4

Permian

Renaud Bouroullec & Cornelis R. Geel with a special recognition to Mark C. Geluk†*

*Corresponding author: renaud.bouroullec@tno.nl

ABSTRACT

The Permian System in the Netherlands is subdivided into the Lower Rotliegend, Upper Rotliegend and Zechstein groups. These groups were deposited in a large epicontinental basin extending from the UK to Poland. The Lower Rotliegend Group, deposited during the early Permian, unconformably overlays older strata (at the Base Permian Unconformity), is composed of volcanics and volcaniclastics and is only preserved locally in the Netherlands. After a significant erosional phase (Saalian Unconformity), the middle to upper Permian Upper Rotliegend sediments were deposited under warm and arid climatic conditions and are preserved in a large part of the Dutch sector. A broad southern and a much smaller northern lake edge depositional system composed of fluvial, eolian and playa-lake deposits are represented in the Netherlands. These systems are separated by the E-W oriented Silver Pit Lake in which clays and evaporites of the Silverpit Formation accumulated. With increasingly dry conditions, rapid marine floodings of the basin were accompanied by decreasing clastic input and thick evaporites and marginal carbonates, known as the Zechstein Group accumulated in the Netherlands and neighbouring regions. The thick layer of Zechstein rock salt is deformed into many salt bodies, sometimes localized along pre-existing faults, which often played a key role in Dutch diapirism and strongly influenced the post-Permian structural development. The depositional thickness of the Permian reaches almost 2000 m in the northern offshore. The Upper Rotliegend Group contains more than 95% of the natural gas resources in the Netherlands and it is a target for geothermal projects and CO_2 storage. The Zechstein Group contains exploitable rock salt and potassium-magnesium salts.

<< Slope carbonates of the Concretionary Limestone Member at Marsden Bay, South Shields (northeast England), equivalent to the slope facies of the Dutch Z2 Carbonate Member. Photo: Aart-Peter van den Berg van Saparoea.

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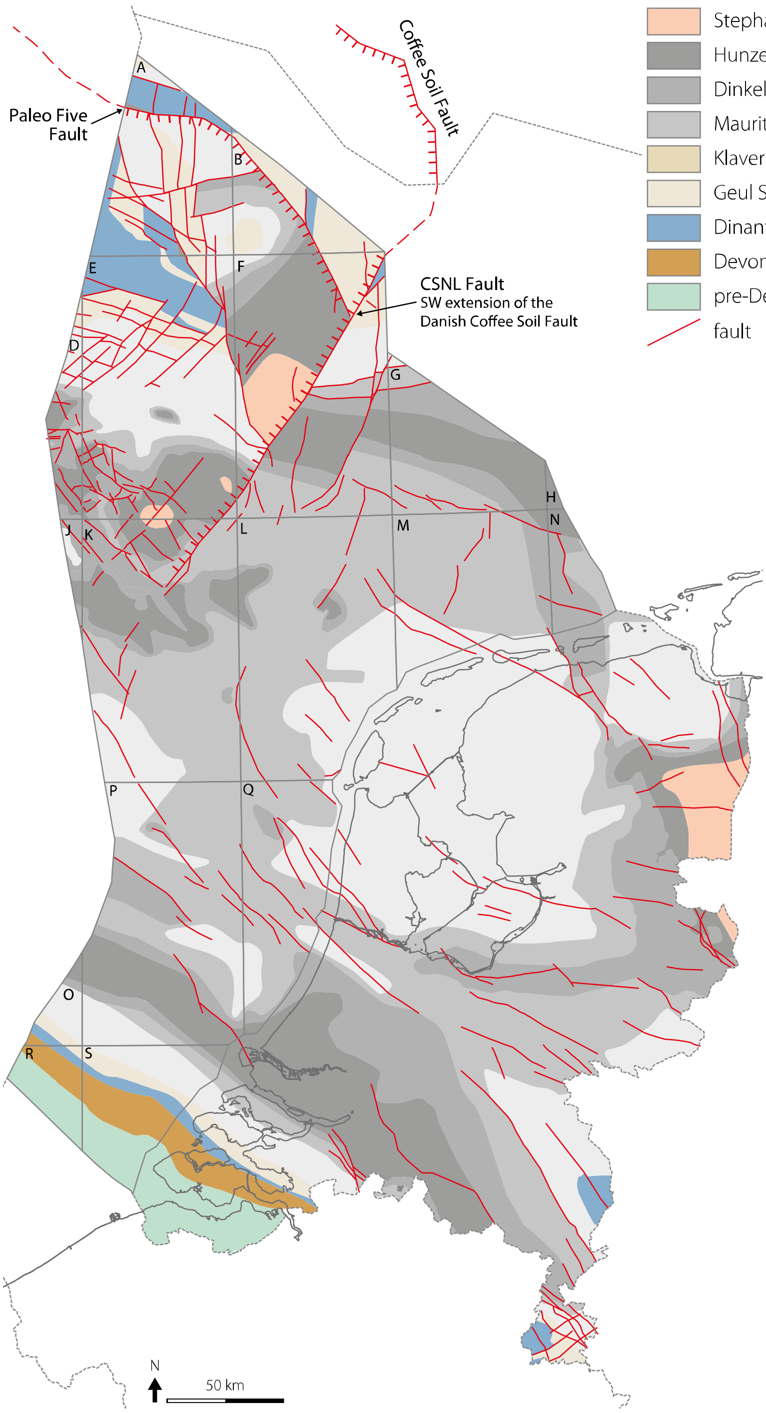
Introduction

Permian strata were deposited unconformably on top of gently deformed Carboniferous strata. The base of the Permian is often referred to as the Base Permian Unconformity (or BPU) (Fig. 4.1). In large parts of the Netherlands, the Permian overlies the Westphalian sequence and, locally, the Stephanian, Namurian and Dinantian (Huis in 't Veld & Den Hartog Jager, 2025, this volume). Middle to Late Devonian rocks subcrop in the south along the Brabant Massif and in the northern part of the offshore around the Elbow Spit High. Permian rocks contain important hydrocarbon reservoirs and seals (Remmelts et al., 2025, this volume), exploitable salt deposits (Groenenberg et al., 2025, this volume), good carbon sequestration storage potential (Juez-Larré et al., 2025, this volume) and form an important deep geothermal target (Mijnlieff et al., 2025, this volume).

In the Netherlands, a major hiatus represents most of early Permian (most of the Cisuralian to the lower part of the Guadalupian) to middle Permian time (Fig. 4.2). This un-



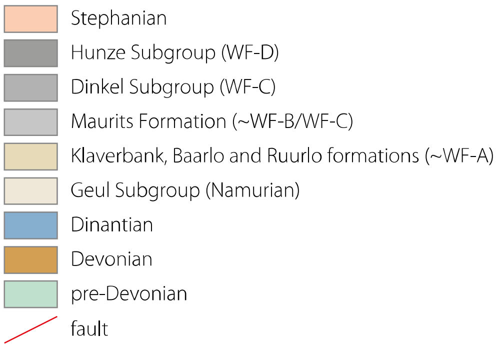


Figure 4.1. Base Permian subcrop map based on 1) recent regional mapping in the northern part of the Dutch offshore by TNO-GDN, 2) recent well-based stratigraphic updates of the Upper Carboniferous by Roustiau et al. (2022) and 3) previously published Base Permian Subcrop maps from Mijnlieff (2002) and Kombrink et al. (2010). Note the newly mapped Paleo Five Fault, a large south-verging normal fault that extends to the UK North Sea sector and has a vertical offset of 4.5 km at top Devonian level. The Coffee Soil NL Fault (CSNL Fault) is a newly interpreted crustal scale fault that, via the German offshore (Entenschnabel), corresponds to the SW extension of the Danish Coffee Soil Fault. In the Dutch sector, Stephanian strata are preserved on the downthrown block to the northwest of the fault. This fault likely acted as a lateral ramp of the Coffee Soil and Paleo Five faults system during the Devono-Carboniferous. A stratigraphic scheme of the upper Carboniferous is provided in Huis in 't Veld, R., & Den Hartog Jager, D. (2025, this volume, Fig. 3.4).

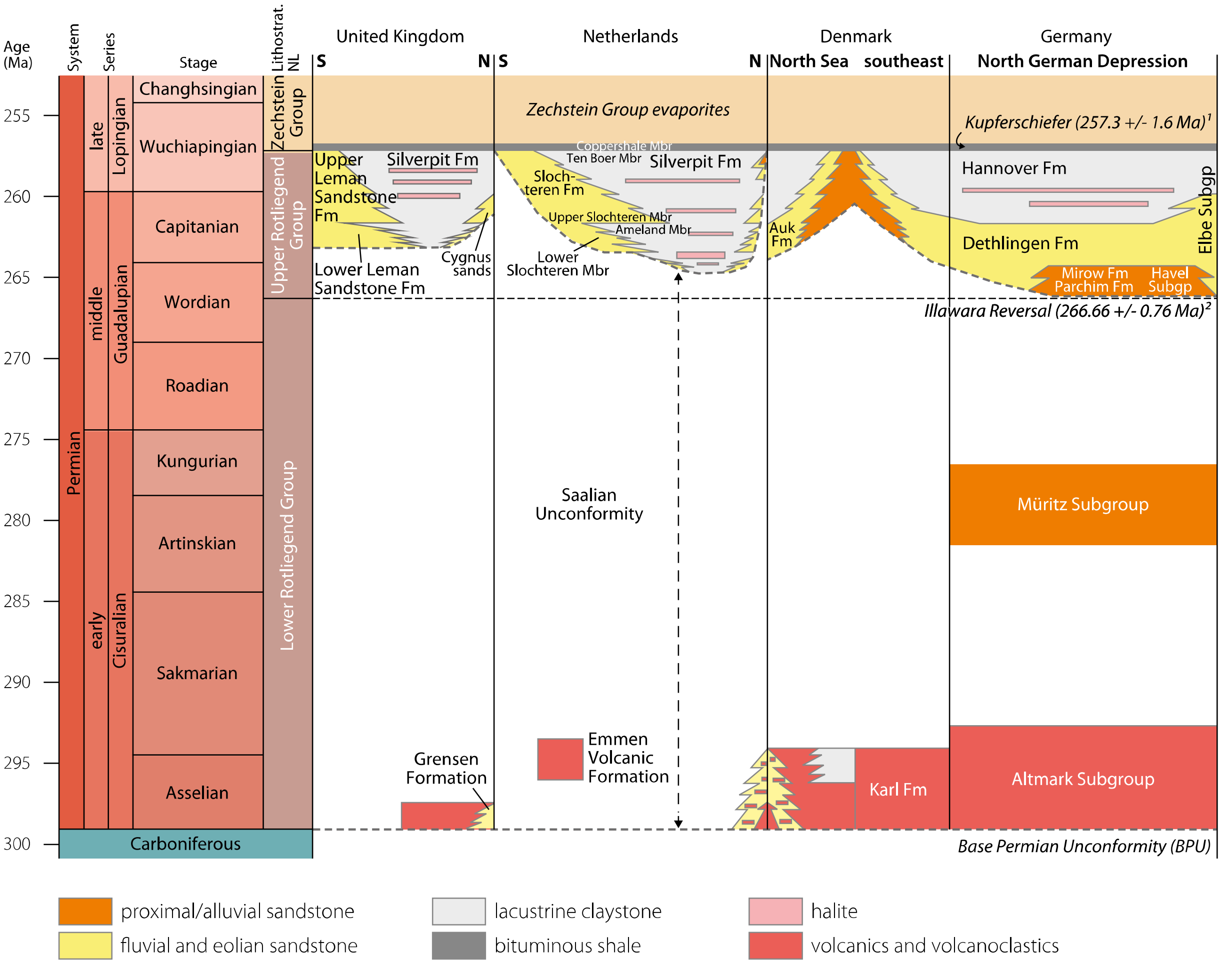


Figure 4.2. Tectonostratigraphic chart of the Permian of the UK, the Netherlands, Denmark and Germany. Modified from Gast et al. (2010). 1 = Re-Os isochron age for the Kupferschiefer (Brauns et al., 2003); 2 = age according to the geomagnetic polarity timescale for the Permian (Hounslow & Balabanov, 2016).

conformity is referred to as the Saalian Unconformity and it is often mistaken for the BPU because the Lower Rotliegend sediments deposited between those two erosional events are only sparsely preserved (Fig. 4.2). During middle and late Permian times, the Netherlands became part of the large E-W trending complex of sedimentary basins usually referred to as the Southern Permian Basin (SPB), which stretched from the UK to Poland and experienced significant thermal subsidence (Figs 4.3, 4.4; Ziegler, 1990; Geluk, 2005; Pharaoh et al., 2010). The depositional area gradually expanded during the middle and late Permian towards the London-Brabant Massif and the Rhenish Massif, which formed its southern margin, and the Mid North Sea High and Ringkøbing-Fyn High which formed its northern margin. The Lower Saxony Basin and the Dutch Central Graben formed areas of volcanic activity during the early to middle Permian (Fig. 4.7). During the middle Permian, differential subsidence of the Southern Permian Basin started. Sediment supply was mainly from the Variscan Mountains in the south and to a minor extent also from the highs north of the basin, including the Elbow Spit High.

The depositional thickness of the Permian increases from less than 50 m in the southern Netherlands to almost 2000 m in the northern offshore area. Some smaller intra-basinal paleo-highs such as the Peel-Maasbommel Complex, Dalfsen High, Winterton High and Elbow Spit High received little to no Permian sediments (Fig. 4.5). That the Texel-IJsselmeer High was a high during the Permian is still debated as it could be a younger structure. The present-day thickness of the Permian is highly variable due to 1) significant post-depositional erosion at the Mid-Cimmerian, Late-Cimmerian and Sub-Hercynian unconformities, and 2) salt dissolution and movements strongly affecting the original thickness distribution. A depth map of the base of the Permian is shown in Huis in 't Veld & Den Hartog Jager (2025, this volume). The depth of the base of the Zechstein Group ranges from less than 1 km in the eastern Netherlands to over 9 km in the Dutch Central Graben.

Stratigraphy

The Permian in the Netherlands is divided into three groups (Fig. 4.2; Van Adrichem Boogaert & Kouwe, 1994):

1. The Lower Rotliegend Group, a succession of volcanic, volcaniclastic, and clastic rocks with a geographically limited distribution.
2. The Upper Rotliegend Group, predominantly comprising sandstones in the onshore, southwestern offshore and in the northern offshore around the Elbow Spit High, and claystones with some halite beds in the E-W trending basin axis.
3. The Zechstein Group, mainly comprising marine evaporites, carbonates and claystones with minor sandstones (Zechstein Fringe Sandstone members; Fig. 4.11) in the south of the Netherlands.

The contact between the Lower and Upper Rotliegend or Zechstein groups is unconformable (Saalian Unconformity; Figs 4.2, 4.6), whereas the contact between the Upper Rotliegend and the Zechstein Group is conformable.

Traditionally, the Permian deposits have been subdivided into a Lower Permian Rotliegend and an Upper Permian Zechstein. Until recently, the former was considered to represent the early Permian, and the latter the late Permian (Menning, 1995; Plein, 1995; Glennie, 1998). Radiometric dating of the Lower Rotliegend Group in Germany documents an early Permian age (Plein, 1995; Stemmerik et al., 2000), but middle Permian ages in the Netherlands (Sissingh, 2004; Geluk, 2005). The Upper Rotliegend Group is almost completely devoid of fossils, having been deposited under hypersaline or oxidizing conditions. Here, other tools than biostratigraphy may be applied, such as chemo-stratigraphy, magneto-stratigraphy and sequence stratigraphy (George & Berry, 1994; Yang & Baumfalk, 1994; Schuurman, 1998). Rocks of the Zechstein Group, especially the carbonates and claystones, yield palynomorphs and marine fossils (bryozoa, bivalves and algae).

In 2003 the Permian Stratigraphic Committee agreed upon a three-fold subdivision of the Permian (Remane et al., 2003). Following that, the Lower Rotliegend Group, can be ascribed to the early to middle Permian, the Upper Rotliegend Group to the middle to early late Permian and the Zechstein Group to the late Permian (Fig. 4.2; Van Ojik et al., 2011). Where it is absent, the hiatus between the Upper Rotliegend and the Carboniferous in the Netherlands spans the entire early and part of the middle Permian.

A different approach to the subdivision of Permian deposits makes use of sequence stratigraphy, which aims for a better understanding of the depositional interrelations of the sediments. Sequence-stratigraphic models of the Upper Rotliegend Group have been published by George & Berry (1994), Yang & Baumfalk (1994) and Plein (1995); all models propose that wet-dry Milankovitch-driven climatic cycles with a periodicity of 100 and 200 ka controlled sedimentation. These high-resolution sequences are grouped in larger-scale cycles, with a duration of between 0.7 to 1.4 Myr. Cyclicity in the Zechstein has been described traditionally as governed by initial transgres-

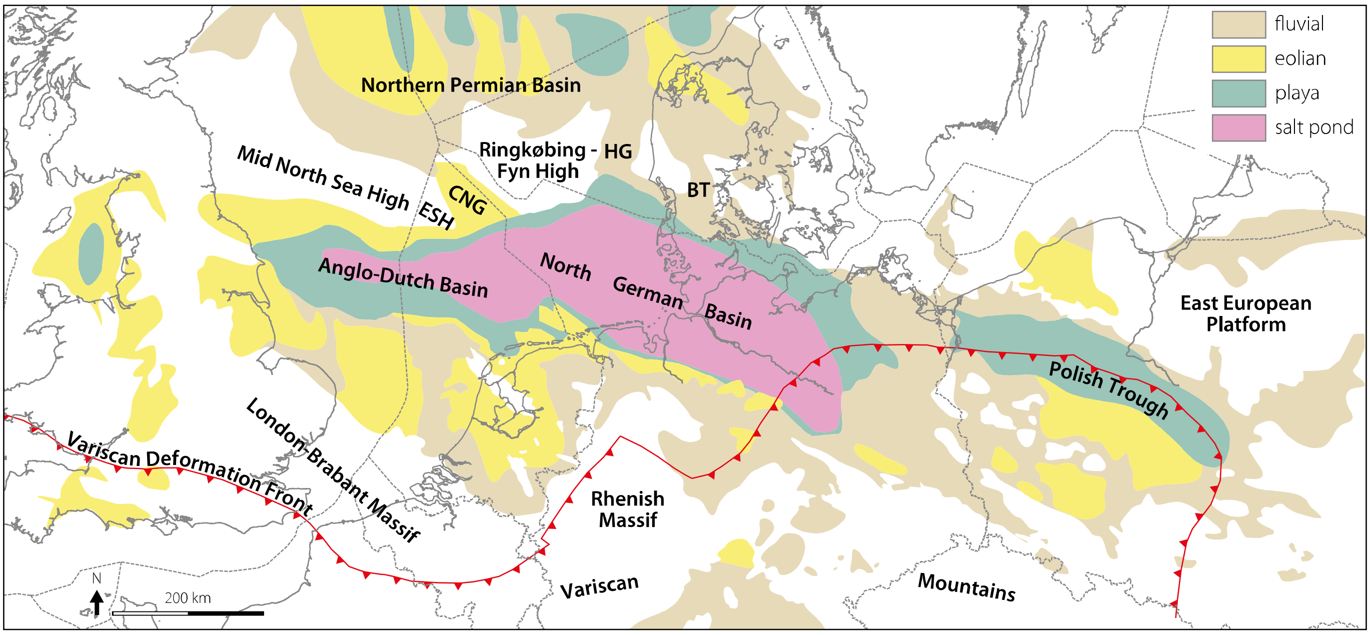


Figure 4.3. Present-day distribution and depositional environment of the Upper Rotliegend Group (late middle to early late Permian) in the Southern Permian Basin. BT = Bramble Trough; CNG = Central North Sea Graben; ESH = Elbow Spit High; HG = Horn Graben. (Modified from Geluk, 2005, 2007; De Bruin et al., 2015).

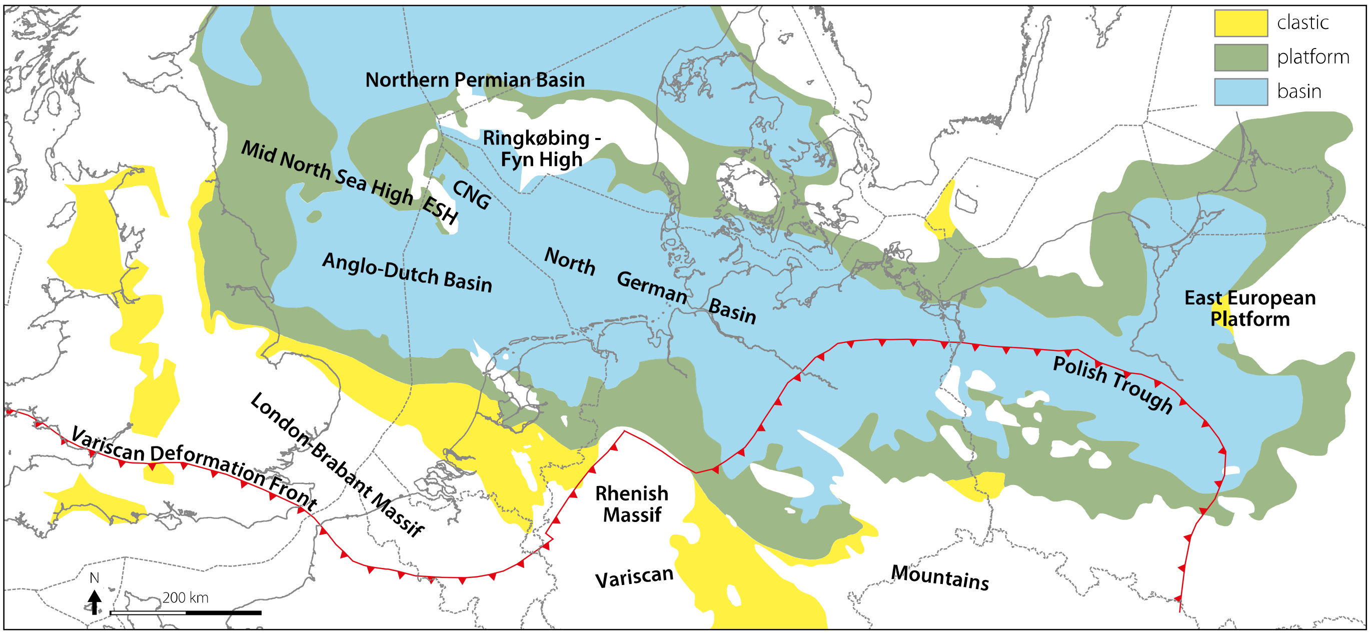


Figure 4.4. Present-day distribution and depositional environment of the Z2 Carbonate of the Zechstein Group (late Permian) in the Southern Permian Basin. CNG = Central North Sea Graben; ESH: Elbow Spit High. (Modified from Lokhorst, 1998; Taylor, 1998; Geluk, 2005, 2007; Bouroullec et al., 2022; Peeters et al., 2023).

sions, followed by regressive phases with evaporite deposition (Richter-Bernburg, 1955). These cycles, bounded by maximum flooding surfaces, are called genetic stratigraphic sequences (Galloway, 1989). A more modern view was published by Tucker (1991), who proposed an evaporite-carbonate sequence stratigraphy with sequence boundaries at the tops of the carbonates. The first indications for the Zechstein type cyclicity already appear in the upper part of the Rotliegend.

Regional correlations

The Permian in the Netherlands can generally be correlated with the adjacent countries without major problems (Fig. 4.2). The equivalents of the clastics, volcanics, and volcaniclastics of the Lower Rotliegend Group are known as the Karl Formation in Denmark and in the adjacent UK central North Sea (Stemmerik et al., 2000) and as the Altmark Group in Germany (Plein, 1995). The Grensen Formation (Fig. 4.2), located on the northern side of the Mid North Sea High on the eastern side of the UK offshore sector around the Flora Field and Grensen Nose, is time equivalent to the Karl Formation. This correlation is based on the K-Ar dating of 299 +/- 1.6 Ma of a volcanic extrusive unit which is unconformably overlain by the Grensen Formation (Martin et al., 2002).

The Upper Rotliegend Group correlates with the Auk Formation in the UK central North Sea and with the Silverpit and Leman formations of the UK southern North Sea (Johnson et al., 1994). The equivalent in Germany is the Elbe Subgroup (Gast et al., 2010); equivalents of the underlying formations occur in Germany and Poland (Geluk, 2005), and possibly also in Netherlands eastern offshore (Corcoran & Lunn, 2014). Equivalents of the Upper Rotliegend Group have been described as the so-called Zechstein conglomerate in northeast Belgium (De Craen & Swennen, 1992) and in the Lower Rhine coal-mining area in Germany (Schlimm & Thiermann, 1988). These are considered time equivalents of the youngest Upper Rotliegend or, alternatively, of the oldest Zechstein sediments. The Zechstein Group in the Netherlands correlates with the Zechstein Supergroup of the UK Southern North Sea and with the German Zechstein. Most of the unit names are identical. A major discrepancy, however, affects the definition of the top of the group in the different countries. In the UK, this top is picked considerably lower than in the Netherlands and Germany; as a result, rocks considered part of the Permian Zechstein in the latter two countries are assigned to the Triassic Bacton Group in the UK southern North Sea (Geluk, 2005).

Tectonic evolution

The deposition of the Permian postdates the Variscan Orogeny in western Europe. The compressive movements of this orogeny ended during the Asturian (Westphalian D) (Ziegler, 1990) and/or during the Stephanian, at which time the orogen collapsed (Arthaud & Matte,

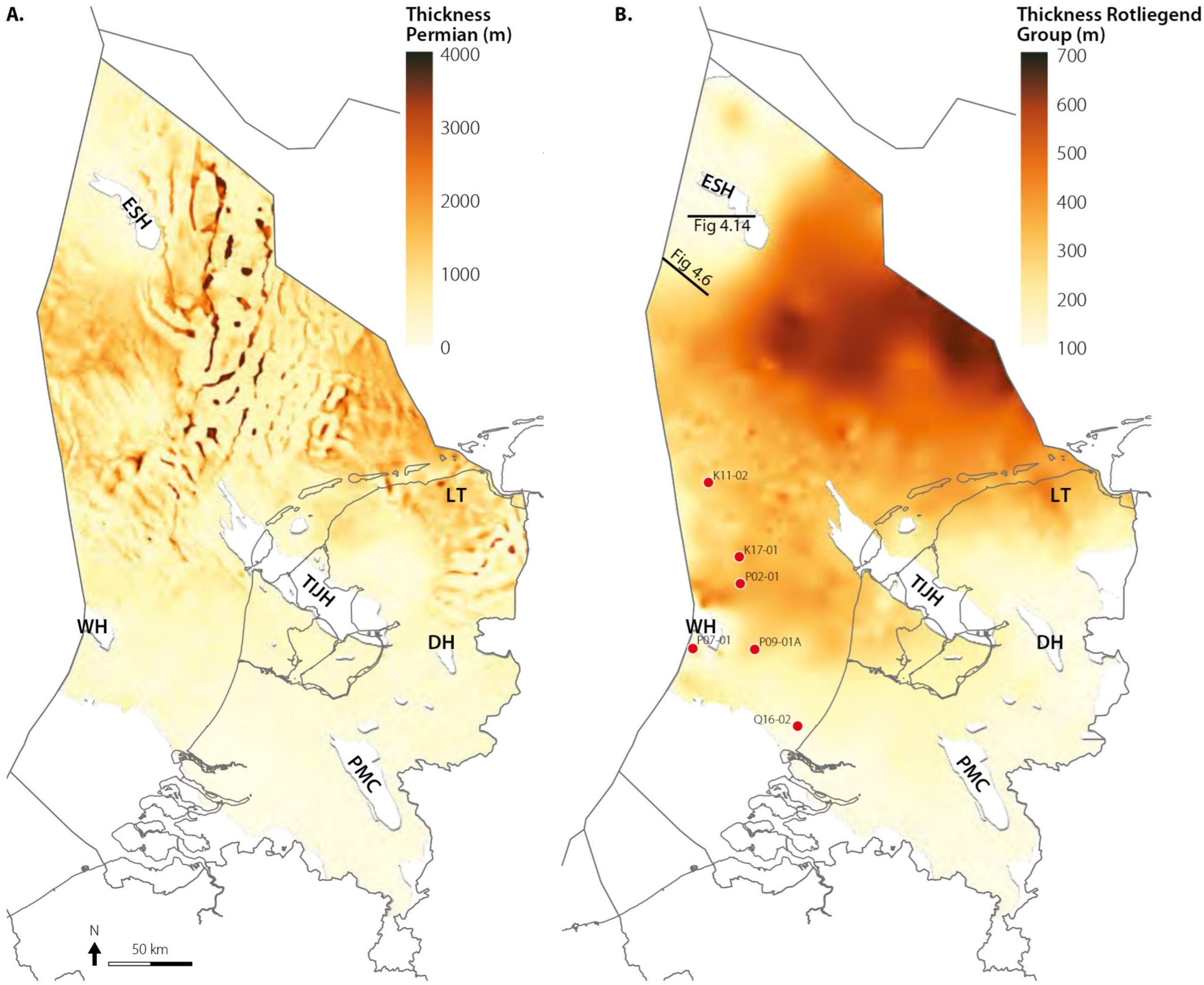


Figure 4.5. Thickness maps of the complete Permian System (a) and Rotliegend Group (b). A Permian succession thicker than 2500 m corresponds to Zechstein salt bodies (salt diapirs and walls). DH = Dalfsen High; ESH = Elbow Spit High; LT = Lauwerszee Trough; PMC = Peel-Maasbommel Complex; TIJH = Texel-IJsselmeer High; WH = Winterton High. Note that a map for the thickness of the Zechstein Group is shown in Bouroullec & Ten Veen (2025, this volume).

1977; Ziegler, 1989). Some of the deformation of Carboniferous strata to the north of the Variscan Front in the Netherlands post-dates the Variscan folding and has been attributed to late Carboniferous or early Permian wrench tectonics (Pharaoh et al., 2010). This late Variscan tectonic phase was accompanied by widespread plutonic and volcanic activity (Heeremans et al., 2004), which affected the Netherlands only marginally compared to Germany or Poland. The Stephanian history of the SPB is poorly understood as this was a period of uplift and erosion during the later phases of Variscan shortening. It resulted in a major unconformity between the Permian and older deposits known as the Base Permian Unconformity.

Several minor tectonic pulses took place during the late Permian (Gast, 1988; Plein, 1995; Glennie, 1998; Geluk, 1999). These are thought to herald the Permian breakup of Pangea (Vai, 2003). The pulses occurred prior to and during the deposition of the Upper Rotliegend Group (the Saalian and Altmark I to III pulses; Plein, 1995) and during deposition of the Zechstein (Tubantian I; Geluk, 1999), when a connection between the Southern Permian Basin and the Barents Sea was created. The Saalian and Altmark pulses influenced the distribution of basal Upper Rotliegend sands (Van der Baan, 1990; Van de Sande et al., 1996; NITG, 1998). The Tubantian II pulse is thought to be of compressional origin and related to the Uralian orogeny (Geluk, 2005). It marks the second, final, consolidation of Pangea at the end of the Permian (Vai, 2003).

There is evidence for considerable differential fault movement during deposition of the Z1 (Werra) Formation (Wolf, 1985; Ziegler, 1989; Geluk, 1999): the Tubantian I phase. The fault activity concentrated on the anhydrite platforms at the margins of the Zechstein basin. Loading of rapidly deposited anhydrite on a differentiated substrate is thought to have amplified these movements (Geluk, 1999). A series of half grabens and pull-apart-type basins formed, with fault offsets up to 250 m in the Central Netherlands Basin. During this faulting, the first fault – dip-closed traps in Upper Rotliegend sandstones were created, only 3 to 5 Myr after their deposition.

The syn-depositional Tubantian II movements of the upper Zechstein are more difficult to identify, but are seen in an unconformable contact between the Zechstein Upper Claystone and older Zechstein rocks. They resulted mainly in tilting and uplift and have been interpreted by Geluk (2005) as being related to mild compression. Source areas south of the basin were uplifted, and sands were shed into the basin in the western offshore area and the UK sector (Z4 or Hewett Sandstone).

Permian unconformities

The Base Permian Unconformity (BPU) is one of the most important unconformities in the regional geology of the southern North Sea (De Jager & Geluk, 2007). Where the Upper Rotliegend overlies Visean to Stephanian deposits, this hiatus represents 35 to 80 Myr (Figs 4.1, 4.2, 4.6). The BPU often represents an amalgamation of several unconformities into a single mega-unconformity (Glennie, 1998) that encompasses the entire early Permian. Where the Upper Rotliegend overlies Namurian to Stephanian deposits, as is the case in most of the Netherlands, this hiatus duration is 40 to 60 Myr. The term 'Saalian Unconformity' should be used with care since it refers to one such event, located in places where lower Permian deposits are still present above the BPU.

The Saalian Unconformity (Stille, 1924) can be distinguished from the BPU where lower Permian deposits are still present (Fig. 4.2), in the Netherlands only in small areas in the east and the north (Fig. 4.8). The time gap represented by the Saalian hiatus is poorly constrained in the Netherlands due to the lack of well penetrations and dating, but recent publications from neighbouring basins that include dating in shed some new light on the hiatus. In parts of mid-European basins, following the early Permian volcanism, sedimentation restarted in the late Permian at the time of the major geomagnetic Illawarra Re-

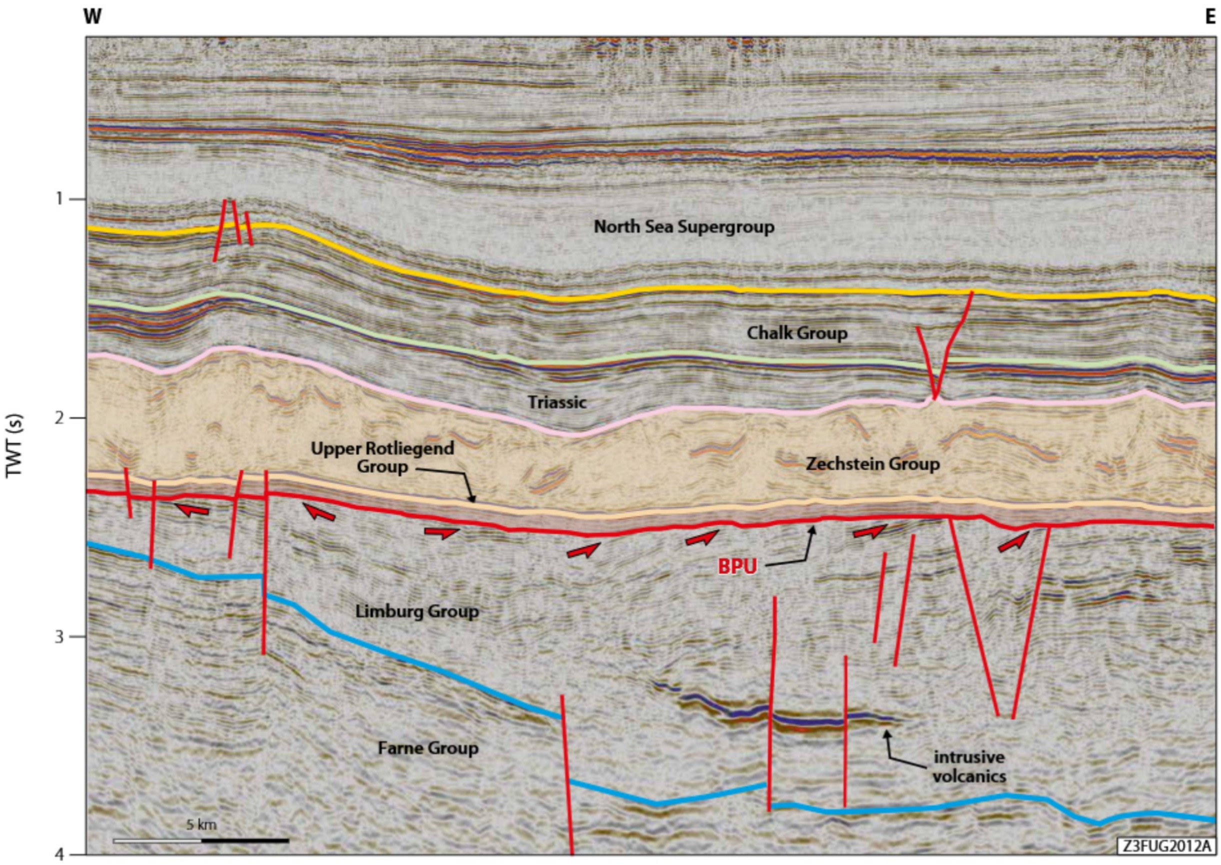
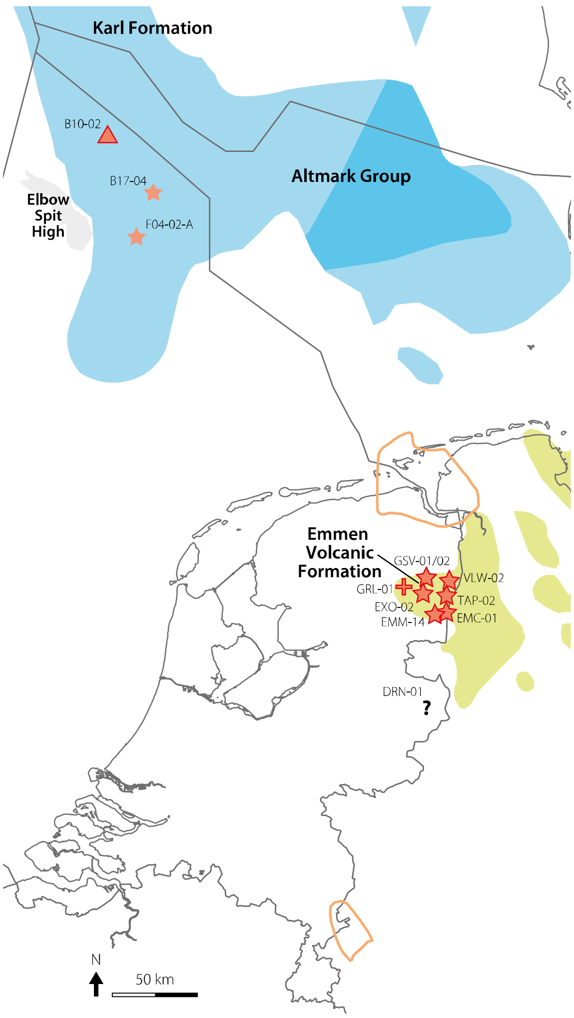


Figure 4.6. Interpreted seismic time section in the northwestern part of the Dutch offshore. The Base Permian Unconformity (BPU) here also includes the Saalian Unconformity and is clearly expressed as an angular unconformity, while the base and top of the Zechstein Group are concordant. See Fig. 4.5b for location.

versal (266.66 ± 0.76 Ma; Hounslow & Balabanov, 2018). Lützner et al. (2021) indicate that the duration of early Permian volcanism in this pull-apart Thuringian Forest Basin of central Germany was relatively short, around 4 Myr, from 300 Ma to 296 Ma and was followed by a hiatus of 25 Myr before deposition resumed in the middle to late Permian. The extent of the Saalian hiatus in the Netherlands may therefore be shorter than previously estimated (e.g. 40 Myr by Pharaoh et al., 2010).

Despite the extended period of non-deposition, the unconformities may be very difficult to identify in some areas, because of the general absence of fossils and the similarity of the red beds of the Asturian, Stephanian and Permian. Biostratigraphic zoning based on insects, especially cockroach wings, as well as amphibians, vertebrate footprints and conchostracans has been used successfully in German, Czech and Polish basins (Opluštil et al., 2017; Schneider et al., 2020), but no new data are yet available in the Netherlands.



Stratigraphy

Lower Rotliegend Group

Primarily based on well data the Lower Rotliegend Group occurs in the Lower Saxony Basin, the northern part of the Dutch Central Graben, the Step Graben, and extends north-eastward into Germany and Denmark (Fig. 4.7). In the northern offshore and eastern onshore the group is represented by interbedded volcanics, volcaniclastics, and siliciclastics (Fig. 4.8). In the Lower Saxony Basin, it is represented by the Emmen Volcanic Formation. The climatic change that started in the late Westphalian from a hot tropical setting to arid conditions (red beds of Westphalian D and Stephanian) continued during the Rotliegend.

The volcaniclastics in the Lower Saxony Basin (Fig. 4.7) represent a western extension of a large area of volcanics developed in Germany (Plein, 1995) They consist of red-brown to green, spilitic, basaltic volcanics, mudstones and tephra layers. Several stacked lava flows occur in the succession. The thickness of the volcanics reaches a maximum of 80 m (NITG, 2000). The group is placed in the lower Permian in Germany based on radiometric age dating (291-289 Ma) and the lithological composition of the basalts (Plein, 1995). However, a K-Ar age for the Lower Rotliegend Group in the eastern Netherlands (well Drouwenermond-1), records a much younger volcanic pulse, which is probably incorrect (middle or late Permian, 258 ± 6 Ma; Sissingh, 2004; Van Bergen & Sissingh, 2007; Van Bergen et al., 2025, this volume).

Figure 4.7. Locations of Lower Rotliegend Group volcanic rocks as found in wells in the Lower Saxony Basin and the northern Dutch offshore east of the Elbow Spit High. Wells and batholiths taken from Van Bergen et al. (2025, this volume). The distribution and geochemical composition of late Paleozoic volcanic rocks is taken from compilation figure 7.16 in Gast et al. (2010).

In the Dutch Central Graben the wells B10-02, B17-04 and F04-02-A penetrate lower Permian volcanics; that is possibly also the case for wells A15-01 and F07-02. A maximum thickness of 190 m is recorded at well B10-02 (Fig. 4.8). The succession is lithologically similar to that of the Danish Karl Formation (Geluk, 2005). The lateral extent of the group is delineated towards the west, north and south by well data but remains uncertain to the east. It consists of tephra and of basaltic lava flows up to several tens of metres thick, interbedded with claystones and subordinate sandstones. De Bruin et al. (2015) identified an overall NNW-SSE-oriented depositional trend in the northern Dutch offshore with a lower sand content towards the WSW, away from the German and Danish main volcanic provinces. Stemmerik et al. (2000) identified three distinct volcanic pulses in the Permian of the Danish North Sea. The first (300-288 Ma) and second phases (281-276 Ma) both show an andesitic and rhyolitic composition and are present in the western part of the Central North Sea Graben and the Horn Graben. They are followed by a younger, basaltic, pulse (269-261 Ma, middle Permian). Although dates from the Dutch Central Graben are lacking, it is likely that the Danish volcaniclastics correlate with this younger pulse in the Netherlands.

Upper Rotliegend Group

The Upper Rotliegend Group is subdivided into two formations, the Slochteren Formation, which is mainly composed of sandstones and conglomerates and the Silverpit Formation, comprised of claystones, siltstones and evaporites (Figs 4.8, 4.9). The two formations are lateral equivalents with the Silverpit Formation deposited in the deeper, axial part of the Silver Pit Lake and the Slochteren Formation along its margins. The Upper Rotliegend Group reaches a maximum thickness of more than 700 m in the Schill Grund Platform in the eastern offshore but thins rapidly both towards the south and the north (Figs 4.8, 4.9). The oldest sediments of the group probably occur in the eastern offshore in quadrants G, H, M and N. The sequence is locally absent due to erosion on the Texel-IJsselmeer High and nearby smaller highs (Rijkers & Geluk, 1996), and because of nondeposition in most other areas such as the Elbow Spit High (Geluk, 1999; De Bruin et al., 2015).

There is strong evidence that syn-depositional fault movements affected the Upper Rotliegend Group. In the western parts of the Central Netherlands Basin, the thickness varies across major faults (RGD, 1993). It is likely that also the northern part of the West Netherlands Basin formed a fault-bounded depression, where up to 100-m-thick eolian sands occur. Other areas where faulting occurred are the eastern Netherlands (NITG, 1998), the area north of the Texel-IJsselmeer High (RGD, 1991a,b) and the Lauwerszee Trough (RGD, 1995; Fig. 4.5b). Thickness variations across faults are up to 45 m. Some of the syn-depositional faults form positive flower structures indicative of strike-slip motion, but the timing of the deformation is unclear, with some minor reactivation of pre-existing Carboniferous faults being a possibility. Based on the map-view of some of these syn-depositional faults, most are oriented NW-SE and show dextral strike slip (De Bruin et al., 2015).

The *Silverpit Formation* comprises siltstones, claystones and evaporites. In the Dutch Central Graben, tephra layers occasionally occur in its lowermost part. The formation reaches a thickness of over 700 m in the eastern offshore area and was formed in a playa lake depositional environment. In a more proximal setting, the formation is subdivided into two members, the Ameland Member and the Ten Boer Member. In the distal part of the basin, a subdivision into three members is made, i.e. the Lower and Upper Silverpit Claystone and the Silverpit Evaporite members (Fig. 4.9). The evaporitic intervals mainly comprise rock salt with subordinate anhydrite and interbedded clay-siltstones. The individual rock-salt layers form good correlation horizons throughout the Southern Permian Basin (Figs 4.8, 4.9). Their thickness reaches up to 50 m. In northern Germany and part of the adjacent Netherlands offshore (quadrants F, G), these layers have been mobilized into salt pillows. During the Triassic and Jurassic evaporite intervals locally acted as detachment horizons for syn-depositional faults and in Germany even formed diapirs. The salt layers are not composed of pure halite but contain abundant thin claystone beds since they were deposited in playa lake setting, as opposed to the marine conditions that came later during the Zechstein. The formation interfingers southward with the Slochteren Formation forming a lateral facies change and several tongues of the Silverpit Formation (Ameland and Ten Boer members) reach far to the south (Fig. 4.9).

The *Slochteren Formation* consists mainly of conglomerates and sandstones of fluvial and eolian origin. These facies can be distinguished in cores and on dipmeter logs. In the zone where the Slochteren and Silverpit formations interfinger, the former splits up into two main sandstone members, the Lower and Upper Slochteren members, separated by clay- and siltstones of the Ameland Member (Figs 4.9, 4.10a, 4.11). Eventually, both Slochteren members grade northward (in the south) and southward (in the north) into siltstones and claystones of the Silverpit Formation in the basin axis. The Lower Slochteren Member is present in the central and northern parts of the offshore and in the northern part of the onshore (Fig. 4.10a). It varies in thickness due to the presence of pre-existing

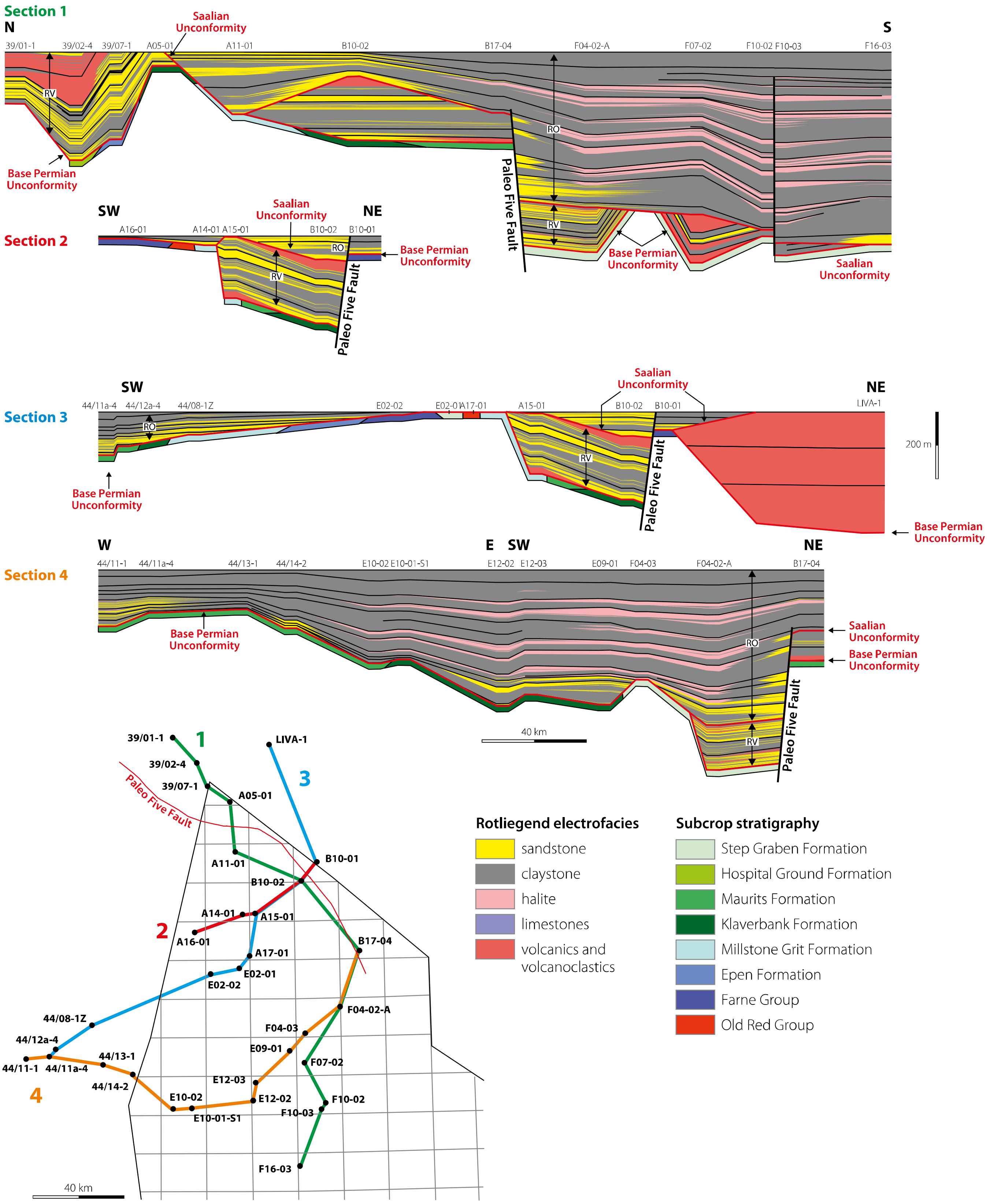


Figure 4.8. Stratigraphic correlation panels of the Lower and Upper Rotliegend groups in the Dutch Northern Offshore. Panels are flattened on the top Rotliegend, which is locally eroded in the northern part of the Dutch offshore and in the UK sector. RO = Upper Rotliegend Group; RV = Lower Rotliegend Group.

paleo-highs and -lows. The Upper Slochteren Member is well developed along the southern basin margin and is less conglomeratic than the Lower Slochteren Member. The fluvial systems of the Slochteren Formation were oriented at right angles to the basin axis with a south-to-north run-off from the southern margin of the SPB and a mainly north-to-south run-off from the northern margin.

In the southern part of the basin, the Upper Slochteren Member is partially composed of two fluvial systems located in the Dutch southern offshore and northeast onshore areas. (Fig. 4.10b). These two wadi belts were separated by a large area where eolian sediments accumulated. Detailed studies indicate that fluvial and eolian facies are interbedded in a complex way and shifted laterally through time (George & Berry, 1994; Verdier, 1996; Fryberger et al., 2011); rapid vertical and lateral facies alternations occur even on a metre-scale. Eolian sandstones vertically dominate the middle part of the formation (NITG, 2000). Within the eolian deposits a further distinction can be made between dunes, which occur predominantly in the southern central areas, and damp to dry sand flats closer to the playa lake (Glennie, 1998; Fig. 4.11). The Slochteren Formation along the northern margin of the SPB is not developed as extensively as in the southern margin (Figs 4.8, 4.10a, 4.11). There, the drainage area was limited to a much smaller area, composed of Devono-Carboniferous strata exposed on the Mid North Sea High and Elbow Spit High in the Dutch offshore. The recent Cygnus discovery (Catto et al., 2017), located 50 km to the west of the UK/Dutch border, has up to 50 m thick stacked Lower Leman Sandstone units suggesting that comparable sand-rich Slochteren sandstones may be present along the southern and eastern flanks of Elbow Spit High. Paleo-reliefs of up to 46 m formed by differential erosion of the Carboniferous subcrop are observed in the vicinity of the Cygnus Field in the UK sector.

The *Ten Boer Member* forms a transitional unit between the sandy Upper Slochteren Sandstone and the marine sediments of the Coppershale Member (or Kupferschiefer) of the basal Zechstein Group (Figs 4.9, 4.11). It marks the end of the clastic sedimentation and the onset of the Zechstein transgression, consists of shales and fine-grained sandstones and forms part of the Silverpit Formation. Locally, close to the basin edge, it may contain substantial amounts of sand. The sandstone beds are thought to have been deposited by fluvial channels and associated unconfined sheet floods in the distal part of fluvial systems (Donselaar et al., 2011). The informal Akkrum Sandstone member (equivalent to the Hyde Sandstone in the UK) which is locally present in Friesland and which is also known as the Grauliegend, can be regarded as one of the thicker sandstone beds of the Ten Boer Member. A common, but not yet fully understood phenomenon is the Weissliegend facies. Originally described as a white to grey coloured formational unit that comprises the upper 50 to 60 m of the uppermost part of the Rotliegend sandstone (Glennie & Buller, 1983; Strömbäck & Howell, 2002). It contains mass-flow and in-situ soft-sediment deformed deposits and is thought to have formed when the Zechstein Sea flooded the Rotliegend sand sea. Whether the deformation was the result of a sudden flooding, or a gradual rise of the groundwater table remains uncertain. In any case, the Weissliegend has poor reservoir properties and is variable in thickness.

The Zechstein transgression reached the Southern Permian Basin from the Barents Sea region in the north, through a proto-Atlantic rift graben that first flooded the Northern Permian Basin (Glennie & Buller, 1983; Ziegler, 1990). The Horn Graben and the Central Graben formed N-S passages to the Southern Permian Basin which subsequently became flooded. A number of predecessors of the Zechstein transgression have been recorded in the Rotliegend and have been employed to make large-scale correlations across the basin (Legler & Schneider, 2008; Minervini et al., 2011). Based on a variety of biological, lithological, and geochemical indicators, Legler & Schneider (2008) concluded that at least some of the correlation markers represent marine ingressions.

Due to their depth of burial, the Rotliegend sediments are prone to and have been subjected to a variety of diagenetic processes. An extensive discussion of all these topics is beyond the scope of this chapter. The interested reader is referred to overview studies by Gaupp et al. (1993) and Gaupp & Okkerman (2011).

Zechstein Group

The Zechstein Group comprises five evaporite cycles (Z1-Z5), each of formation rank (Van Adrichem Boogaert & Kouwe, 1994). The Zechstein Upper Claystone Formation covers these cycles unconformably (Fig. 4.11). The lithostratigraphy of the Zechstein closely conforms to the concepts of genetic sequence stratigraphy (Galloway, 1989); three formation boundaries are picked on maximum flooding surfaces (base Z1: Coppershale Member; base Z3: Grey Salt Clay Member; base Z4: Red Salt Clay Member). These units form important correlation markers between the basin and basin-fringe deposits within the Southern Permian Basin (Geluk et al., 1996, 1997; Taylor, 1998). With respect to the distribution of the Upper Rotliegend, minor overstepping of the basin margins took place during the Zechstein (Geluk et al., 1996). The depositional thickness of the Zechstein Group increases from less than 50 m in the southern Netherlands, to over 1200 m in the northern offshore.

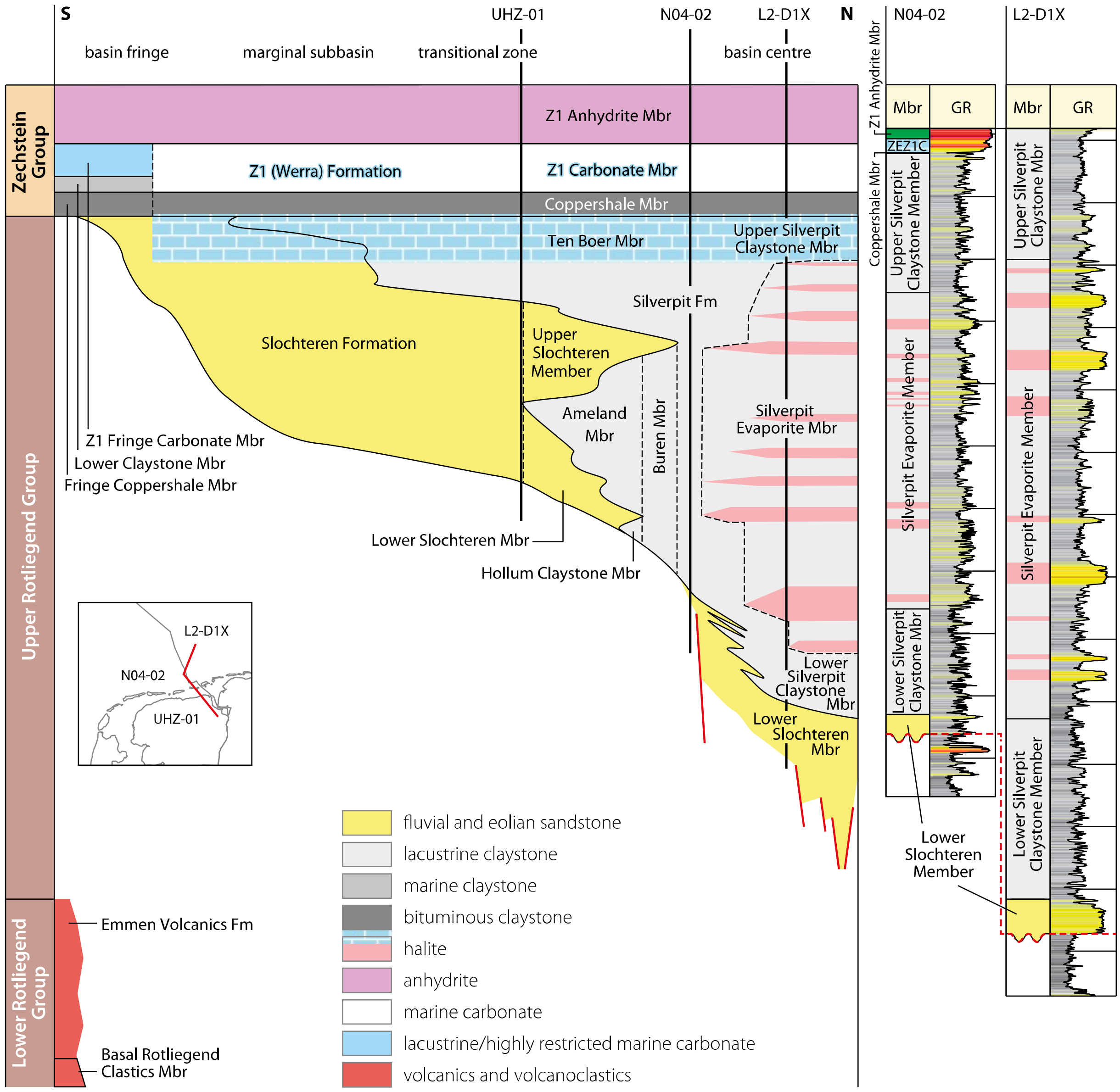


Figure 4.9. Stratigraphic subdivision of the Slochteren and Silverpit formations of the Upper Rotliegend Group in the eastern Dutch offshore and western German offshore. Modified from Doornenbal et al. (2019).

Deposition of the Z1 (*Werra*) Formation started with the Coppershale Member, a 0.5-m-thick, finely laminated claystone with a total organic-carbon content of up to 5% (Lokhorst, 1998), which represents a major marine transgression (Fig. 4.11). It was deposited in most of the Southern Permian Basin and provides an excellent marker horizon. It is found in most of the Netherlands, except for the southern onshore area. In some places (for example, in the Coevorden field) it forms a drape over ancient Carboniferous relief, with the Rotliegend missing. The Werra Formation further comprises claystone, sandstone, carbonate, anhydrite, and salt deposits, organized in several members (Figs 4.12a,b, 4.13b,d). The thickest occurrence, up to 500 m, is located in the eastern part of the Netherlands, in the province of Drenthe, where an anhydrite platform developed. The formation onlaps onto the London-Brabant Massif. In the main basin, the formation has a constant thickness of some 50 m. The N-S orientation of the anhydrite platform in the east, parallel to the occurrence of the Lower Rotliegend volcanics, points to a structural control on the outline of this platform.

The platform and slope deposits of the Z1 Carbonate consist of up to 200 m of marls and carbonates, in contrast to the 8 to 10 m of carbonate in the sediment starved basinal setting (Figs 4.12b, 4.13b). A carbonate platform was also present along the Mid North Sea and Ringkøbing-Fyn High (Taylor, 1998). Small carbonate platforms have been encountered in the southern part of the country and in adjacent parts of Germany (Visser, 1955; Fuchtbauer, 1980). Potassium-magnesium salts in the Z1 occur only in the eastern Netherlands (NITG, 1998). South of the Central Netherlands Basin, the formation is composed mainly of claystones, while in the offshore area, medium to fine-grained fluvial sandstones occur. Local sourcing of fine-grained siliciclastic material may have taken place from the Texel-IJsselmeer High (Van Adrichem Boogaert & Burgers, 1983). The carbonates and anhydrites from the Z1 cycle form important top seals for Rotliegend gas accumulations in the Netherlands (Van Ojik et al., 2021).

The Z2 (*Stassfurt*) Formation comprises a basal carbonate unit, the Z2 Carbonate, followed by the Z2 Basal Anhydrite and Z2 Salt members (Figs 4.11, 4.12c,d, 4.13a,c). In the southern onshore area, the formation is represented by anhydrite bearing claystones, while local sandstones (Z2 Fringe Sandstone Member) occur in the western offshore (Figs 4.11, 4.12c). The formation is less than 50 m thick in the southern Netherlands but locally reaches more than 700 m thick in the northern offshore due to salt movement (see Bouroullec & Ten Veen, 2025, this volume). The southern limit of the Z2 Carbonate (equivalent to the Hauptdolomit Formation in UK) lies considerably further to the north compared to the Z1 Carbonates. Within the Z2 Carbonate, three facies realms can be identified: platform, slope and basin (Figs 4.12d, 4.13a,b, 4.14; Van de Sande et al., 1996; Geluk, 2000; Bouroullec et al., 2022). The basinal deposits comprise 8 to 12 m thick, dark-coloured, bituminous, finely laminated carbonates,

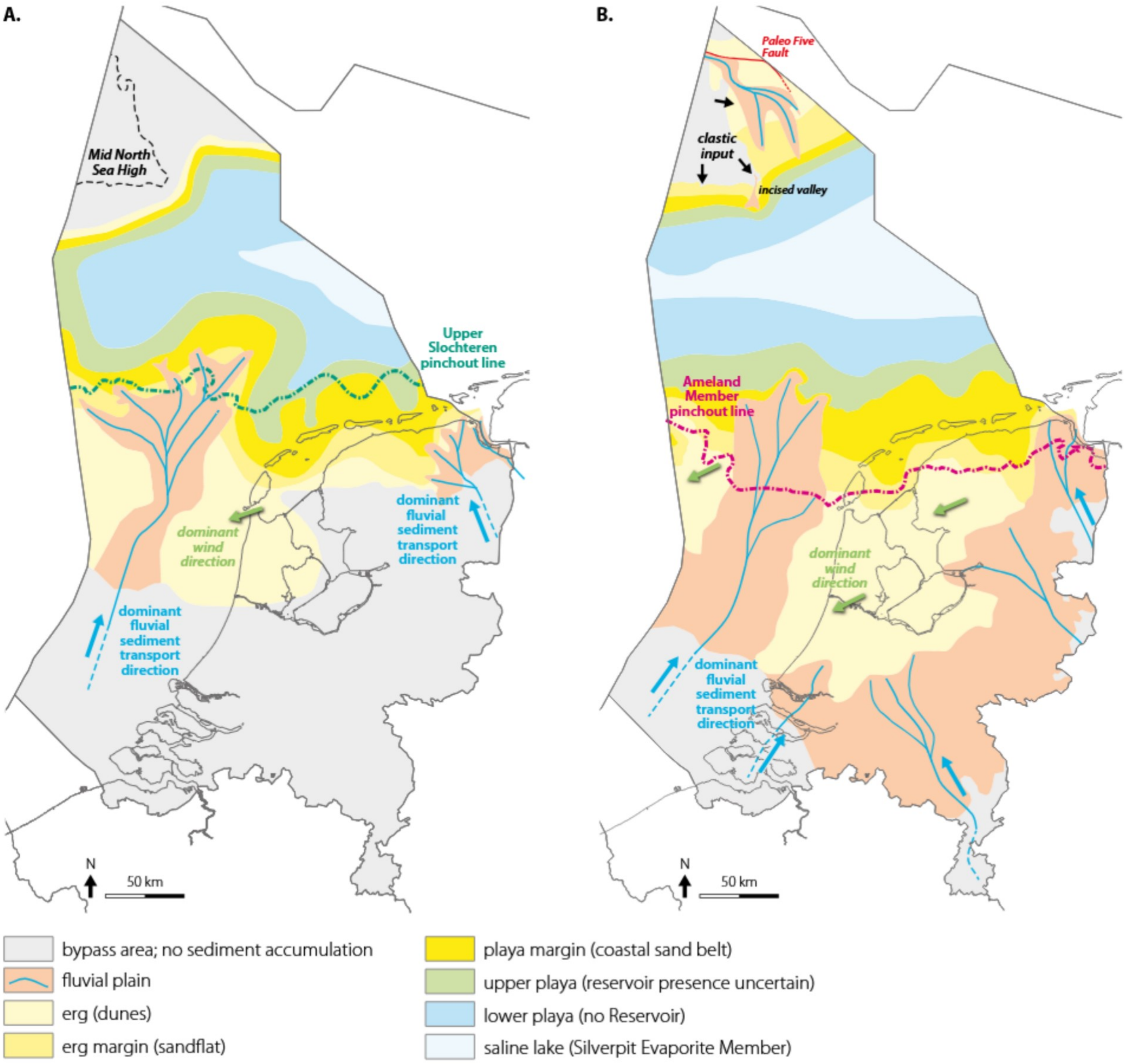


Figure 4.10. Depositional setting of a) the Lower Slochteren Member and b) the Upper Slochteren Member. Modified after Gast et al. (2010), De Bruin et al. (2015), Houben et al. (2020) and Kortekaas et al. (2023).

known as 'Stinkschiefer' (Fig. 4.13c). These rocks have source rock potential, with a total organic-carbon content of up to 1.2% (Lokhorst, 1998). Apart from the basinal deposits, high-TOC carbonates have also been found in slope and lagoonal deposits in Poland (Słowakiewicz & Gąsiewicz, 2013). Bituminous, thicker bedded slope deposits are sometimes referred to as 'Stinkkalk'. In the vicinity of the carbonate platforms slumps and turbidites of displaced shelf deposits have been identified (Amiri-Garroussi & Taylor, 1992; Van de Sande et al., 1996). The slope facies includes light-coloured limestones and dolomites, as well as of platform sediments redeposited by mass flows. In the eastern Netherlands, these facies reach a thickness of over 200 m (Van de Sande et al., 1996). The platform facies comprises a complex of oolitic, pelletoidal, bioclastic and pisolitic pack- and grainstones and finely laminated wackestones (Clark, 1986; Van der Baan, 1990; Strohmenger et al., 1996; Patruno et al., 2018). These reflect a wide range of depositional settings: sabkha, tidal flats, algal shoals, lagoons and ooid bars and shoals (Strohmenger et al., 1996; Patruno et al., 2018). 3D seismic interpretation reveals a complex outline of the platform, including isolated off-platform highs (Van de Sande et al., 1996). The shape of the Z1 Anhydrite platform controlled to a great extent the facies distribution of the Z2 Carbonate. The carbonates grade southward into anhydritic clay-siltstones, and in the eastern Netherlands, rock salt (NITG, 2000). In the eastern Netherlands, the Z2 carbonate platform complex measures some 50 to 70 km in a N-S direction, whereas in the western offshore area this is much less, between 10 and 30 km. Recent mapping of the Z2 carbonate platform in the northern Dutch offshore (Bouroullec et al., 2022) shows several isolated platforms around the Elbow Spit High and in quadrant A, at the northern tip of the Dutch offshore (Fig. 4.14). Some of these platforms show a clear platform-slope-basin geometry. The area between the platforms and the paleo-topographic high formed around the then-exposed core of the Elbow Spit High and consists of lagoonal deposits as described for the core of well A16-01 (Bouroullec et al., 2022).

The topography of the Z2 carbonates controlled the thickness and distribution of the overlying units; the thickest rock salts were deposited in the basinal zones, with only thin salt in platform areas. The depositional thickness of the Z2 Salt is more than 600 m in the basin. It is mainly composed of halite (>95%), within which three stages of deposition can be identified (Geluk, 2000; Geluk et al., 2000). During the first two stages the initial topography persisted, and platform halites graded northward into deeper-water salt complexes (intercalated halite, polyhalite and carnallite), whereas the third stage of salt deposition filled most of the remaining relief of the basin. At the top, a regionally well-developed potassium-magnesium salt unit occurs. Because of the extensive salt movement, the units overlying the Z2 Salt have become strongly deformed too, which complicates the reconstruction of their primary thickness and composition. In addition, salt may have been dissolved. Dissolution of salts is well known from the UK (Glennie, 1998; Patruno et al., 2018; Grant et al., 2019) and has been recognized in the Netherlands as well (Houben et al, 2020). It results in displacement of the overlying section. The dissolution slopes, which indicate the limits of salt removal, may be recognized on seismic.

The Z3 (*Leine*) Formation comprises the Z3 Fringe Sandstone, Z3 Fringe Claystone, Grey Salt Clay, Z3 Carbonate, Z3 Main Anhydrite and Z3 Salt members (Figs 4.11, 4.12e,f). The basal member of the formation, the Grey Salt Clay Member, forms an important regional marker within the Zechstein. Its thickness varies from 5 to 10 m. The facies pattern of the Z3 Carbonate is more complex compared to the Z2 Carbonate (Geluk, 2000; Grant et al., 2019), reflecting the levelling out of the paleo-topography by deposition of the Z2 Salt (Fig. 4.12e). In the basin centre the carbonate comprises a dark-coloured limestone of a few metres thickness only. The slope facies comprise laminated and bioturbated carbonate mudstones and silty dolomites, with a thickness of up to 40 m. The platform facies mainly consist of grey microcrystalline dolomites and algal boundstones. These are considered by Taylor (1998) to represent predominantly shallow, quiet-water, possibly lagoonal deposits. Oolitic and bioclastic grainstones locally occur in the area adjacent to the slope (Van Adrichem Boogaert & Burgers, 1983; Baird, 1993) and on the landward margin of the platform. In the southwestern offshore area, the carbonate grades into fluvial sandstones (Fig. 4.12e; Geluk et al., 1997).

The Z3 Main Anhydrite was deposited only on the northern part of the Z3 carbonate platform and slope and in the basin. The thickness of this anhydrite reaches up to 100 m, showing complex and rapid changes (NITG, 2000). Movement of the underlying Z2 Salt caused the breaking-up of this member into large slabs, known as rafts, floaters, stringers, or allochthons, which became embedded in the salt and may locally present potential drilling hazards by causing drilling fluid losses or influx of high-pressure brines or gas. The Z3 Salt is composed of a basal halite and an upper part comprising two thick potassium-magnesium salt layers. The salts encountered include beds up to 10 m thick of the rare mineral bischofite ($MgCl_2 \cdot 6H_2O$), one of the most soluble salts on earth, and kieserite, carnallite and sylvite which may be commercially exploited (Coelewij et al., 1978; Raith et al., 2017). These salts are present only in the northeastern onshore and northwestern offshore. The thickness of the Z3 Salt reaches 300 to 400 m.

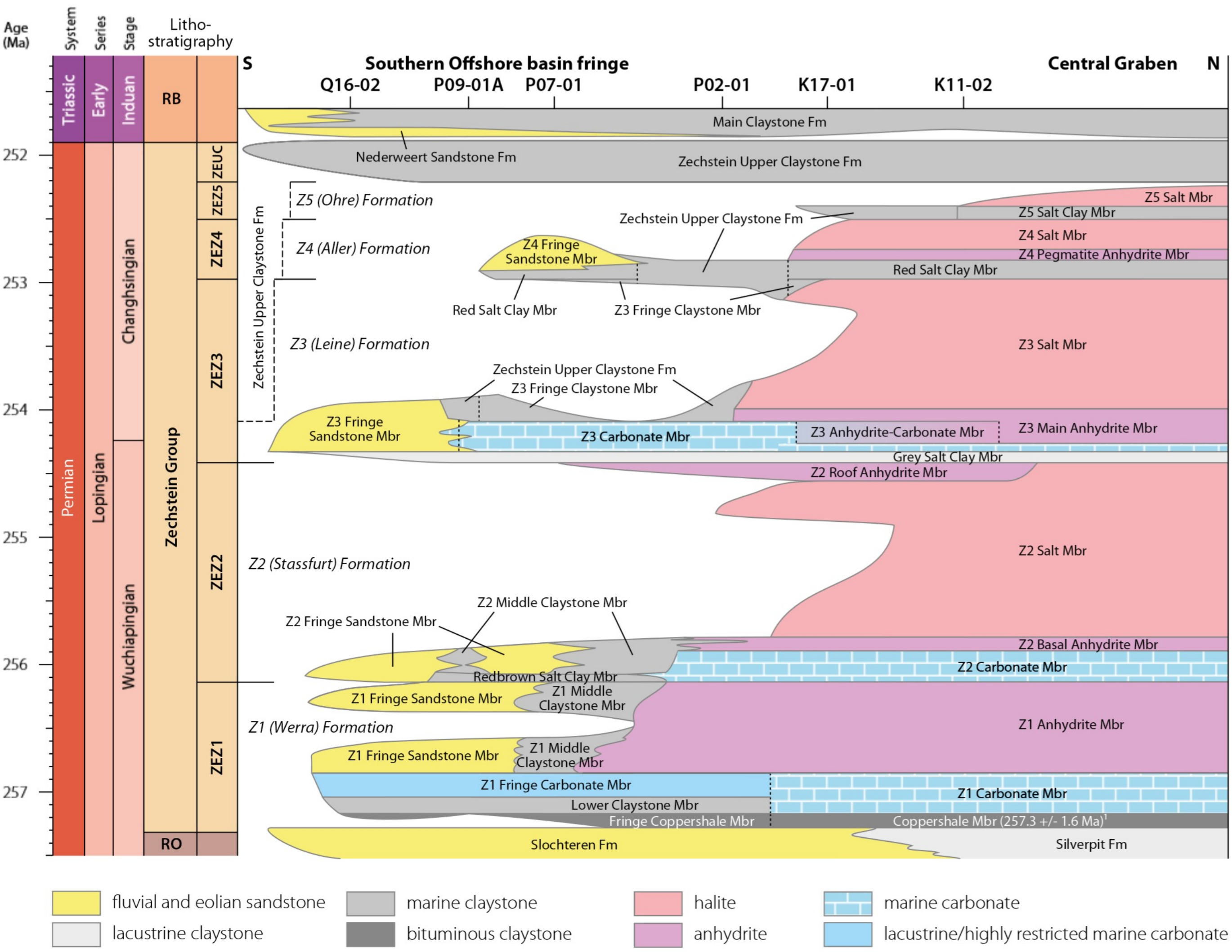


Figure 4.11. *Tectonostratigraphic chart of the Zechstein Group. In the Netherlands, this group consists of five evaporite cycles (Z1-Z5). For location of the wells see Fig. 4.5b. Modified from Van Adrichem Boogaert & Kouwe (1994). 1 = Re-Os isochron age for the Coppershale (Kupferschiefer) (Brauns et al., 2003).*

The Z4 (*Aller*) Formation is composed of the basal claystone of the Red Salt Clay Member and the Z4 Fringe Sandstone Member, followed by the thin Z4 Pegmatite Anhydrite and the Z4 Salt members (Fig. Figs 4.11, 4.12g). The lower two members are laterally extensive, whereas the Z4 Salt is found only in the depocentres or as isolated occurrences in half grabens (Geluk, 1999). The thickness of the salt reaches 150 m. Potassium-magnesium salts occur in the middle part of the salt; its upper part is composed of an alternation of halite and claystone. Along the southern basin margin, the formation comprises anhydritic claystones, deposited in sabkhas, and medium to coarse-grained fluvial sandstones in the southwestern offshore area (Fig. 4.12g). These sandstones are known in the UK as the Hewett Sandstone (Geluk et al., 1996).

The occurrence of the Z5 (*Ohre*) Formation is limited to the northeast of the country and to the northwestern offshore and outlines the depocentres towards the end of Zechstein sedimentation (Fig. 4.11). It comprises a basal claystone with a thickness of several metres followed by up to 15 m of halite. Younger Zechstein salts (Z6 and Z7) have been reported from northwest Germany (Best, 1989), but these are absent in the Netherlands, possibly due to nondeposition.

The Zechstein Upper Claystone Formation occurs throughout the country and accumulated disconformably on older rocks of the Zechstein and Upper Rotliegend Group (Fig. 4.11). Based upon its palynological content, the formation has been included in the Zechstein Group (Van Adrichem Boogaert & Kouwe, 1994). It is composed of red and grey anhydritic claystones and sandstones, deposited in a lacustrine to mudflat setting. Its thickness varies from 10 to 50 m.

Paleogeography

Deposition during the Permian took place north of the Variscan Mountains in the large Southern Permian Basin at paleolatitudes of around 10 to 20°N, comparable to the present-day Sahara. The mountains provided the main source of sediments that were transported northward and also prevented southern humid air masses from the Tethys Ocean from reaching the SPB (Glennie, 1998), resulting in an arid climate in the Netherlands and in neighbouring regions.

Lower Rotliegend Group

In early Permian times there was widespread intrusive igneous activity in the Netherlands (Van Bergen & Sissingh, 2007; De Bruin et al., 2015). During the middle Permian, local extrusive volcanism (Lower Rotliegend Group) occurred at different times in relation to wrenching along deep-seated faults in the Lower Saxony Basin and the Dutch Central Graben (Figs 4.6, 4.7). In the latter, minor amounts of clastic sediments were deposited. This extrusive volcanism is younger than in Germany and Poland, where it already started in late Carboniferous to early Permian times (Plein, 1995; Jakobsen et al., 2020). The

Wind and solar energy in the Permian

The Permian period was a time of great climatic change in the earth's history. During this period, the earth experienced a transition from a warm, wet climate to a much drier, desert-like climate. The main cause was the completion of the assembly of the supercontinent Pangea (see Paleomap reconstruction from Scotese (2014) below) which stretched from the North Pole to the South Pole and was surrounded by the Panthalassa Ocean. The obstruction of equatorial ocean currents and the presence of orogenic belts across nearly the whole western edge of Pangea resulted in rain shadows and persistent dry conditions.

This change in climate had a significant impact on the sedimentary deposits that were laid down during this time. Wind and sun were the most important agents affecting deposition in these vast desert-type environments.

Northeast trade winds prevailed in much of the interior of the continent. They were responsible for the erosion, transportation, and the eventual deposition of much of the sediment of the Permian age.

The sun also played a major factor in sedimentation during the Permian. Rotliegend sediments already witnessed periodic drying up and evaporation of shallow lakes as shown by the numerous mud cracks, anhydrites, and halite deposits. The evaporitic nature of the supercontinent became even more pronounced during deposition of the Zechstein evaporites, carbonates and siliciclastics.

Both wind and sun played major roles during the Permian and were instrumental in the creation of a very good reservoir, the Slochteren Sandstone and a world-class seal, the Zechstein evaporites. Today, the Netherlands are moving away from fossil fuels and toward a largely wind- and sun-powered energy supply system, bringing back in the forefront those agents that made the Dutch Permian geology what it is.

pulses are thought to have accompanied the opening of the Horn and the Central North Sea grabens (Glennie, 1997; Stemmerik et al., 2000). Prior to the deposition of the sediments of the Upper Rotliegend Group, erosion resulted in highly differentiated and locally deep truncation of the Carboniferous. The paleo-relief was not completely levelled out (Van der Baan, 1990; Van de Sande et al., 1996; De Bruin et al., 2015) and differential weathering and faulting were responsible for local relief of up to 45 m (Geluk & Mijnlieff, 2001; De Bruin et al., 2015). In the northeast of the country, the area of middle Permian volcanic activity still retained a positive relief and became covered only by the Zechstein transgression or, locally, by sediments belonging to the youngest part of the Upper Rotliegend Group (NITG, 2000).

Upper Rotliegend Group

Accumulation of sediments of the Upper Rotliegend Group started in Poland and northeast Germany during the early Permian (Upper Rotliegend I; Plein, 1995), expanded with time and reached the northern offshore of the Netherlands in the middle Permian (Fig. 4.10). Deposition did not keep pace with basin subsidence, resulting in a large inland depression lying below sea level (Glennie & Buller, 1983). In the central part of this area, a large playa lake developed where claystones and rock salt were deposited (Fig. 4.3). The bordering systems were formed by wadis with episodic run-off. With prevailing northeast trade winds, sand was deflated from fluvial deposits during dry periods and accumulated down-wind as dunes or, close to the playa lake, as damp sand flats (Glennie, 1998). In the Netherlands, sediments were supplied mainly from the southeast, where the Variscan Mountain belt was being eroded. Large amounts of sand and clay were transported northward by dryland river systems, with sands deposited in proximal settings in the south of the Netherlands and clay deposited in the distal settings in the central part of the SPB. A narrower and thinner sandy system also developed in the northern part of the Dutch offshore where Devonian and Carboniferous strata subcrop along Elbow Spit High and neighbouring paleo-highs in the UK. The Elbow Spit High likely was a sediment source and was drained southward, and possibly eastward, by ephemeral fluvial systems. The thickest Rotliegend sandstone in the Dutch offshore, >350 m, has been found in the P05 to Q04 areas. Further north, the eolian dune belt grades into playa deposits consisting of sandflats with increasing amounts of intercalated clay (Van Ojik et al., 2021).

The climate during deposition of the Upper Rotliegend Group was characterized by an alternation of wet and dry periods possibly influenced by Milankovitch cycles (Yang & Baumfalk, 1994; Howell & Mountney, 1997; Van den Belt & Van Hulten, 2011; De Jong et al., 2020). This cyclicity resulted in a periodic expansion and retreat of the lacustrine facies belts, and a complex alternation of fluvial and eolian deposits at the margins of the lake.

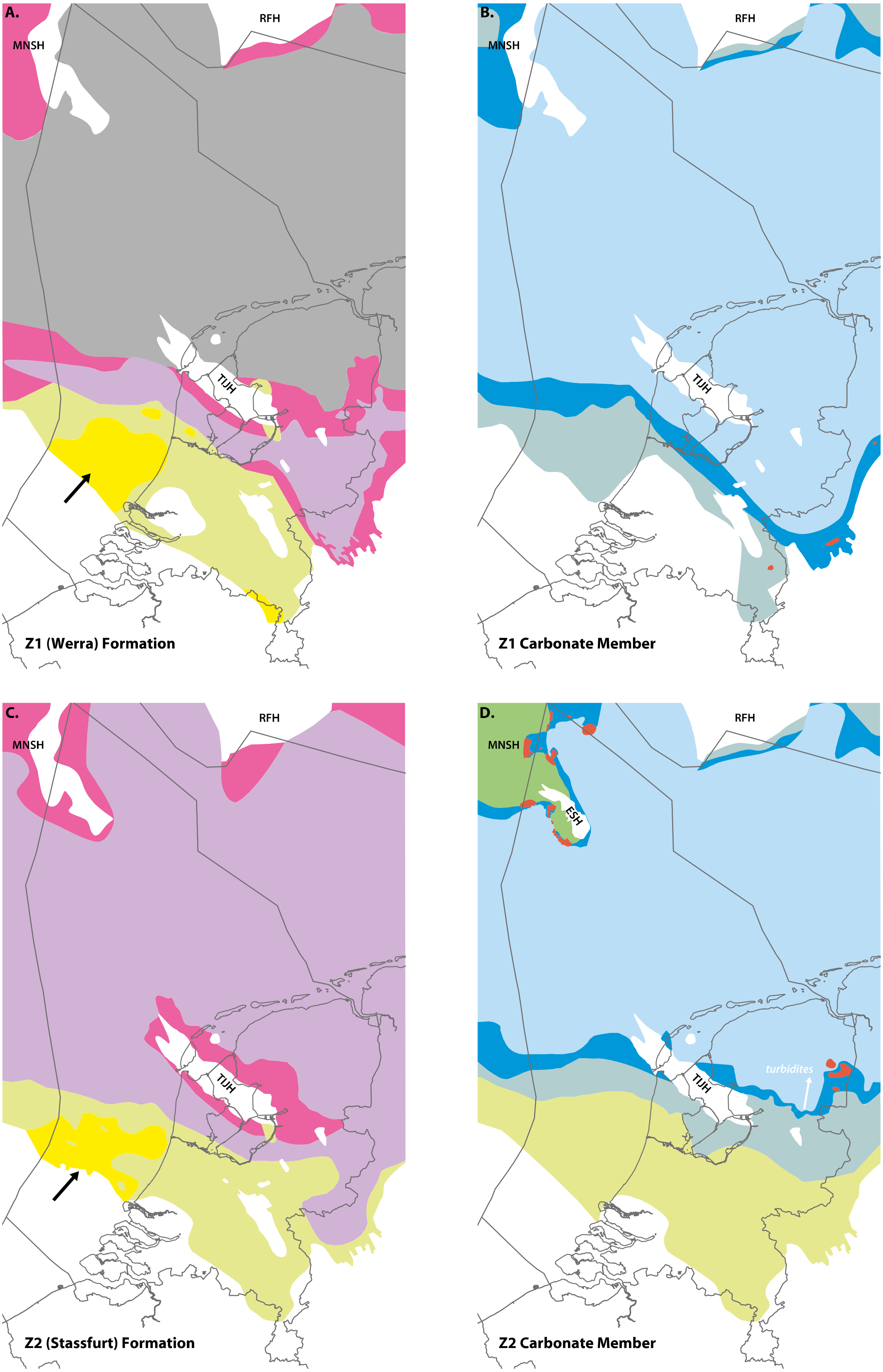
Zechstein Group

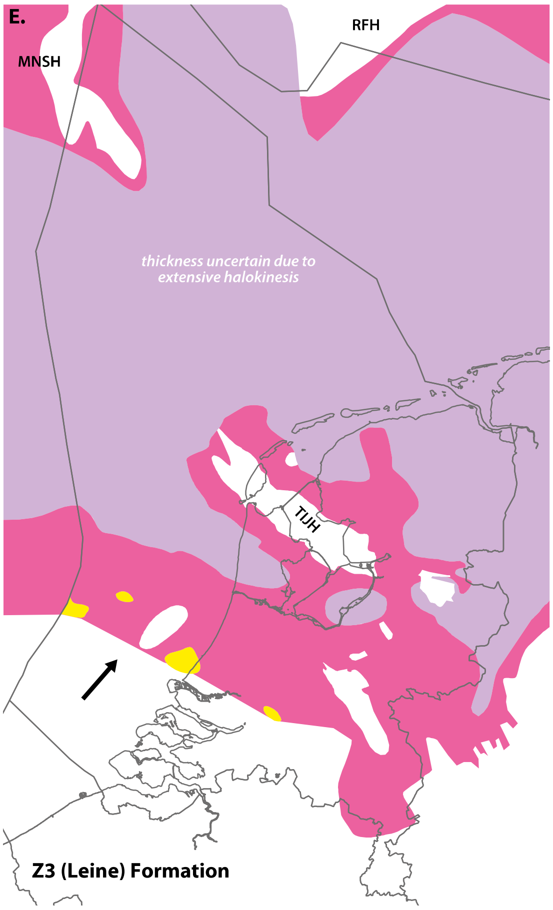
The claystone of the Ten Boer Member of the Upper Rotliegend Group represents an important transgressive phase, as well as a transitional phase to the overlying marine Zechstein transgression. The sudden marine transgression resulted in flooding and widespread reworking and redeposition of dune sands during the late Permian (Weissliegend facies of Glennie & Buller, 1983).

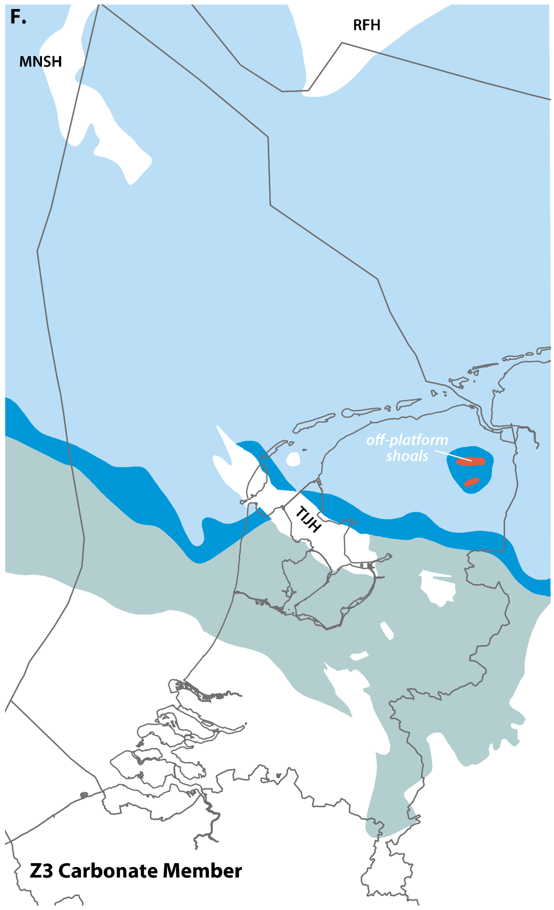
Under the prevailing dry climate, widespread cyclic deposition of evaporites took place. The controlling mechanism behind the cyclicity is thought to have been glacio-eustatic (Ziegler, 1990). Five Zechstein cycles have been identified in the Netherlands (Figs 4.11, 4.12), the bases of which are marked by transgressions. In the early cycles (Z1 to Z3), normal-marine conditions were established throughout the Southern Permian Basin, connected to the north to the Barents Sea region (Ziegler, 1990). Clastic influx was pushed back to the basin margins (Geluk et al., 1996) and carbonates were laid down as a series of prograding and aggrading sigmoidal shaped bodies, in which the facies belts and the area of maximum thickness shifted with time towards the north (Grant et al., 2019). During later cycles (Z4 and Z5) no carbonates were deposited as the conditions were permanently hypersaline.

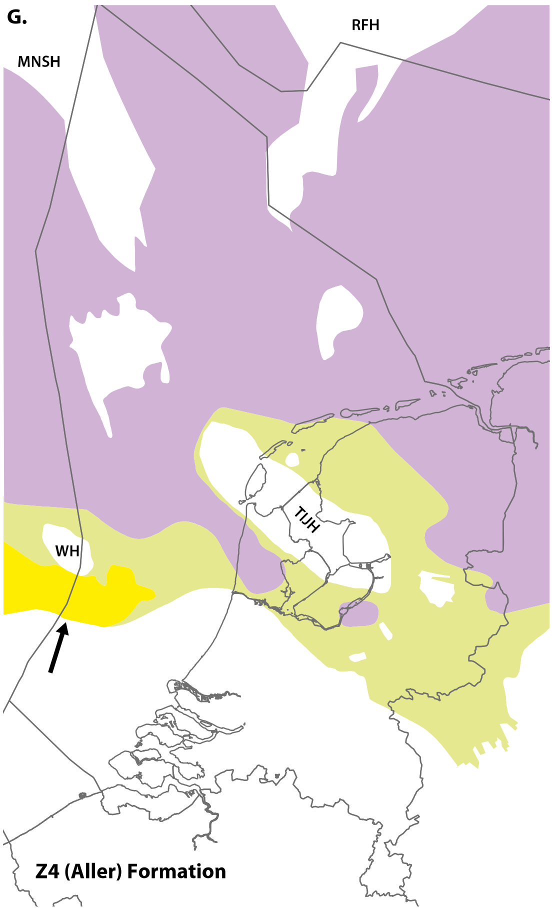
Following the initial transgression, a starved basin up to 200 m below the paleo sea level formed. Marine deposition started with the anoxic sediments of the Coppershale Member (Sweeney et al., 1987), but at a later stage, normal-marine oxic conditions were established in the basin. The combination of an inclined basin topography, minor faulting and sea-level rise led to the establishment of locally small carbonate platforms over the southern onshore and western offshore areas (Van de Sande et al., 1996; Figs 4.12, 4.14). Around the London-Brabant Massif, extensive mudflats and sabkhas developed, whereas in the western offshore sands were deposited under fluvial to estuarine conditions. The geometry of the carbonate deposits in the western offshore suggests a relief of up to 200 m. After this transgression, the sea level fell, the connection with the Barents Sea became restricted and evaporites were deposited. A large anhydrite platform developed at the basin-ward side of this carbonate platform. In the shallow, warm water, anhydrite accumulated rapidly, in contrast to slow precipitation in the basin area north of the platform (Van der Baan, 1990).

The second Zechstein transgression did not reach as far south as the Z1 transgression (Fig. 4.12a,c). However, an extensive carbonate platform developed, with oolite shoals and lagoons (Van der Baan, 1990; Strohmenger et


A.
MNSH
RFH
TIJH
Z1 (Werra) Formation
B.
MNSH
RFH
TIJH
Z1 Carbonate Member
C.
MNSH
RFH
TIJH
Z2 (Stassfurt) Formation
D.
MNSH
RFH
ESH
TIJH
turbidites
Z2 Carbonate Member







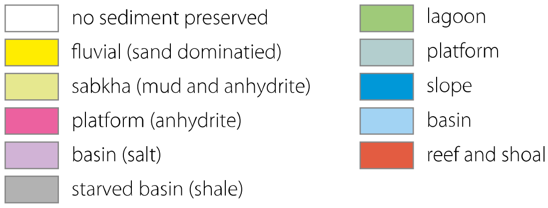


Figure 4.12. Facies (a, c, e and g) and paleogeographic (b, d and f) maps of the Zechstein Group. a) The Z1 (Werra) Formation. Sands were shed into the basin in the western offshore (arrow). In the main basin a condensed succession of carbonates and evaporites was deposited. b) The Z1 Carbonate Member. Carbonate platforms fringed the basin both to the north and to the south. c) The Z2 (Stassfurt) Formation. A thick succession of rock salt was deposited in the centre of the SPB. d) The Z2 Carbonate Member. Well-developed platform facies are deposited in the eastern and northern part of the Netherlands. The carbonate platforms, reefs, shoals, slopes and lagoons located around and above the Elbow Spit High are from Bouroullec et al. (2022) and Peeters et al. (2023). e) The Z3 (Leine) Formation records widespread transgression, with carbonate development extending towards the margins of the basin. f) The Z3 Carbonate Member. This member has the greatest southward extension of all Zechstein carbonates and is characterized by a simpler, ramp-type development than the Z2 Carbonate. g) The Z4 (Aller) Formation is represented by thin sabkha-mudflat deposits. ESH = Elbow Spit High; MNSH = Mid North Sea High; RFH: Ringkøbing-Fyn High; TIJH: Texel-IJsselmeer High; WH: Winterton High. Modified from Geluk (2007), TNO-GDN (2022), Van Ojik et al. (2021) and Bouroullec et al. (2022).

al., 1996; Van de Sande et al., 1996; Geluk, 2000; Fig. 4.12c, d). To the south, this platform graded into a complex of fluvial sandstones, mudflats, sabkhas and salt ponds (NITG, 1998). Lowering of the sea level resulted in widespread evaporite sedimentation and the basin was filled with up to 600 m of halite. The salt deposition was multicyclic, triggered by minor transgressions that caused salinity fluctuations (Geluk, 1995).

The third transgression records the last normal-marine salinities in the basin. This transgression reached much further southward than the previous ones and pushed fluvial deposits back as far as the basin margin (Fig. 14e, f). Less facies variation is seen within the carbonate deposits, as the relief in the basin was largely deflated to a maximum several tens of metres. A carbonate-anhydrite platform occupied most of the area on and around the Texel-IJsselmeer High, while carbonates dominated the southern Netherlands (Fig. 4.12f). Up to 10 m thick beds of bischofite and potassium-magnesium salts in the Z3 Salt indicate that partial desiccation occurred in the northeast of the country. Such thick beds likely required repeated influx of water to form in conjunction with basin-axis increase in accommodation space due to differential compaction of the Silverpit claystones.

From the fourth transgression onwards, conditions in the basin became permanently hypersaline (Ziegler, 1990). Claystones were deposited in hypersaline shallow water environments (Fig. 4.12g), but thick, massive halites and potassium-magnesium salts located in the lower part of the Z4 (Aller) Formation were probably still deposited in a marine environment. In the upper part of the formation, the alternation of saliferous claystone and thin halite indicates a gradual change to playa-type conditions. The brines, however, were still of marine origin. Deposition

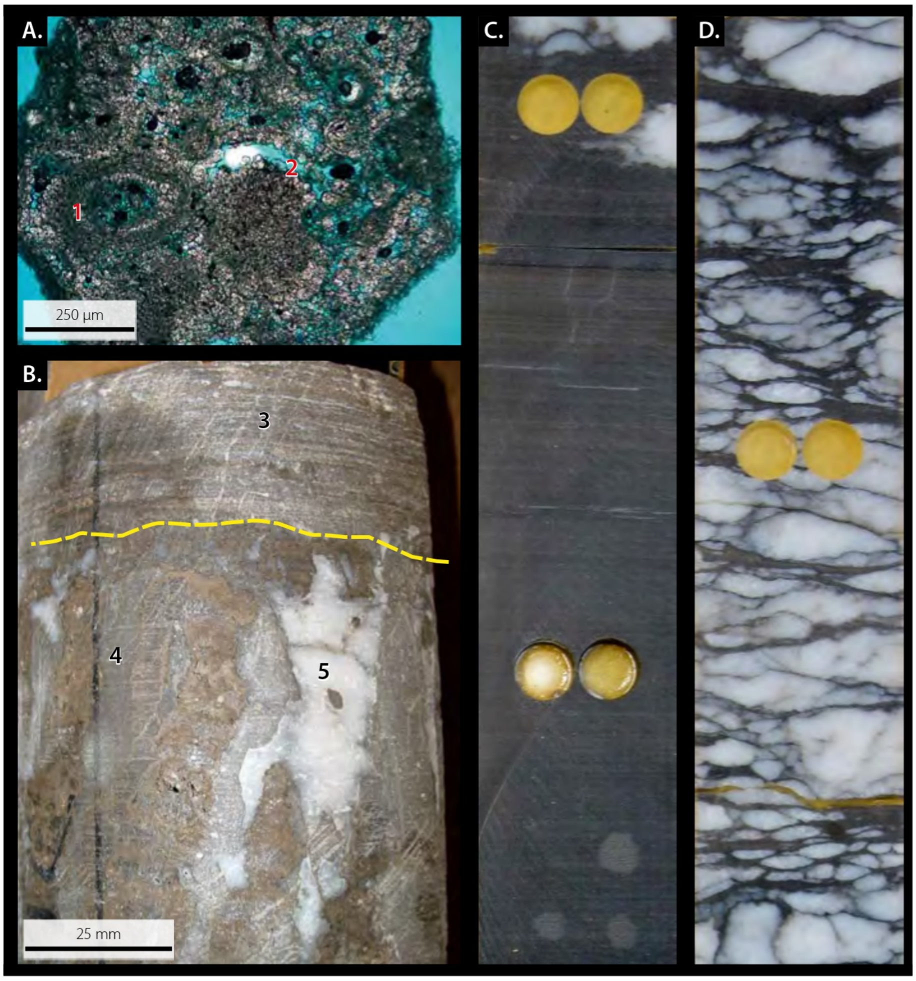


Figure 4.13. *Examples of Zechstein facies as seen in cores and cuttings. a) High-energy oolite facies in ZEZ2C. Thin section of a cutting from well E02-02, 2105 m. 1 = dolomitized oolites; 2 = mouldic porosity caused by partial dissolution of oolites. Microphotograph: Bouroullec et al. (2021). b) Karstified contact (yellow dashed line) between shallow marine carbonates of ZEZ1A. 3 = ZEZ2 carbonate; 4 = large dissolution hole with anhydrite (5). Well E16-03, 3304 m. c) Bituminous, laminated, fine-grained carbonate, known as 'Stinkschiefer', with occasional anhydrite nodules. ZEZ2C, slabbed core from well D15-02, 3212 m. d) Chicken-wire anhydrite of ZEZ1A in a slabbed core from well D15-02, 3213 m.*

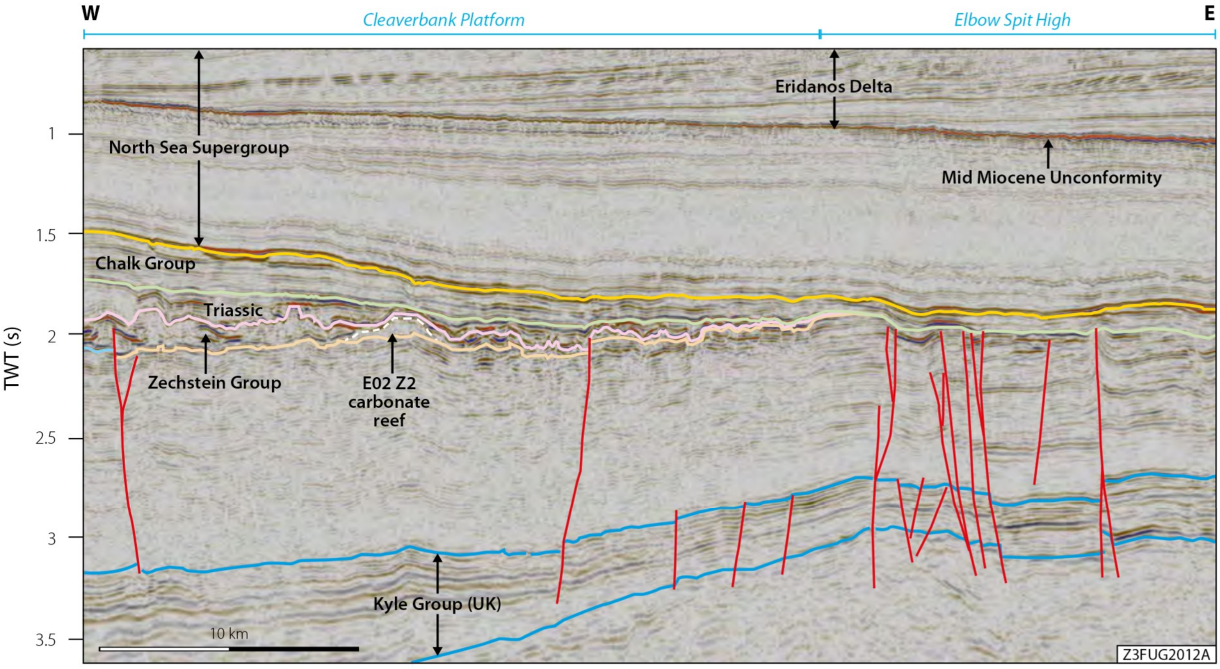


Figure 4.14. Interpreted seismic time section in the northwestern offshore. The Zechstein Group thins to the east and is absent on the Elbow Spit High. A Z2 carbonate platform, referred to as the E02 Z2 carbonate reef, can be readily identified. The platform is part of a series of carbonate platforms located around the Elbow Spit High (see Fig. 4.12d). Modified from Bouroullec et al. (2022). See Fig. 4.5b for location of the seismic line.

was governed by higher-order Milankovitch cycles, with halites representing the dry, and claystones the wet periods (Wagner, 1994; Geluk et al., 1997). The Z5 (Ohre) Formation was likewise deposited under playa conditions.
The higher Zechstein cycles Z6 and Z7, described by Best (1989) from northwest Germany, were not deposited in the Netherlands. Simultaneous with the deposition of these higher cycles, uplift and erosion affected the Netherlands, in some areas even removing the entire Zechstein (Geluk, 1999). The Zechstein Upper Claystone Formation represents a widespread development of sand- and mudflats throughout the Southern Permian Basin (Geluk et al., 1997), and represents the gradual change to continental depositional conditions in the Triassic (McKie & Kilhams, 2025, this volume).

The Permian System constitutes a major reset of the geological evolution in the Netherlands with major climatic, structural and sea level changes occurring in a relatively short amount of time (45 Myr). The occurrence of both the clastic sediments of the Rotliegend groups and the thick and mobile evaporites of the Zechstein Group has made this stratigraphic interval a major focus of research and exploration in the Netherlands and neighbouring countries since the 1950s. The combination of extensive high-quality reservoirs of the Slochteren Formation, the presence of the underlying Westphalian source rocks and the sealing capacity of the Zechstein salt units made the Rotliegend a prime and successful target for hydrocarbon exploration. Today the Permian is still the focus of research and exploration for CCS, geothermal, and hydrogen storage purposes. Many depleted Rotliegend gas fields could have a second life as a permanent storage for CO_2, but saline formation storage could also open some promising avenues for CCS in the Netherlands. The eolian facies of the Upper Rotliegend are also very attractive for geothermal exploration thanks to their high transmissivity. Underexplored areas in the Netherlands, especially where oil and gas plays were unsuccessful due to a lack of source rocks or seal, may soon become attractive for geothermal exploration and hence a new wave of seismic acquisition and exploration wells is being undertaken to fill the remaining knowledge gaps in the subsurface. Finally, Zechstein salt is also seen as a primary target for future hydrogen storage sites, both onshore and offshore within existing or to be developed salt caverns.

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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.28163231.

References

Amiri-Garroussi, K. & Taylor, J.C.M., 1992. Displaced carbonates in the Zechstein of the UK North Sea. Marine and Petroleum Geology 9: 186-196. DOI: 10.1016/0264-8172(92)90090-2

Arthaud, F. & Matte, P., 1977. Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. Geological Society of America Bulletin 88: 1305-1320. DOI: 10.1130/0016-7606(1977)88<1305:LPSFIS>2.0.CO;2

Baird, A., 1993. An assessment of the reservoir potential of the Zechstein of the P and Q Quadrants and adjacent onshore areas, the Netherlands. Stratigraphic Services International Limited (Surrey) open-file report: 44 pp.

Best, G., 1989. Die Grenze Zechstein/Buntsandstein in Nordwest-Deutschland nach Bohrlochmessungen. Zeitschrift der Deutschen Geologischen Gesellschaft 140: 73-85. DOI: 10.1127/zdgg/140/1989/73

Bouroullec, R. & Ten Veen, J.H., 2025. Salt Tectonics. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 457-491. DOI: 10.5117/9789463728362_ch12

Bouroullec, R., Peeters. S., Geel, K., De Haan, H. & Garland, J., 2021. Project ZEPHYR: Hauptdolomite distribution around the Elbow Spit High, seismic mapping. Joint TNO-Cambridge Carbonates Ltd.-EBN report, EBN Kennisbank. https://www.ebn.nl/feiten-en-cijfers/kennisbank/

Bouroullec, R., Kortekaas, M., Brussée, M., Geel, C.R., Den Hartog Jager, D.G. & Peeters, S., 2022. Play 6 Zechstein. https://www.geodeatlas.nl/pages/play-6-zechstein

Brauns, C.M., Pätzold, T. & Haack, U., 2003. A Re-Os study bearing on the age of the Kupferschiefer mineralization at Sangerhausen. XVth International Congress of Carboniferous and Permian Stratigraphy, Utrecht, Abstracts: 66.

Catto, R., Taggart, S. & Poole, G., 2017. Petroleum geology of the Cygnus gas field, UK North Sea: from discovery to development. In: Bowman, M. & Levell, B. (eds): Petroleum Geology of NW Europe: 50 Years of Learning. Geological Society, London, Petroleum Conference Series 8: 307-318. DOI: 10.1144/PGC8.39

Clark, D.N., 1986. The distribution of porosity in Zechstein carbonates. In: Brooks, J., Goff, J.C. & Van Hoorn, B. (eds): Habitat of Palaeozoic gas in N.W. Europe. Geological Society of London, Special Publications 23: 121-149. DOI: 10.1144/GSL.SP.1986.023.01.09

Coelewij, P.A.J., Haug, G.M.W. & Van Kuyk, H., 1978. Magnesium-salt exploration in the northeastern Netherlands. Geologie en Mijnbouw 57: 487-502.

Corcoran, J. & Lunn, S.F., 2014. Old play, new prospectivity - the revival of the Basal Rotliegend Play, offshore Netherlands and Germany. 76th EAGE Conference and Exhibition 2014, 1-5. DOI: 10.3997/2214-4609.20140742

De Bruin, G., Bouroullec, R., Geel, K., Abdul Fattah, R., Van Hoof, T., Pluymaekers, M., Van der Belt, F., Vandeweijer, V.P. & Zijp, M., 2015. New petroleum plays in the Dutch northern offshore. TNO (Utrecht), Report No. 2015 R10920. https://www.nlog.nl/sites/default/files/2018-11/NORTHERN_OFFSHORE_TNO_report_2015_R10920_0.pdf

De Craen, M. & Swennen, R., 1992. Sedimentology and diagenesis of the ankeritized basal Zechstein conglomerate in the Campine Basin (Bree borehole, NE Belgium). Geologie en Mijnbouw 71: 145-160.

De Jager, J. & Geluk, M.C., 2007. Petroleum geology. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW, Amsterdam): 241-264.

De Jong, M.G.G., Donselaar, M.E., Boerboom, H.T.W., Van Toorenenburg, K.A., Weltje, G.J. & Van Borren, L., 2020. Long-range, high-resolution stratigraphic correlation of Rotliegend fluvial-fan deposits in the central Dutch offshore. Marine and Petroleum Geology 119: 104482. DOI: 10.1016/j.marpetgeo.2020.104482

Donselaar, M.E., Overeem, I., Reichwein, J.H.C. & Visser, C.A., 2011. Mapping of fluvial fairways in the Ten Boer Member, Southern Permian Basin. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98, 105-118. DOI: 0.2110/pec.11.98.0105

Fryberger, S.G., Knight, R., Hern, C., Moscariello, A. & Kabel, S., 2011. Rotliegend facies, sedimentary provinces, and stratigraphy, Southern Permian Basin UK and the Netherlands: A review with new observations. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98, 51-88. DOI: 10.2110/pec.11.98.0051

Fuchtbauer, H., 1980. Composition and diagenesis of a stromatolitic bryozoan bioherm in the Zechstein 1 (northwestern Germany). In: Fuchtbauer, H. & Peryt, T. (eds): The Zechstein basin with emphasis on carbonate sequences. Contributions to Sedimentology 9. 233-251.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. AAPG Bulletin 73: 125-142. DOI: 10.1306/703C9AF5-1707-11D7-8645000102C1865D

Gast, R.E., 1988. Rifting im Rotliegenden Niedersachsens. Die

Geowissenschaften 6: 115-122.
Gast, R.E., Dusar, M., Breitkreuz, C., Gaupp, R., Schneider, J.W., Stemmerik, L., Geluk, M.C., Geißler, M., Kiersnowski, H., Glennie, K.W., Kabel, S. & Jones, N.S., 2010. Rotliegend. In: Doornenbal, J.C. & Stevenson, A.G. (eds): Petroleum geological atlas of the Southern Permian Basin area. EAGE Publications b.v. (Houten): 101-121.
Gaupp, R. & Okkerman, J.A., 2011. Diagenesis and reservoir quality of Rotliegend sandstones in the northern Netherlands - A review. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98: 193-226. DOI: 10.2110/pec.11.98.0193
Gaupp, R., Matter, A., Platt, J., Ramseyer, K. & Walzebuck, J., 1993. Diagenesis and fluid evolution of deeply buried Permian (Rotliegendes) gas reservoirs, Northwest Germany. American Association of Petroleum Geologists Bulletin 77: 1111-1128. DOI: 10.1306/BDFF8E0C-1718-11D7-8645000102C1865D
Geluk, M., 1995. Stratigraphische Gliederung der Z2-(Staßfurt-) Salzfolge in den Niederlanden: Beschreibung und Anwendung bei der Interpretation von halokinetisch gestörten Sequenzen. Zeitschrift der Deutschen Geologischen Gesellschaft 146: 458-465. DOI: 10.1127/zdgg/146/1995/458
Geluk, M., 1999. Late Permian (Zechstein) rifting in the Netherlands: models and implications for petroleum geology. Petroleum Geoscience 5: 189-199. DOI: 10.1144/petgeo.5.2.189
Geluk, M.C., 2000. Late Permian (Zechstein) carbonate-facies maps, the Netherlands. Netherlands Journal of Geosciences 79 (1): 17-27. DOI: 10.1017/S0016774600021545
Geluk, M.C., 2005. Stratigraphy and tectonics of Permo-Triassic basins in the Netherland and surrounding areas. PhD thesis Utrecht University (the Netherlands): 171 pp.
Geluk, M.C., 2007. Permian. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW, Amsterdam): 63-84.
Geluk, M.C. & Mijnlieff, H., 2001. Controls on the distribution and thickness of Permian basal Upper Rotliegend sandstones, the Netherlands - probing the limits of the Rotliegend play area. 63rd EAGE Conference and Exhibition (Amsterdam). EAGE (Houten): 522. DOI: 10.3997/2214-4609-pdb.15.P522
Geluk, M.C., Bruckner-Röhling, S. & Röhling, H.G., 2000. Salt occurrences in the Netherlands and Germany: New insights in the formation of salt basins. In: Geertman, R. (ed.): Salt 2000, Proceedings of the 8th World Salt Symposium (The Hague). Elsevier (Amsterdam): 125-130.
Geluk, M.C., Plomp, A. & Van Doorn, T.H.M., 1996. Development of the Permo-Triassic succession in the basin fringe area, southern Netherlands. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands. Kluwer Academic Publishers (Dordrecht): 57-78. DOI: 10.1007/978-94-009-0121-6_7
Geluk, M.C., Van Wees, J.-D., Grönloh, H. & Van Adrichem Boogaert, H.A., 1997. Palaeogeography and palaeotectonics of the Zechstein Group (Upper Permian) in the Netherlands. In: Proceedings of the XIII International Congress on the Carboniferous and Permian (Krakow, Poland). Polish Geological Institute (Warsaw) 157(2) 63-7363-75.
George, G.T. & Berry, J.K., 1994. A new palaeogeographic and depositional model for the Upper Rotliegend, offshore The Netherlands. First Break 12: 147-158. DOI: 10.3997/1365-2397.1994012
Glennie, K.W., 1997. Recent advances in understanding the southern North Sea Basin: a summary. In: K. Ziegler, P. Turner & S.R. Daines (eds): Petroleum Geology of the Southern North Sea: Future Potential. Geological Society (London): 17-29. DOI: 10.1144/GSL.SP.1997.123.01.03
Glennie, K.W., 1998. Lower Permian - Rotliegend. In: Glennie, K.W. (ed.): Petroleum geology of the North Sea - Basic concepts and recent advances. Blackwell Scientific Publishing (Oxford): 137-173. DOI: 10.1002/9781444313413.ch5
Glennie, K.W. & Buller, A.T., 1983. The Permian Weissliegend of NW Europe: the partial deformation of aeolian dune sands caused by the Zechstein transgression. Sedimentary Geology 35: 43-81. DOI: 10.1016/0037-0738(83)90069-6
Grant, R.J., Underhill, J.R., Hernández-Casado, J., Barker, S.M. & Jamieson, R.J., 2019. Upper Permian Zechstein Supergroup carbonate-evaporite platform palaeomorphology in the UK Southern North Sea. Marine and Petroleum Geology 100: 484-518. DOI: 10.1016/j.marpetgeo.2017.11.029
Groenenberg, R., Den Hartogh, M. & Fokker, P., 2025. Salt Production. In: Ten Veen, J.H. Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 603-625. DOI: 10.5117/9789463728362_ch16
Heeremans, M., Timmerman, M.J., Kirstein, L.A. & Faleide, J.I., 2004. New constraints on the timing of late Carboniferous - early Permian volcanism in the central North Sea. In: Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M. & Larsen, B.T. (eds): Permo-Carboniferous magmatism and rifting in Europe 223: 177-194. DOI: 10.1144/GSL.SP.2004.223.01.08
Houben, S, Bouroullec, R., De Haan, H., Geel, K., Ventra, D., Janssen, N., Verreussel, R., Peeters, S., Veenstra, F., Monaghan, A., Kearsey, T., Wakefield, O., Vane, C., Hennissen, J., Barron, H. & Stewart, B. , 2020. Paleo-Five Project: Paleozoic petroleum potential of the five countries area, Southern-Central North Sea. TNO (Utrecht), Report No. 2020 R10231: 358 pp.
Hounslow, M.W. & Balabanov, Y.P., 2018. A geomagnetic polarity timescale for the Permian, calibrated to stage boundaries. In: Lucas, S.G. & Shen, S.Z. (eds): The Permian timescale. Geological Society of London, Special Publications 450: 61-103. DOI: 10.1144/SP450.8
Howell, J. & Mountney, N., 1997. Climatic cyclicity and accommodation space in arid to semi-arid depositional systems: an example from the Rotliegend Group of the UK southern North Sea. In: Ziegler, K., Turner, P. & Daines, S.R. (eds): Petroleum geology of the southern North Sea: future potential. Geolog-

ical Society of London, Special Publication 123: 63-86. DOI: 10.1144/GSL.SP.1997.123.01.05

Huis in 't Veld, R. & Den Hartog Jager, D., 2025. Late Carboniferous. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 95-125 DOI: 10.5117/9789463728362_ch03

Intergeos, 1989, Buntsandstein of the Netherlands offshore. International Geoservices B.V. report EP890020 (Leiderdorp): 80 pp.

Jakobsen, F., Britze, P., Thöle, H., Jähne-Klingberg, F., Doornenbal, H. & Vis, G.-J., 2020. Harmonized stratigraphic chart for the North Sea area NL-DE-DK. GeoERA report D3: 330 pp.

Johnson, H., Warrington, G. & Stoker, S.J., 1994. Permian and Triassic of the Southern North Sea. In: Knox, R.W.O'B. & Cordey, W.G. (eds): Lithostratigraphic nomenclature of the UK North Sea. British Geological Survey (Nottingham): 141 pp.

Juez-Larré, J., Groenenberg, R., Dinkelman, D., Huijskes, T., Koornneef, J.M., Van Gessel, S.F. & Bos, C.F.M., 2025. Underground storage. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 729-767. DOI: 10.5117/9789463728362_ch20

Kombrink, H., Besly, B.M., Collinson, J.D., Den Hartog Jager, D.G., Drozdzewski, G., Dusar, M., Hoth, P., Pagnier, H.J.M., Stemmerik, L., Waksmundzka, M.I. & Wrede, V., 2010. Carboniferous. In: Doornenbal, J.C. & Stevenson, A.G. (eds): Petroleum geological atlas of the Southern Permian Basin area. EAGE Publications b.v. (Houten): 80-99.

Kortekaas, M., Bouroullec, R., Peeters, S., Van Unen, M., Swart, M., Den Hartog Jager, D., Wiarda, E., Nolten, M. & Beintema, K., 2023. Play 7 Rotliegend. geodeatlas.nl/pages/play-7-rotliegend

Legler, B. & Schneider, J.W., 2008. Marine ingressions into the Middle/Late Permian saline lake of the Southern Permian Basin (Rotliegend, Northern Germany) possibly linked to sea-level highstands in the Arctic rift system. Palaeogeography, Palaeoclimatology, Palaeoecology 267: 102-114. DOI: 10.1016/j.palaeo.2008.06.009

Lokhorst, A. (ed.), 1997. NW European Gas Atlas. Netherlands Institute of Applied Geosciences TNO (NITG-TNO, Haarlem): 154 pp.

Lützner, H., Tichomirowa, M., Käßner, A. & Gaupp, R., 2021. Latest Carboniferous to early Permian volcano stratigraphic evolution in Central Europe: U–Pb CA–ID–TIMS ages of volcanic rocks in the Thuringian Forest Basin (Germany). International Journal of Earth Sciences 110: 377-398. DOI: 10.1007/s00531-020-01957-y

Martin, C.A.L., Stewart, S.A. & Doubleday, P.A., 2002. Upper Carboniferous and Lower Permian tectonostratigraphy on the southern margin of the central North Sea. Journal of the Geological Society 159: 731-749. DOI: doi.org/10.1144/0016-764900-174

McKie, T. & Kilhams, B., 2025. Triassic. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 155-183. DOI: 10.5117/9789463728362_ch05

Menning, M., 1995. A numerical time scale for the Permian and Triassic periods: an integrated time analysis. In: Scholle, P.A., Peryt, T.M. & Ulmer-Scholle, D.S. (eds): The Permian of northern Pangea. Springer-Verlag (Berlin): 77-97. DOI: 10.1007/978-3-642-78593-1_6

Mijnlieff, H., 2002. Top Pre-Permian distribution map & some thematic regional geologic maps of the Netherlands. Poster 55th ICCP Meeting, Utrecht (Netherlands, ICCP). https://www.nlog.nl/sites/default/files/postermijnlieficcp.pdf

Mijnlieff, H., Buijze, L., Rosendaal, E., Schoof, F., Vorage, R. & Van Wees, J.-D., 2025. Geothermal energy. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 701-727. DOI: 10.5117/9789463728362_ch19

Minervini, M., Rossi, M. & Mellere, D., 2011. Cyclicity and facies relationships at the interaction between aeolian, fluvial, and playa depositional environments in the Upper Rotliegend: Regional correlation acrosss UK (Sole Pit Basin), the Netherlands, and Germany. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98: 119-146. DOI: 10.2110/pec.11.98.0119

NITG, 1998. Geological Atlas of the subsurface of the Netherlands (1:250,000), Explanation to Map Sheet X Almelo–Winterswijk. Netherlands Institute of Applied Geoscience (NITG-TNO, Haarlem): 134 pp

NITG-TNO, 2000. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheet VI Veendam–Hoogeveen. Netherlands Institute for Applied Geoscience TNO - National Geological Survey (Utrecht): 152, 152 pp.

Opluštil, S., Jirásek, J., Schmitz, M. & Matýsek, D., 2017. Biotic changes around the radioisotopically constrained Carboniferous–Permian boundary in the Boskovice Basin (Czech Republic). Bulletin of Geosciences 92: 95-122. DOI: 10.3140/bull.geosci.1638

Patruno, S., Reid, W., Jackson, C.A.-L. & Davies, C., 2018. New insights into the unexploited reservoir potential of the Mid North Sea High (UKCS quadrants 35-38 and 41-43): a newly described intra-Zechstein sulphate–carbonate platform complex. In: Bowman, M. & Levell, B. (eds): Petroleum Geology of NW Europe: 50 Years of Learning. Geological Society, London, Petroleum Geology Conference Series 8: 87-124. DOI: 10.1144/PGC8.9

Peeters, S.H.J., Geel, C.R., Garland, J. & Bouroullec, R., 2023. Seismic and petrographic characterisation of the Zechstein Hauptdolomit Platforms around the Elbow Spit High, Dutch offshore. Journal of Petroleum Geology 46: 361-382. DOI: 10.1111/jpg.12842

Pharaoh, T.C., Dusar, M., Geluk, M.C., Kockel, F., Krawczyk, C.M., Krzywiec, P., Scheck-Wenderoth, M., Thybo, H., Vejbæk, O.V. & Van Wees, J.-D., 2010. Tectonic evolution. In: Doornenbal,

J.C. & Stevenson, A.G. (eds): Petroleum geological atlas of the Southern Permian Basin area. EAGE Publications b.v. (Houten): 25-57.
Plein, E., 1995. Norddeutsches Rotliegendbecken; Rotliegend-Monographie Teil II. In: Deutsche Stratigraphische Kommission (ed.): Stratigraphie von Deutschland I. Courier Forschungsinstitut Senckenberg 183: 193 pp.
Raith, A.F., Urai, J.L. & Visser, J., 2017. Structural and microstructural analysis of K–Mg salt layers in the Zechstein 3 of the Veendam Pillow, NE Netherlands: development of a tectonic mélange during salt flow. Netherlands Journal of Geosciences 96: 331-351. DOI: 10.1017/njg.2017.31
Remane, J., Cita, M.B., Dercourt, J., Bouysse, P., Repetto, F. & Faure-Muret, A. (eds), 2003: International Stratigraphic Chart. International Union of Geological Sciences: International Commission on Stratigraphy (Paris): 1 pp .
Remmelts, G., Nelskamp, S., De Jager, J. & Geluk, M.C., 2025. Petroleum Geology. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 535-575. DOI: 10.5117/9789463728362_ch14
Richter-Bernburg, G., 1955. Statigraphische Gliederung des Deutschen Zechsteins. Zeitschrift der Deutschen Geologischen Gesellschaft 105: 843-854. DOI: 10.1127/zdgg/105/1955/843
Rijkers, R.H.B. & Geluk, M.C., 1996. Sedimentary and structural history of the Texel-IJsselmeer High, the Netherlands. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands. Kluwer Academic Publishers (Dordrecht): 265-284. DOI: 10.1007/978-94-009-0121-6_22
Rijks Geologische Dienst, 1991a. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheet I Vlieland-Terschelling. Geological Survey of the Netherlands (Haarlem): 77 pp.
Rijks Geologische Dienst, 1991b. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheet II Ameland-Leeuwarden. Geological Survey of the Netherlands (Haarlem): 87 pp.
Rijks Geologische Dienst, 1993. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheet IV Texel-Purmerend. Geological Survey of the Netherlands (Haarlem): 128 pp.
Rijks Geologische Dienst, 1995. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheet III Rottumeroog-Groningen. Geological Survey of the Netherlands (Haarlem): 113 pp.
Roustiau, A., Bouroullec, R., Dijk, J., Den Hartog Jager, D., Nelskamp, S. & Swart, M., 2022. Play 8 Carboniferous. https://www geodeatlas.nl/pages/play-8-carboniferous
Schlimm, W. & Thiermann, A., 1988. Perm. In: Hilden, H.D.(ed.): Geologie am Niederrhein. Geologisches Landesamt Nordrhein-Westfalen (Krefeld): 142 pp.
Schneider, J.W., Spencer, G.L., Scholze, F., Voigt, S., Marchetti, L., Klein, H., Opluštil, S., Werneburg, R., Golubev, V.K., Barrick, J.E., Nemyrovska, T., Ronchi, A., Day, M.O., Silantiev, V.V., Rößler, R., Saber, H., Linnemann, U., Zharinova, V. & Shen, S.-Z., 2020. Late Paleozoic-early Mesozoic continental biostratigraphy—links to the Standard Global Chronostratigraphic Scale. Palaeoworld 29: 186-238. DOI: 10.1016/j.palwor.2019.09.001
Schuurman, W.M.L., 1998. Carboniferous high-resolution stratigraphy the integrated approach - an example from the Cleaver Bank High Area, offshore the Netherlands. TNO report NITG-98-095-A: 3 pp.
Scotese, C.R., 2014. Atlas of Permo-Carboniferous Paleogeographic Maps (Mollweide Projection), Maps 53-64, Volumes 4, The Late Paleozoic, PALEOMAP Atlas for ArcGIS, PALEOMAP Project (Evanston, IL, USA). DOI: 10.13140/2.1.1837.8244
Sissingh, W., 2004. Palaeozoic and Mesozoic igneous activity in the Netherlands: a tectonomagmatic review. Netherlands Journal of Geosciences 83 (2): 113-134. DOI: 10.1017/S0016774600020084
Słowakiewicz, M. & Gąsiewicz, A., 2013. Palaeoclimatic imprint, distribution and genesis of Zechstein Main Dolomite (Upper Permian) petroleum source rocks in Poland: Sedimentological and geochemical rationales. In: Gąsiewicz, A. & Słowakiewicz, M. (eds): Palaeozoic climate cycles: Their evolutionary and sedimentological impact. Geological Society of London, Special Publications 376: 523-538. DOI: 10.1144/SP376.21
Stemmerik, L., Ineson, J.R. & Mitchell, J.G., 2000. Stratigraphy of the Rotliegend Group in the Danish part of the Northern Permian Basin, North Sea. Journal of the Geological Society 157 (6): 1127-1136. DOI: 10.1144/jgs.157.6.1127
Stille, H., 1924. Grundfragen der vergleichenden Tektonik. Gebrüder Borntraeger (Berlin): 443 pp.
Strohmenger, C., Antonini, M., Jäger, G., Rockenbauch, K. & Strauss, C., 1996. Zechstein 2 Carbonate reservoir facies distribution in relation to Zechstein sequence stratigraphy (Upper Permian, northwest Germany): an integrated approach. Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine 20: 1-35.
Strömbäck, A.C. & Howell, J.A., 2002. Predicting distribution of remobilized aeolian facies using sub-surface data: the Weissliegend of the UK Southern North Sea. Petroleum Geoscience 8: 237-249. DOI: 10.1144/petgeo.8.3.237
Sweeney, M., Turner, P. & Vaughan, D.J., 1987. The Marl Slate: a model for the precipitation of calcite, dolomite and sulphides in a newly formed anoxic sea. Sedimentology 34: 31-48. DOI: 10.1111/j.1365-3091.1987.tb00558.x
Taylor, J.C.M., 1998. Upper Permian - Zechstein. In: Glennie, K.W. (ed.): Petroleum geology of the North Sea - Basic concepts and recent advances. Blackwell Scientific Publishing (Oxford): 174-212. DOI: 10.1002/9781444313413.ch6
TNO-GDN, 2022. Fringe Sandstone members (ZEZ1S to ZEZ4S). In: Stratigraphic Nomenclature of the Netherlands. https://www.dinoloket.nl/en/stratigraphic-nomenclature/z1-fringe-sandstone-member (idem for z2, z3, z4)

Tucker, M.E., 1991. Sequence stratigraphy of carbonate-evaporite basins: models and application to the Upper Permian (Zechstein) of northeast England and adjoining North Sea. Journal of the Geological Society 148: 1019-1036. DOI: 10.1144/gsjgs.148.6.1019

Vai, G.B., 2003. Development of the palaeogeography of Pangaea from Late Carboniferous to Early Permian. Palaeogeography, Palaeoclimatology, Palaeoecology 196: 125-155. DOI: 10.1016/S0031-0182(03)00316-X

Van Adrichem Boogaert, H.A. & Burgers, W.F.J., 1983. The development of the Zechstein in the Netherlands. In: Kaasschieter, J.P.H. & Reijers T.J.A. (eds): Petroleum geology of the southeastern North Sea and the adjacent onshore areas. Geologie en Mijnbouw 62: 83-92. DOI: 10.1007/978-94-009-5532-5_8

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1993. Stratigraphic nomenclature of the Netherlands; revision and update by RGD and NOGEPA, Section D: Permian (Lower Rotliegend, Upper Rotliegend and Zechstein Groups). Mededelingen Rijks Geologische Dienst 50: 1-42.

Van Bergen, M.J. & Sissingh, W., 2007. Magmatism in the Netherlands: expression of the north-west European rifting history. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW, Amsterdam): 197-222.

Van Bergen, M.J., Vis, G.-J., Sissingh, W., Koornneef, J. & Brouwers, I., 2024. Magmatism in the Netherlands: expression of the north-west European rifting history. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 393-455. DOI: 10.5117/9789463728362_ch11

Van den Belt, F.J.G. & Van Hulten, F.F.N., 2011. Sedimentary architecture and palaeogeography of Lower Slochteren aeolian cycles from the Rotliegend desert-lake margin (Permian), the Markham area, Southern North Sea. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98: 161-176. DOI: 10.2110/pec.11.98.0161

Van der Baan, D., 1990. Zechstein reservoirs in the Netherlands. In: Brooks, J. (ed.): Classic petroleum provinces. Geological Society of London, Special Publications 50, 379-398. DOI: 10.1144/GSL.SP.1990.050.01.24

Van de Sande, J.M.M., Reijers, T.J.A. & Casson, N., 1996. Multidisciplinary exploration strategy in the northeast Netherlands Zechstein 2 Carbonate play, guided by 3D seismic. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands. Kluwer Academic Publishers (Dordrecht): 125-142. DOI: 10.1007/978-94-009-0121-6_12

Van Ojik, K., Böhm, A.R., Cremer, H., Geluk, M.C., De Jong, M.G.G., Mijnlieff, H.F. & Nio, S.D., 2011. The rationale for an integrated stratigraphic framework of the Upper Rotliegend II depositional system in the Netherlands. In: Grötsch, J. & Gaupp, R. (eds): The Permian Rotliegend of the Netherlands. SEPM Special Publication 98: 37-48. DOI: 10.2110/pec.11.98.0037

Van Ojik, K., Den Hartog Jager, D. & Roustiau, A., 2021. Play 7 Rotliegend. https://www geodeatlas.nl/pages/play-7-rotliegend

Verdier, J.P., 1996. The Rotliegend sedimentation history of the southern North Sea and adjacent countries. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands. Kluwer Academic Publishers (Dordrecht): 45-56. DOI: 10.1007/978-94-009-0121-6_6

Visser, W.A., 1955. The Upper Permian in the Netherlands. Leidse Geologische Mededelingen 20: 185-194. https://repository.naturalis.nl/pub/505894

Wagner, R., 1994. Stratygrafia osadów i rozwój basenu cechsztyńskiego na Niżu Polskim. Prace Państwowego Instytutu Geologicznego 146: 71 pp.

Wolf, R., 1985. Tiefentektonik des linksniederrheinischen Steinkohlengebietes. Beiträge zur Tiefentektonik westdeutscher Steinkohlenlagerstätten. Geologisches Landesamt Nordrhein-Westfalen (Krefeld) 105-167.

Yang, C.S. & Baumfalk, Y.A., 1994. Milankovitch cyclicity in the Upper Rotliegend Group of the Netherlands offshore. In: De Boer, P.L. & Smith, D.G. (eds): Orbital forcing and cyclic sequences. International Association of Sedimentologists Special Publication 19: 47-61. DOI: 10.1002/9781444304039.ch5

Ziegler, M.A., 1989. North German Zechstein facies patterns in relation to their substrate. Geologische Rundschau 78: 105-127. DOI: 10.1007/bf01988356

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe, second edition. Shell Internationale Petroleum Mij. B.V. and Geological Society (London): 239 pp.