of the older strata (as well as shallow paleo-salt features). This holds especially for rift shoulders represented by the Step Graben and Terschelling Basin (which were not yet loci of Jurassic deposition at that time), Cleaverbank Platform and Schill Grund Platform. The Middle Jurassic Werkendam Member is only locally present in the Roer Valley Graben, the West Netherlands Basin, the Broad Fourteens Basin and the Dutch Central Graben. The role salt tectonics played during this period is therefore unknown.
- IX. The latest part of the Middle Jurassic (Callovian) to the late Middle Volgian (TMS-1 and TMS-2 in Figs 12.3 and 12.5) consists of a growth stratigraphic interval highly affected by the continued salt withdrawal from the Dutch Central Graben axis toward its margins (Bouroullec et al., 2016, 2017, 2018; Verreussel et al., 2018, 2025, this volume). The depositional area widened during the Kimmeridgian with platform areas such as the Step Graben and the Terschelling Basin becoming part of the larger rift system thanks to a change from E-W to NE-SW rifting (Bouroullec et al., 2017; Verreussel et al., 2018). During the Late Jurassic-Early Cretaceous, crustal extension accelerated across the North Sea rift system driven by the reorganization of the stress field due to the opening of the Arctic-North Atlantic rift system and the related clockwise, westwards rotation of Laurentia-Greenland relative to Eurasia (Ziegler, 1988, 1990; Torsvik et al., 2002). This reorganization resulted in NW-SE-trending transtensional basins that formed along the southern margin of the Southern Permian Basin. Outside of the rift basins large areas were uplifted, exposed and eroded (Figs 12.3b,c, 12.5, 12.8). Evidence that salt bodies acted as sediment pathways during the latter part of this period has been documented on the Schill Grund and Cleaverbank platforms (Bouroullec et al., 2017, 2018, 2019). Most of the contemporaneous sediment pathways located on the rift shoulders toward the basinal sinks were, however, originally located away from the still growing salt bodies. When some of those salt bodies collapsed, due to the lack of salt flowing into their locations (salt welding out

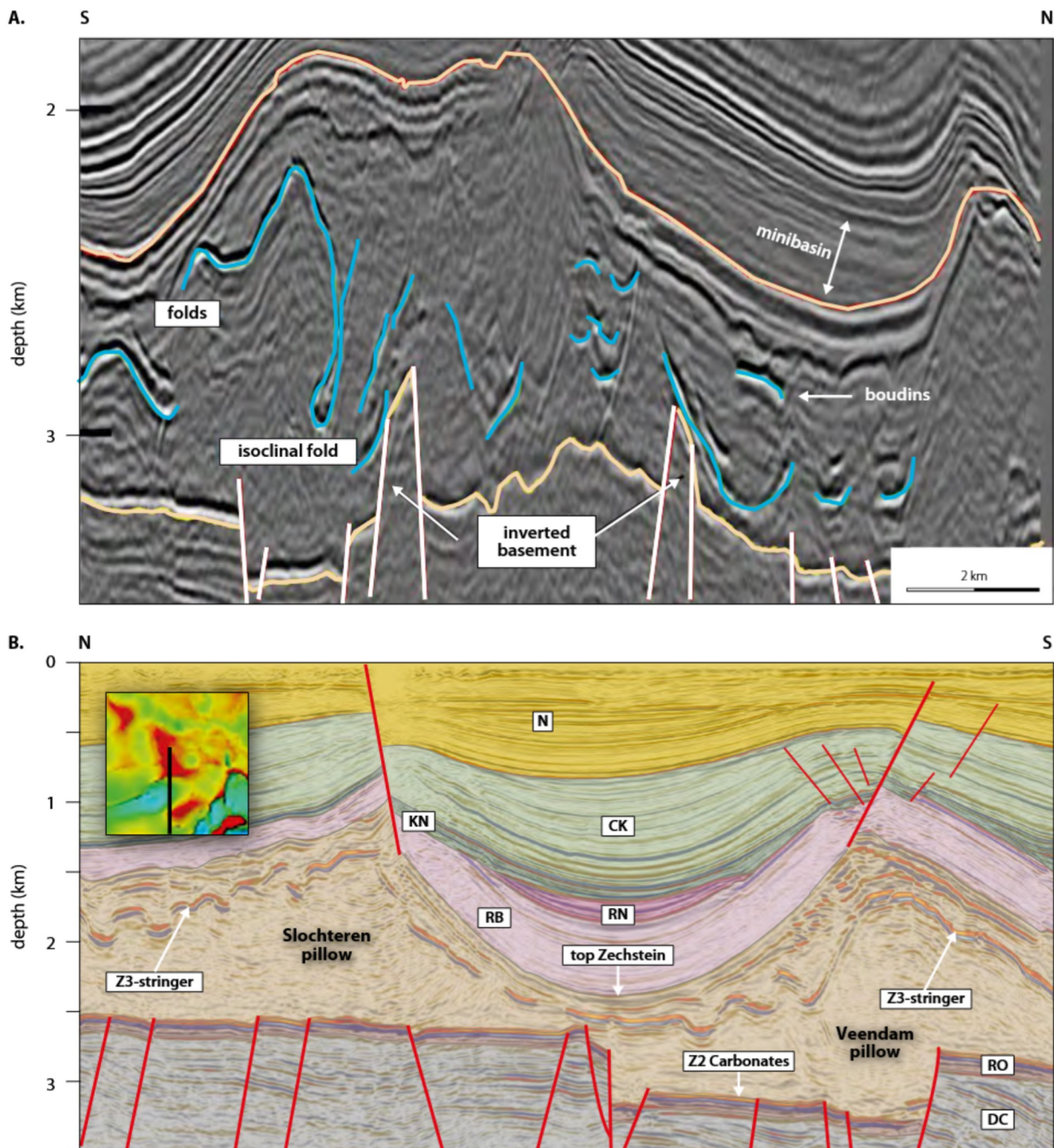


Figure 12.20. Zechstein salt stringers. a) N-S seismic depth section through the Cleaverbank Platform. Stringers are shown as blue lines. Note that the isoclinally folded stringers are located approximately above the basement-block bounding faults, whereas the boudins occur above the fault block. Location shown in Fig. 12.2b. Reprinted from Van Gent et al. (2011) with permission from Elsevier. b) N-S profile through the Slochteren and the Veendam salt pillows (see Fig. 12.2b and inset map showing top Zechstein for location). The Z3 stringer became separated (boudinaged) under the mini basin and was folded and thrust in the salt pillows. Seismic interpretation based on Raith et al. (2016). N = North Sea Supergroup; CK = Chalk Group; KN = Rijnland Group; RN = Upper Germanic Trias Group; RB = Lower Germanic Trias Group; RO = Upper Rotliegend Group; DC = Limburg Group.

in neighbouring regions), they occasionally became sediment sinks (collapse structures) or acted as sediment conduits to more distal zones, especially where collapse salt walls are located in the vicinity of the rift basins. Most of the turtle structures observed in

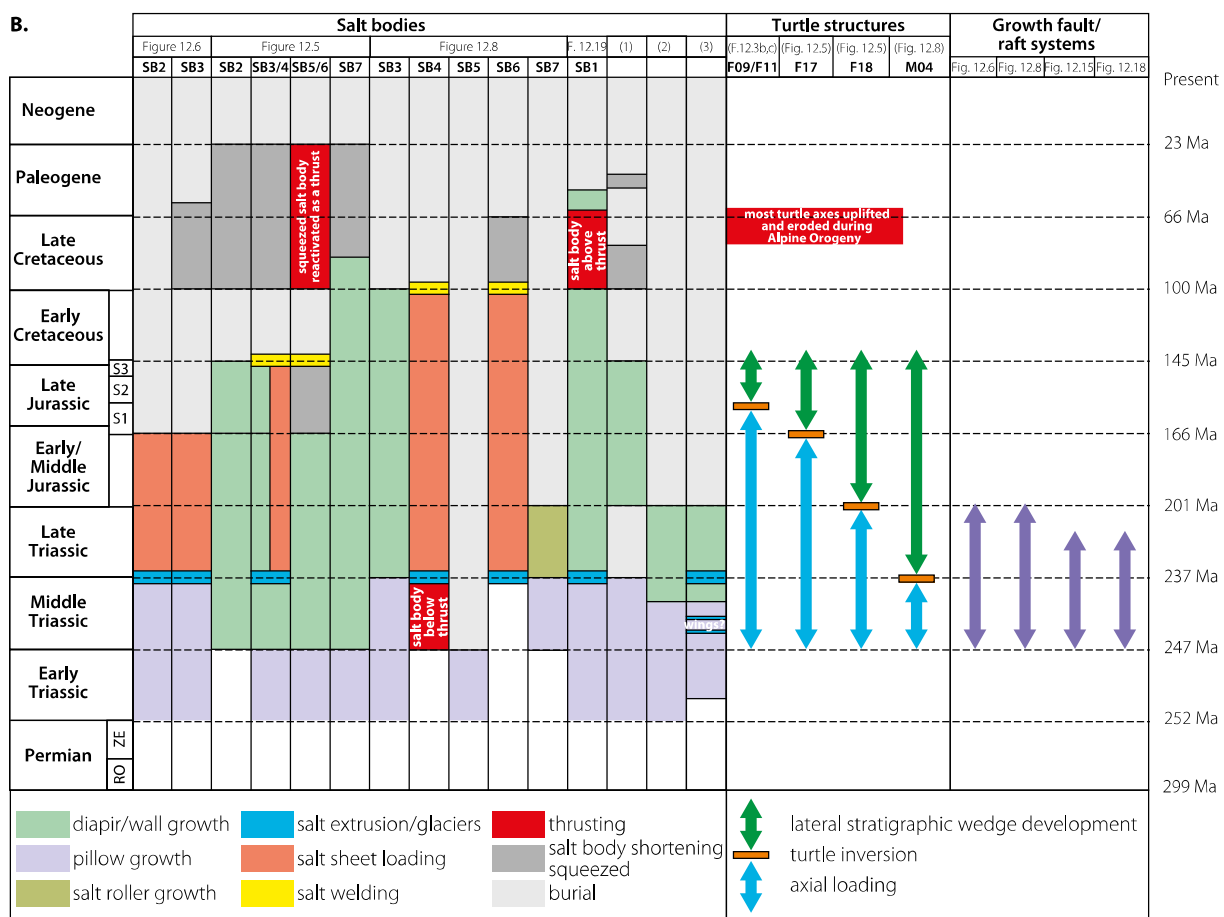
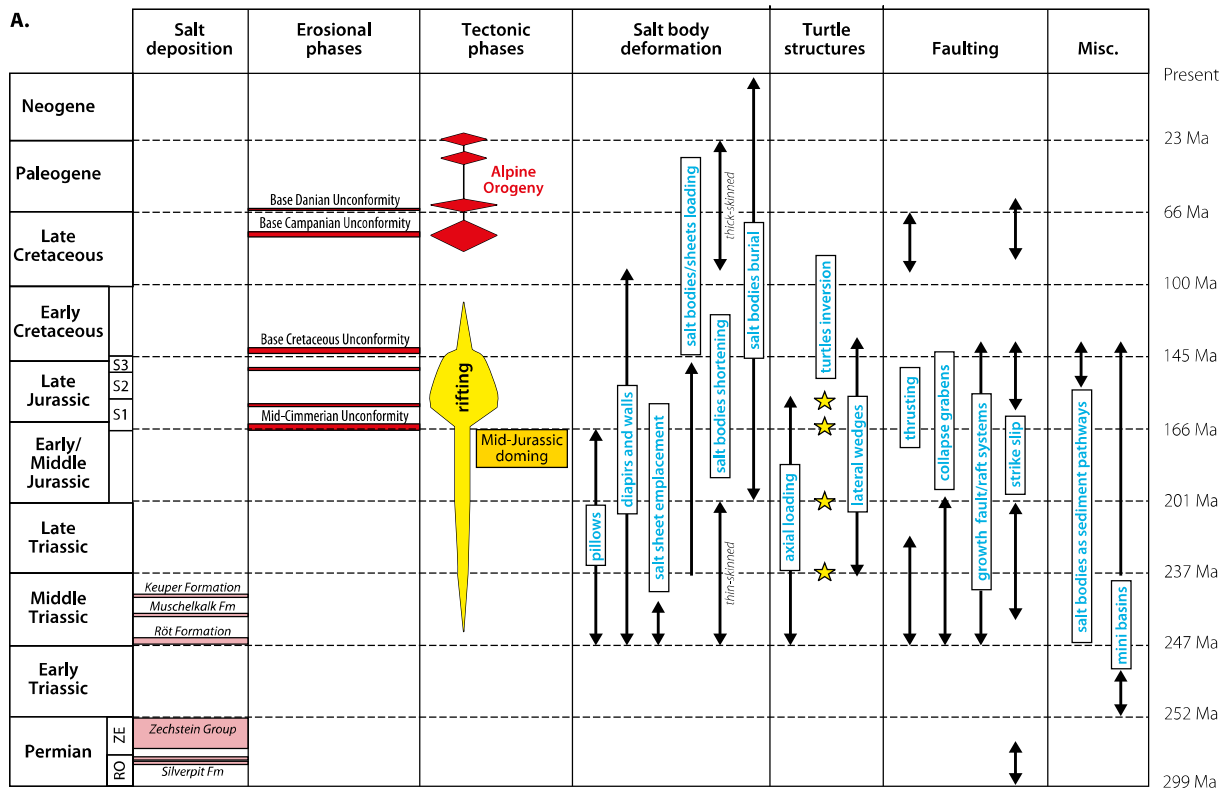
the Dutch offshore entered their inversion stage during this period. The timing of inversion spans from the Late Triassic (Turtle M4 in Fig. 12.8), through the Kimmeridgian (F17 and F18 turtles in Fig. 12.5) to the Middle Volgian (Fog turtle in, Fig. 3b, c). Hence,

most of the younger Late Jurassic to Early Cretaceous accumulations in the Dutch Central Graben are in rim synclines around these turtle structures.

- X. The late Volgian (Late Jurassic) and Ryazanian (earliest Early Cretaceous) (TMS-3; Bouroullec et al., 2018; Verreussel et al., 2025, this volume) was a period of continued salt tectonics but is distinguished from the previous period by the presence of an erosional event at its onset. This event eroded large amounts of older strata as well as salt bodies in the rift basins. Especially on the rift shoulders this erosion reached down to Permo-Triassic strata (Fig. 12.3a). Following this erosional event, the Scruff Greensand Formation and Lutine Formation were deposited in the basins and on their neighbouring platforms. During the Late Cretaceous, these deposits were often eroded, especially on the platforms and uplifted parts of the rift and are only preserved at the paleo-basin margins where accommodation was greater.
- XI. After the rifting ceased, deposition of the Early Cretaceous Rijnland Group testifies to a period of relative quiescence during which only regional thermal subsidence occurred. The Rijnland Group often drapes salt bodies and is thicker between pre-existing salt bodies (Figs 12.3a, 12.4a). Most of the thickness changes around salt bodies are more likely to have been caused by differential subsidence rather than reactivation of salt features. In the northern Dutch offshore, where the original salt was thickest, a few collapsed salt bodies show thicker Rijnland Group developments, suggesting that Zechstein salt was still actively withdrawing from the northern tip of the Dutch Central Graben during this period (Fig. 12.16). No new diapirs formed during this period.
- XII. During the Late Cretaceous to Danian deposition of the Chalk Group multiple salt features were reactivated. The presence or absence of thick Zechstein salt plays an important role in the architecture of inverted basins (De Jager, 2007). During multiple phases of the Alpine Orogeny, shortening was expressed as a series of large, uplifted zones in the older rift basins (Figs 12.3, 12.4a,c, 12.8, 12.15a, 12.16a), shortened and squeezed salt bodies (SB5 and SB6 in Fig. 12.3b; SB7 in Fig. 12.5) and thrust faults (Figs 12.18, 12.19). Many of the largest inverted structures were focussed along pre-existing rift-bounding faults with associated salt bodies (e.g. SB1 in Fig. 12.19 that coincides with the northern margin of the Broad Fourteens Basin). In the Dutch subsurface, large thrust faults in the shallow (post-Permian) sequence are often expressed as thin-skinned ramp- and flat thrust systems detaching onto the Zechstein (mother) salt (Fig. 12.19). Reactivation and shortening of pre-existing salt bod-

ies resulted in substantial folding of chalk layers and older supra salt strata (Figs 12.3, 12.4a,b, 12.5, 12.18, 12.19). Such folding allowed for intense faulting and fracturing of the chalk above salt-cored anticlines. The most significant phases of shortening were the Sub-Hercynian (Campanian) and Laramide (Mid Paleocene) phases that triggered major local uplift (especially of the paleo-basin centres) and erosion. Some of the rift bounding faults were inverted during this period and can be salt-cored (SB1 in Fig. 12.19). No extrusion of salt associated with these thrusts has been documented. During the Alpine orogeny some salt bodies were squeezed and their crests uplifted and eroded. Some local intra-Chalk Group carbonate and siliciclastic syn-tectonically reworked sediments, equivalent to the onshore Aachen and Vaals formations, were deposited on the flanks of inverted basins (Van Lochem et al., 2025, this volume). Also, contourites formed in the depocentres located between elevated suprasalt areas and mass transport complexes (including slides and slumps) formed on the steeper slopes (Van der Voet et al., 2018). Multiple transpressional faults were active during this period in the Netherlands (Nalpas et al., 1995; De Jager, 2007; Peeters, 2016). During the transpressive deformation salt bodies along pre-existing rifting-bounding faults were further squeezed, with narrowing of salt stems and formation of vertical welds.

Mid-Paleocene to Present: many faults active during this period are detached on the Zechstein salt bodies, although no significant evidence for salt flow is recognized during this period. During the Cenozoic, the main structural element in the southern North Sea is the Central Graben, which is interpreted as an intracratonic sag basin (Huuse & Clausen, 2001). This is the area with greatest accommodation during the deposition of the late Cenozoic southern North Sea delta. During the Quaternary, a combination of rapid subsidence in the centre of the basin and uplift at the UK and Fennoscandian margins is attributed to intra-plate stresses (Overeem et al., 2001). Although several mechanisms have been proposed to explain Quaternary subsidence, compaction and load-induced subsidence alone explain about 75% of the observed subsidence (Arfaei et al., 2018). Consequently, in the basin centre salt bodies became rapidly buried below a thick (more than 1 km) pile of shallow marine sediments. Despite their deep burial and the fact that salt bodies are not found shallower than strata as young as the Middle Miocene they have a significant influence on the thickness distribution of the Cenozoic interval, which often shows anticlinal domes atop- and flexural depressions around salt bodies. Differential compac-



tion related to thickness variations is one of the explanations for the (relative) up-doming of Cenozoic sediments. The resulting anticlinal structures favour migration and trapping of gas in shallow intervals. Hence most of the shallow gas discoveries in the Netherlands are located above salt bodies (see Remmelts et al., 2025, this volume). Eastward of the intracratonic sink area, i.e. in the northeastern part of the Netherlands and NW Germany, the thickness of the Cenozoic interval is less and several salt diapirs reach up to 100 m below the surface. These shallow depths make such salt diapirs favourable sites for salt production (see Groenenberg et al., 2025, this volume).

Synthesis and outlook

Salt tectonics has shaped the Dutch geology in significant ways since the Triassic. The Netherlands contains one of the most complex salt tectonic provinces in the world since it involves multiple salt layers, tectonic phases and erosion events. The complex structural styles resulting from this multi-stage salt tectonics have often favoured the migration, trapping and sealing of economically significant oil and gas volumes by providing enhanced accommodation for the deposition of thick reservoirs above and around salt bodies. For the coming decades, in which the role of the subsurface in the energy transition will be crucial, an improved understanding of salt tectonics in the Dutch on- and offshore will remain an important topic. Especially for CCUS a good understanding of the behavior of faults that detach onto salt layers and bodies will be crucial. Ongoing and future exploitation of salt onshore will also benefit from a good understanding of shallow salt bodies and layers. Current activities include rock salt and magnesium salt mining, storage of natural gas, nitrogen and diesel, whereas future activities will include storage of hydrogen, compressed air (CAES) and, although still only theoretically feasible, the disposal of nuclear waste. Geothermal activity in the Dutch onshore also targets many stratigraphic intervals that are affected by salt tectonics and new research will help to further reduce the risk of future developments in these structurally challenging areas.

← **Figure 12.21.** *Tectonic summary charts. a) Timing of main salt tectonic features and related phenomena in the Netherlands that formed since the Permian. Yellow stars indicate specific periods of turtle structure inversion. b) Timing of specific salt bodies, turtle structures and growth fault/raft systems shown in this chapter's figures and in three representative publications: (1) Van Winden et al. (2018); (2) De Jager (2012); (3) Ten Veen et al. (2012).*

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here:
<https://doi.org/10.5117/aup.28163951>.

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