Seismic characterization of the Zechstein carbonates in the Dutch northern offshore

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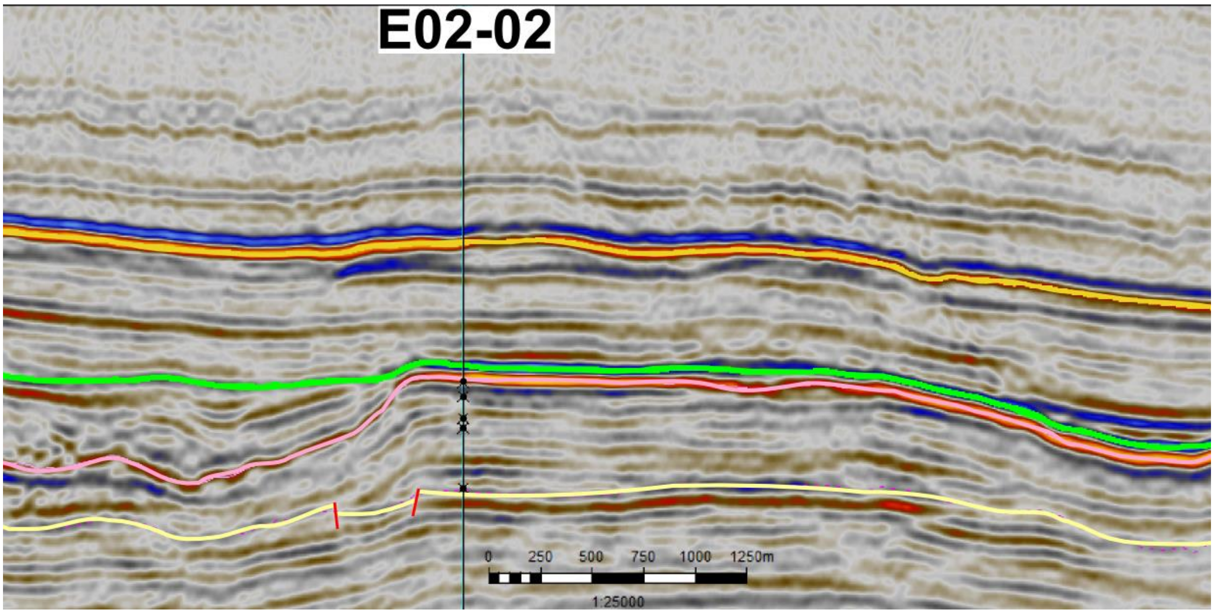
June, 2014

MSc. Thesis: Earth, Life and Climate



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1.0 Abstract

The presence of Zechstein carbonate platform facies is often controlled by the pre-existing paleo-geography and commonly occur on uplifted fault blocks and along the margins of the Southern Permian Basin. Present day Zechstein distribution maps suggest that these platform facies are absent along the margins of the Elbow Spit High in the Dutch northern offshore, while based on the general geological setting their presence might be expected. Only several Dutch and UK wells have drilled the Zechstein or older formations in the study area. Well E02-02 and A16-01 have strong positive indicators for the presence of Zechstein platform facies, with good reservoir characteristics. Well E02-02 drilled a Zechstein platform structure, which was confirmed by a side-wall core sample. A16-01 found stromatolites along the SW margin of the Elbow Spit High, indicating a shallow water environment. Therefore it cannot be ruled out that platform facies exists in a large area along the margins of the Elbow Spit High. This has been investigated with the use of seismic data. First, seismic and petrophysical data will be used to characterize the Zechstein on seismic. That will be used, together with Zechstein analogues from the North-East Netherlands, to identify potential Zechstein platform structures. Second, top and base Zechstein is mapped in great detail and in specific areas the top Zechstein-3 Anhydrite Member is mapped as well. The identified potential Zechstein platform structures are then compared and compared to the proven E02-02 platform. The results show that the Zechstein Group contains several characteristic seismic properties that can be used to identify potential Zechstein platform structure, since a low amplitude seems to correlate with Zechstein platform structures. This study illustrates that Zechstein platform facies exists along the western and eastern margins of the Elbow Spit High, away from the wells that encountered this facies. A modified Zechstein distribution map has been proposed showing the areas with Zechstein platform facies along the Elbow Spit High. This map is based on the identified Zechstein platform structures and well data in the study area. Also a new area with possible Zechstein platform facies is proposed, that roughly correlates with the Step High.

Acknowledgements

I would like to express my gratitude to Bastiaan Jaarsma (EBN), my supervisor, for his patient guidance, enthusiastic encouragement and useful critiques on this research. I would also like to thank prof. Dr. Jan de Jager (UU), my second supervisor, for his advise and useful comments on my work. Guido Hoetz (EBN), for mentoring my process and sharing his knowledge on the Zechstein geology. Maarten-Jan Brolsma (EBN) for giving me the chance to do this research at EBN. I wish to thank Walter Eikelenboom, Roberta Guarnieri, Eveline Rosendaal and Annemiek Asschert for their valuable technical and geological support on this project. My special thanks are extended to the EBN interns Duncan Wijker, Joris Groot and Manuel Bussmann for the pleasant and enjoyable time at EBN. And last but not least all other employees at EBN, thank you for the pleasant time at EBN.

2.0 Introduction

The interest in Zechstein carbonates as a prospective reservoir was triggered after an exploration well in the East Netherlands. The well Corle-1 was drilled in 1923 as a coals/salt exploration well. The cores from the basal Zechstein carbonates and Carboniferous sandstone showed gas bubbles and a strong oil smell was noticed (Reijers et al., 2012). 60 years later the Zechstein Group is a proven and prolific petroleum system, with more than 100 fields in the North-East Netherlands, Germany and Poland (Kotarba & Wagner, 2007 and Reijers et al., 2012). The Zechstein-2 Carbonate play In the NE Netherlands has been extensively described by several authors e.g. Van der Baan, 1990; Van de Sande et al., 1996; Geluk et al., 2000 and Reijers et al., 2012. Gas is sourced from the underlying coal measures of the Westphalian A and B into the slope and platform deposits of the Zechstein-2 Carbonate Member. The gas is trapped into dip and fault-closed structures that are sealed by the overlying Zechstein-2 Anhydrite Member and Zechstein-2 Halite Member. The reservoir quality forms the main uncertainty in this play, especially the porosity and permeability of the reservoir (Van de Sande et al., 1996). The distribution of the different Zechstein-2 Carbonate facies is largely dependent on the pre-existing paleo-relief. The fault blocks of the uplifted East Netherlands High formed the substrate on which several sulphate and carbonate platforms developed (Van der Baan., 1990). A Zechstein facies distribution map published by Geluk et al., (2007) illustrates the present day distribution of the Zechstein-2 Carbonate Member in the Southern Permian Basin (see figure 1). The distribution map shows that an extensive Zechstein-2 Carbonate platform is present along the margins of the Southern Permian Basin.

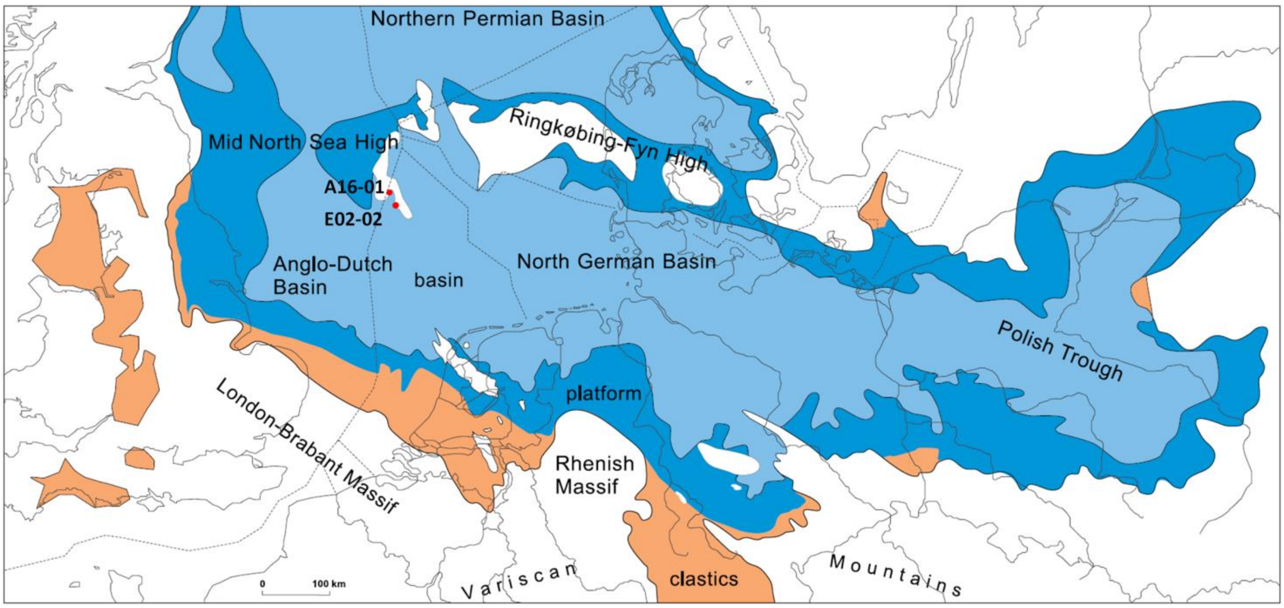


Figure 1: Distribution map for the Zechstein-2 Carbonate Member in the Southern Permian Basin. Wells E02-02 and A16-01, that found Zechstein platform facies in this area, are indicated on the map. Source: Geluk et al., 2007.

The distribution map suggests that Zechstein-2 Carbonate platform facies are absent around the Elbow Spit High in the northern Dutch offshore. Which could be considered questionable since the Elbow Spit High was surfaced above sea-level since Early Devonian times (Kombrink et al., 2012). Along the margins of the high, shallow water conditions could have prevailed, creating the perfect environment for the deposition of shallow water Zechstein platform facies. The well control in the area is very poor and relatively few wells have drilled the Zechstein or older formations in this area. These wells show varying thickness in of the Zechstein-2 Carbonate Member, which is mostly classified as basinal facies in these wells. A previous study EBN study (EBN 2013, unpublished) confirmed that many wells drilled in basinal facies. However, some wells close to the Elbow Spit High clearly show positive indications for Zechstein platform facies, see figure 1. Well E02-02 drilled onto a Zechstein platform along the South-West margin of the Elbow Spit High. The A16-01 well, which lies just North of E02-02, found shallow water platform stromatolites. Hydrocarbons are being produced from Zechstein carbonate reservoirs at the northern margin of the Southern Permian Basin e.g. Auk field (UK) and the German A06-A field. Therefore it cannot be ruled out that platform and slope facies exist in the northern Dutch offshore close to the Elbow Spit High.

This study is aimed to prove the existence of Zechstein carbonate platforms in the Dutch northern offshore. The evaluated area comprises parts of the A and E blocks in the North Sea (see figure 2) and is mainly focused around the Elbow Spit High, see figure 1. For this study the top and base Zechstein will be mapped, and in specific areas the top Zechstein-3 Anhydrite Member will be evaluated. Seismic data, well data and synthetics will be used to evaluate the Zechstein on seismic in the study area. The proven Zechstein E02-02 platform will be extensively discussed and a schematic reconstruction will be made. Also seismic data from the NE Netherlands will be analyzed as a Zechstein analogue to the Dutch northern offshore. Furthermore the regional tectonic setting will be discussed and the Zechstein group will be evaluated.

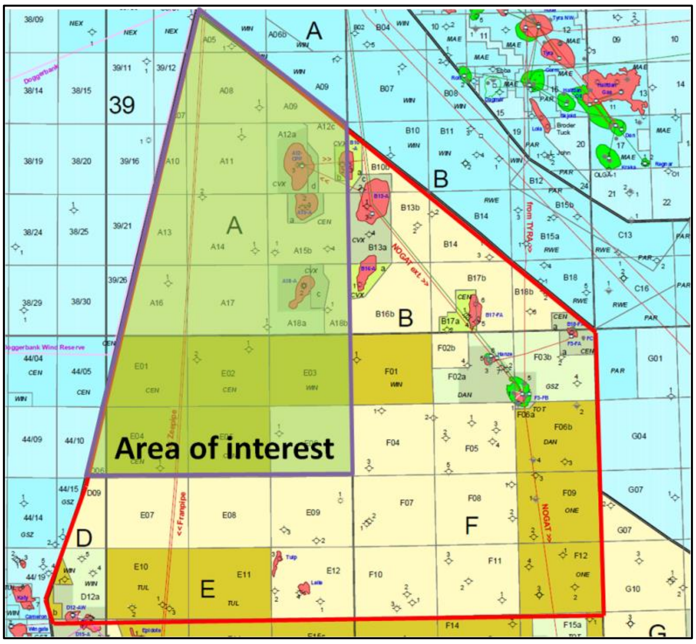


Figure 2: DEFAB area encircled by the red outline. Within tine DEFAB area the area of interest can be found, which is outlined by the purple color.

This research has been carried out as part of the regional DEFAB prospectivity review in the Dutch northern offshore at EBN Utrecht, and as a master thesis at the Utrecht University. The report is subdivided into the chapters: Geological history, Zechstein litho-stratigraphy, The search for Zechstein carbonates, Methods, Results, Zechstein seismic characterization, Discussion and Conclusion. The chapter Zechstein seismic characterization can be read separately from the report.

3.0 Geological & Tectonic History of the Netherlands

The Southern Permian Basin

This chapter summarizes the tectonic and geological development of the southern North Sea area, with a focus on the Netherlands and the Southern Permian Basin. The Southern Permian Basin (SPB) is the largest sedimentary basin in Europe, and underlies Northern Poland, Northern Germany, Denmark, the Netherlands and a significant portion of the North, see figure 3. The SPB is situated in the former East-West trending Variscan foreland basin that evolved into an intracratonic basin during late Paleozoic times. The SPB is bounded in the South by the Rhenisch and the Bohemian massifs, which are part of the Variscan orogenic belt. The Western boundary, of the Southern Permian Basin, is confined by the outline of the former Variscan thrust belt. In the East it gently advances onto the Precambrian European Craton [Guterch et al., 2010]. The Paleozoic crust on which the SPB lies is a mosaic of orogenic terranes, which accreted to Baltica to the North and to the European Craton to the East, during the Caledonian and Variscan orogenic cycles, see figure 4 [Ziegler 1990]. To the North the Southern Permian Basin is bounded by the Mid North Sea High and Ringkøbing-Fyn High. Both highs separate the Southern Permian Basin with the Northern Permian Basin. The Northern Permian Basin underwent a similar development as the Southern Permian Basin, both basins were isolated from the oceans and subsided significantly below sea-level. At the beginning of the Late Permian both basins were flooded by a sudden influx of water from the Arctic seas (Pharaoh et al., 2010).

The following section gives a brief overview of the geological development of the North Sea area, with the focus on the Late Permian Zechstein times. The book Geology of the Netherlands, the Southern Permian Basin Atlas and Millennium Atlas were used for reference of this section.

Introduction

The geological history of the Netherlands can be divided into four main tectonic phases:

1. Caledonian &Variscan orogenies which resulted in the assembly of Pangea;
2. Mesozoic rifting accompanied with Pangea break-up;
3. Alpine collision resulting in widespread inversion during the Late Cretaceous and Early Tertiary;
4. Oligocene to recent development of the Rhine Graben.

Figure 5 gives a stratigraphic overview and timing of the plate tectonic phases.

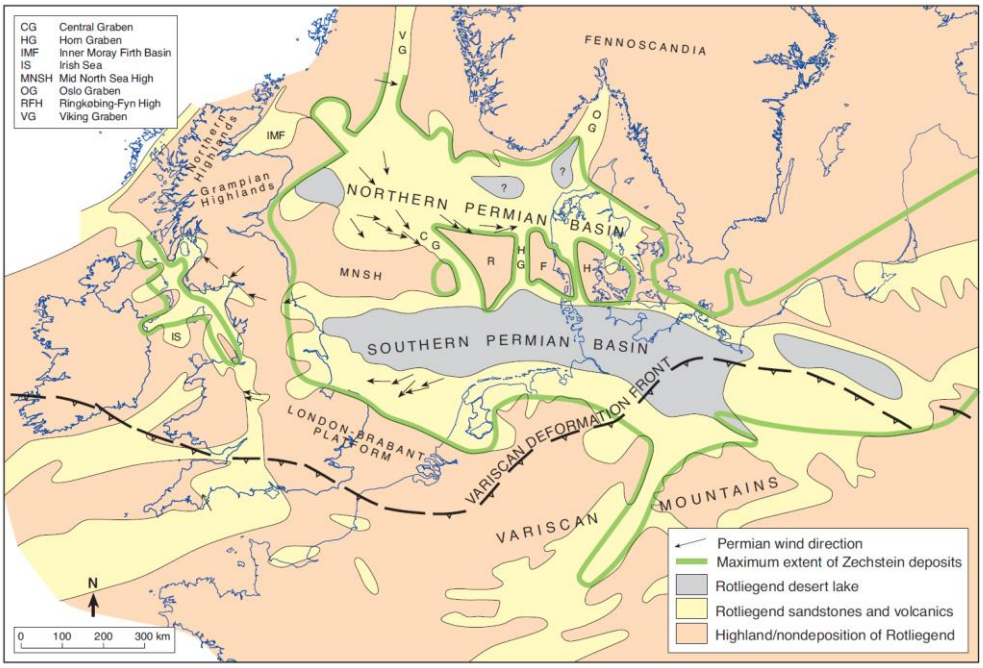


Figure 3: Map which indicating the rough outline of the Southern and Northern Permian Basins. Source: Millennium Atlas (2003), pp 227.

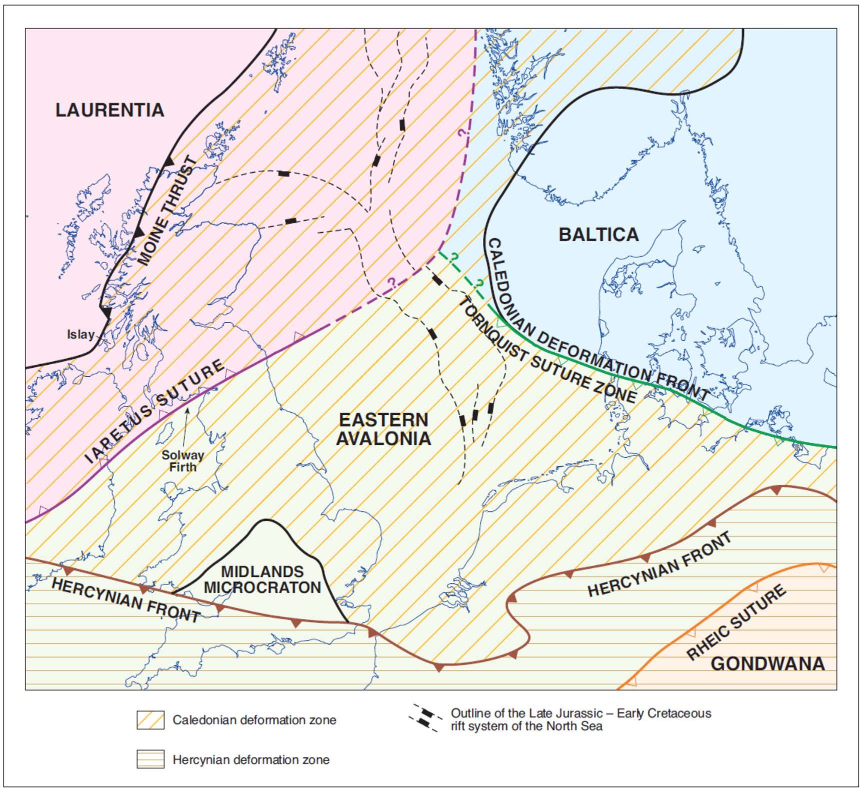


Figure 4: Sketch map of the North Sea basement and tectonic features, indicating the mosaic of orogenic structures. Source Millennium Atlas, (2003) pp 76.

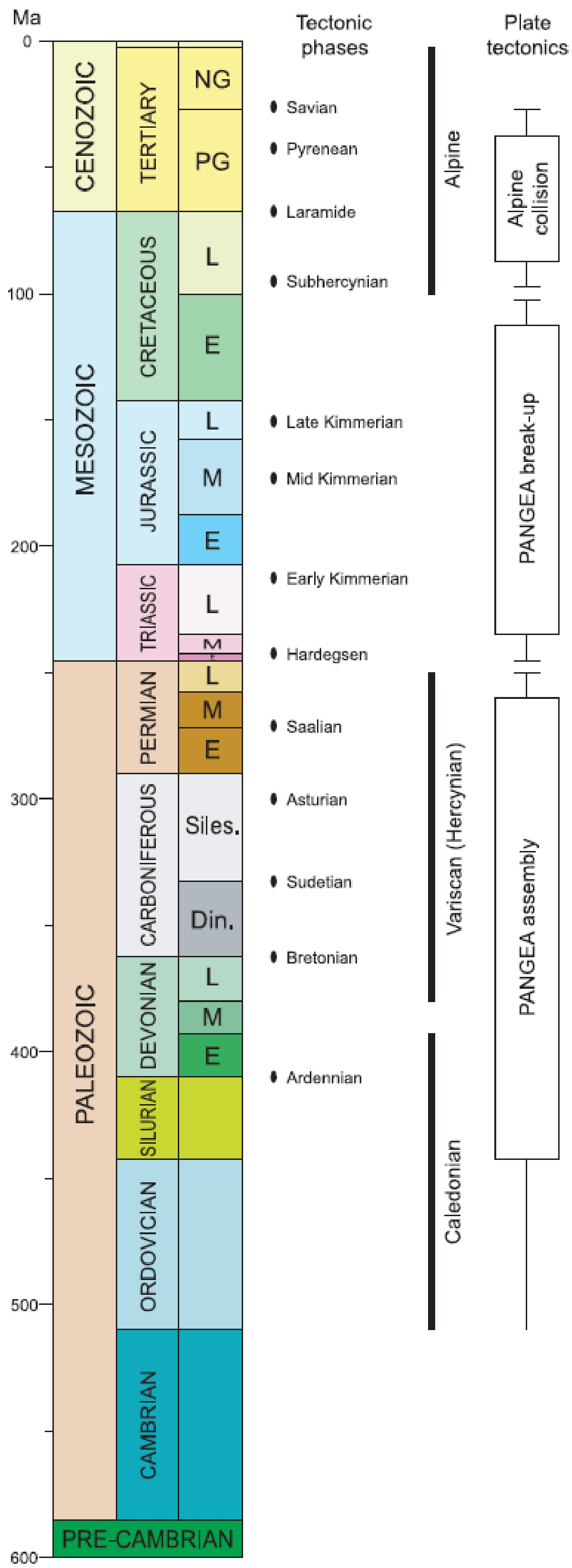


Figure 5: Tectonic phases in the Netherlands and their relation to plate tectonic events. Source: De Jager, 2007..

The Caledonian orogeny (550 - 400Ma) was the result of the collision between the three micro continents Baltica, Avalonia and Laurentia. During the Ordovician, Avalonia was separated from Gondwana and moved northwards, opening the Rheic Ocean between Gondwana and Avalonia, see figure 6. At the end of the Ordovician Baltica and Avalonia collided, resulting in the closure of the Tornquist Ocean, between Avalonia and Baltica. During Silurian and earliest Devonian times, Laurentia collided with the Baltica/Avalonia continent, closing the Iapetus Ocean. This newly created continent is referred to as Laurussia or as the “Old Red” continent.

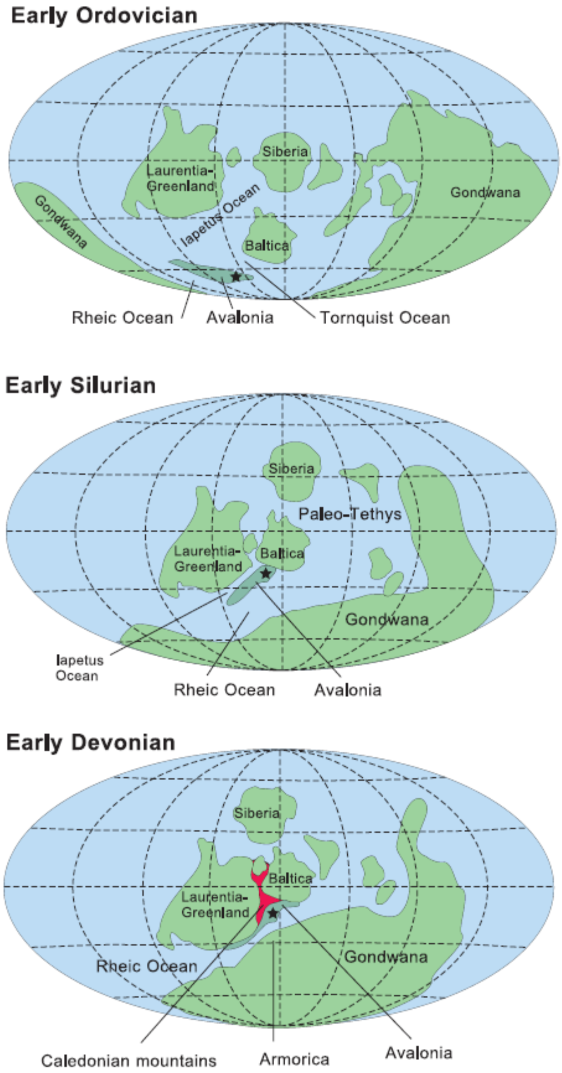


Figure 6: Plate tectonic reconstruction, illustrating the most important collisions during the Ordovician, Silurian and Devonian. This figure show shows the northwards drift of Avalonia and its collision with Baltica and Laurentia. Source: Geluk, Dusar and de Vos, 2007.

During the Late Devonian and Early Carboniferous the Variscan orogeny (400 – 300Ma) started with the collision between Laurussia and Gondwana, creating the supercontinent Pangea, see figure 6. This has resulted in the closure of the Rheic Ocean and the formation of the Rheno-Hercynian fold and thrust belt. The Variscan front was the suture between Gondwana and Laurussia. North of the Variscan front a foreland basin developed, which was the precursor of the Southern Permian Basin. When the tectonic activity of the Variscan mountain front ceased, this foreland basin evolved into an intra-cratonic basin. The Southern Permian Basin was bordered to the South by the Variscan mountain front and the London-Brabant Massif and to the North by the Mid North Sea High and Ringkøbing-Fyn High.

After a period of tectonic quiescence Mesozoic rifting commenced during the Triassic, which was associated with the break-up of Pangea. Mesozoic rifting in the North Sea was characterized by two failed rifting events: 1) Middle – Late Triassic East-West extension, 2) Late Jurassic North East – South West extension. The result was that the Southern Permian Basin became dissected by a graben system. The Late Cretaceous and Early Paleocene were characterized by the convergence between Africa-Arabia and Eurasia and the closure of the Tethys Ocean. This tectonic event resulted in the development of the Alpine orogenic system. During this period compressive stresses were exerted by the evolving Alpine orogeny onto its northern foreland, this resulted in inversion of Mesozoic extensional structures. The last and still ongoing structural process is the rifting in the lower Rhine Graben, which propagated northwards into the Netherlands during the Late Tertiary (De Jager, 2007)

Devonian

During the earliest Devonian the SPB area was still under the influence of the collision between Avalonia/Baltica and Laurentia. This compressional phase resulted in the inversion of the Brabant Trough, which was filled with Silurian sediments (Geluk et al., 2007). After the Caledonian orogeny this structure became the stable London-Brabant Massif, on which the Variscan front abutted (De Jager, 2007).
A strong pulse of rifting, that started already during the Early Devonian, led to the formation of a rift basin on the Rheno-Hercynian Shelf, the Rheno-Hercynian basin. Extension, or back-arc extension, was associated with the subduction of the Rheic oceanic plate beneath Laurussia (Van Adrichem Boogaert & Kouwe, (1993-1997).
Gondwana started to converge with Laurussia during the Late Devonian, which marked the start of the Variscan (Hercynian)orogenic event. The period of the Variscan orogeny was still part of the Pangea assembly plate tectonic event, see figure 6. At the end of the Devonian initial contact between Gondwana and Laurussia was established and the Rheno-Hercynian zone was closed again.

After the Caledonian orogenic event, in the Early Devonian, sediments of the “Old Red” continent covered the area of the future North Sea. During the Devonian, transgression occurred from South to North across the eastern part of the London-Brabant Massif. As a result, carbonates and clastics of Devonian age can be found on the flanks of the London-Brabant Massif. The transgression extended northwards into the central North Sea area, depositing carbonates and evaporates of the Kyle Formation. Regression occurred during the Late Devonian and the sea retreated from the North Sea area. Subsequently covering the area with fluvial sands and claystones of the Upper Old Red Group, which consists mainly of red-bed facies(Geluk et al., 2007). In the Area of the Elbow Spit High, some volcanism occurred while along the margins of the London-Brabant Massif conditions remained marine (Van Adrichem Boogaert & Kouwe, 1993-1997). Well A17-01 in the Dutch offshore reached Devonian plutonic rocks, it is the only well reaching Devonian strata in the Dutch Northern offshore.

Carboniferous

The end of the Devonian was characterized with the closure of the Rheno-Hercynian zone, a back-arc basin north of the Variscan suture zone. This closure was associated with the collision of Gondwana and Laurussia, creating the Variscan orogeny. A flexural foreland basin developed North of the Variscan front, due the northwards movement of the Variscan front. The Variscan orogeny roughly had an E-W trend through Belgium, changing to SW-NE into Germany (Ziegler, 1990).The Netherlands area became landlocked as a result of the Variscan mountains front, and no deformation as far north as the Netherlands has been observed(De Jager, 2007).During the Namurian to Westphalian C, the foreland basin experienced a period of tectonic quiescence. This period has been described as a classic sag phase of 20Ma. During this phase a thick package, up to 5500m, of sediments were deposited in the basin. The Namurian sediments were mainly of marine and lacustrine origin, while the Westphalian sequence contains coastal- and fluvialplain deposits, coal seams and some thin marine intercalations (Van Buggenum & Den Hartog Jager, 2007).The end of the Carboniferous is associated with renewed tectonic activity. Extension occurred during the Stephanian and Early Permian, also known as the Saalian phase. As a result Stephanian red beds lie unconformable over the Westphalian in Germany and East Netherlands.

The Variscan foreland basin experienced extremely high rates of subsidence. As a result of the high subsidence rates the succession started with deeper marine to lacustrine basin and delta sediments, followed by sediment deposited in a slightly deeper shallow-marine environment. This reflects the fact that sedimentation rates could not keep up with the subsidence rates. The well-known coal measures in the Carboniferous were deposited under humid tropical condition, reflecting periodic growth of extensive tropical forests and flooding of the area (Van Adrichem Boogaert & Kouwe, (1993-1997)).Migration of the Variscan foreland basin from a humid climate belt around the equator towards the arid climate zone of the Northern Hemisphere, resulted in a gradually ceasing of the deposition of the coal measures during the Westphalian C and early D. The increasingly arid climate during this period resulted in the deposition of red-bed facies. During the Westphalian D and Stephanian, the sedimentation had a more fluvial and sheetflood character (Van Adrichem Boogaert & Kouwe, (1993-1997)).

Permian

The Early Permian is characterized by late Variscan tectonism, which resulted in trans-tensional rifting and the forming of pull-apart basins, mainly in north-east Germany and western Poland. Wrenching in northern Germany and Poland was accompanied by extensive in- and extrusive volcanism (De Jager, 2007). The basins formed during this late Variscan tectonic event were filled with Lower Rotliegend clastics and volcanics. The Netherlands was affected by this only marginally, and Lower Rotliegend deposits, of the Emmen Formation, are only found in Emmen, Drenthe area (Van Adrichem Boogaert & Kouwe, 1993-1997). Clastic sedimentation in the Early Permian, started in East Germany and Poland, and gradually moved towards the South and western part of the basin. However in the Netherlands and northern offshore Early Permian deposits are only found in isolated depressions, which contain ~10’s meters sediment. The Saalian tectonic phase ended the deposition of Lower Rotliegend in most of the NW Europe basins. This is followed by an interval of non-deposition and regional uplift, resulting in the removal of large quantities of sediment, creating the

Base Permian Unconformity (BPU). The resulting paleo-geography after the Saalian phase, controlled the evolution of Mesozoic and Cenozoic structural elements.

A rift zone developed between Greenland and Scandinavia at the start of the Late Permian. The rift zone connected the low-lying Northern and Southern Permian Basin with the Barents Sea, causing a sudden transgression into both basins. Both basin were subsided below sea-level, due to the decaying thermal anomaly during the Early Permian. The Southern Permian Basin flooded periodically as a result of obstruction of the narrow sea-way and cyclic deglaciation and glaciation of Gondwana (Van de Baan, 1990). Periodically flooding resulted in cyclic deposition of the Zechstein Formations, starting with carbonate deposition and with increasing salinity anhydrite and salt deposition. The Southern Permian Basin was completely filled with Zechstein deposits, and deposition became restricted to the very depocentre of the basin (Van Adrichem Boogaert & Kouwe, 1993-1997).

The Lower Rotliegend is mainly characterized by volcano-clastic deposits, which are only found in specific confined areas, such as the Ems Low. Climate during the Upper Rotliegend was hot and arid, the basin had subsided several hundreds of meters below sea-level. This resulted that the Southern Permian Basin was the site of a large desert lake with wadis and dune fields(Van der Baan, 1990). The most well-known formation deposited during the Upper Rotliegend is the Slochteren sandstone Formation, which is the reservoir rock for the giant Groningen gasfield. The Slochteren Formation pinches out northwards into coarse grained alluvial-fans, wadi and shale deposits of the Silverpit Formation. In Late Permian times, as a result of transgression, sedimentation changed from continental to marine claystone and later marine carbonates. Carbonate deposition changed to anhydrite and salt precipitation with increasing salinity.

Base Permian Unconformity

The BPU comprises the entire Early Permian, and is generally defined where the Upper Rotliegend overlies the Namurian to Stephanian deposits. In most of the Netherlands this unconformity represents 40-60Ma. The BPU is a so called mega-unconformity, formed out of multiple unconformities. The unconformity, despite its large gap in sedimentation, is often difficult to distinguish. This is due to the lack of fossil content and similar red-bed characteristics across the boundary (Geluk, 2007). The BPU has a pronounced paleo-topography associated with different subcropping Carboniferous units. Sand prone Carboniferous units, such as the Westphalian C & D, were more resistant against weathering and formed ridges. While the shaly/coaly Carboniferous, Westphalian A&B, were less resistant against weathering and formed lows (Geluk, 2007). Figure 7 gives a good overview of the different Carboniferous units below the BPU.

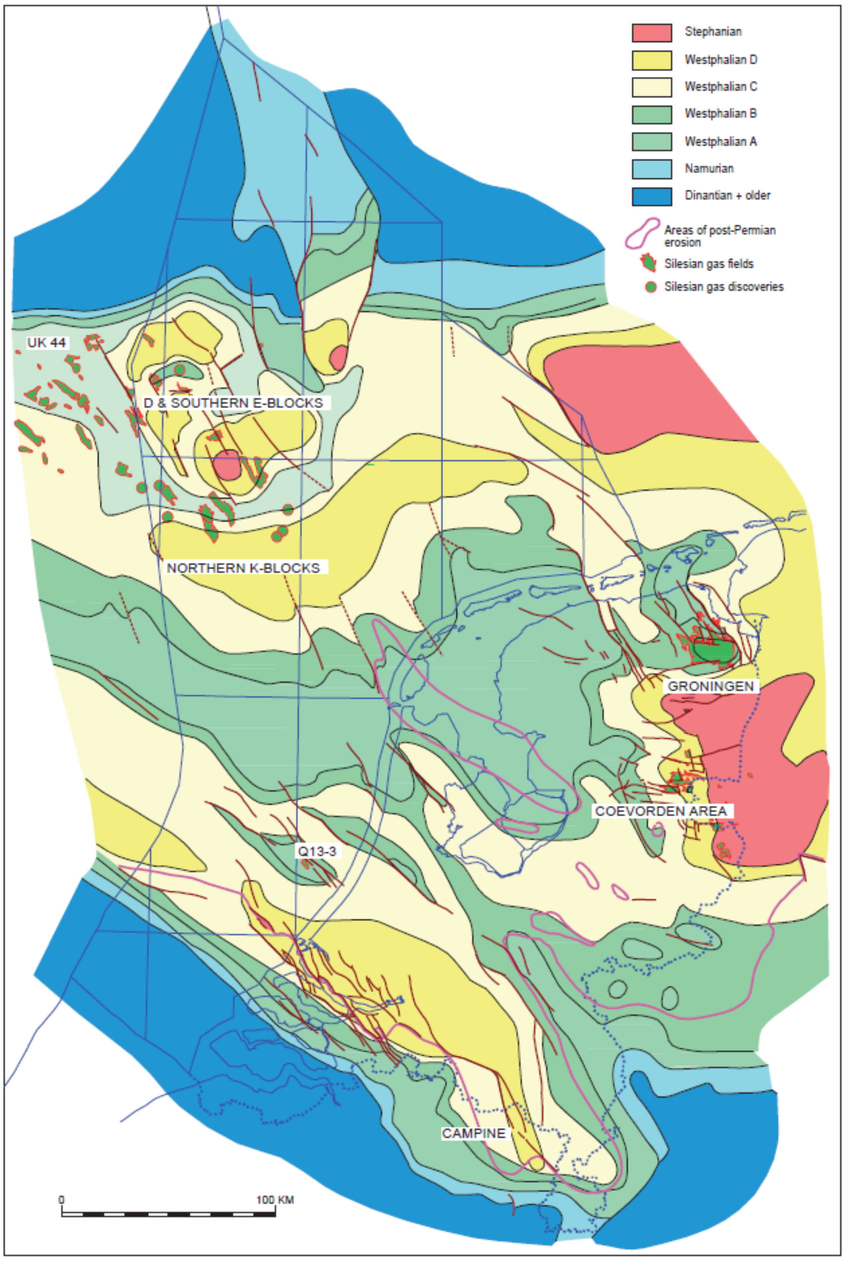


Figure 7: Subcrop map of the Base Permian Unconformity, illustrating the different Carboniferous units subcropping below the Base Permian Unconformity. Source: Van Buggenum & Den Hartog Jager, 2007.

Tectonic pulses

South to Westward extension of the basin occurred during the Late Permian. This extension was accompanied by a number of tectonic pulses, associated with the breaking & collapse of the Variscan front (Geluk, 1999). These tectonic pulses were the Saalian and Altmark I to III and occurred before and during the Upper Rotliegend, and resulted in the connection between the Southern Permian Basin and the Barents Sea. The connection between the Southern Permian Basin and the Barents Sea resulted into the catastrophic flooding of the Southern Permian Basin and first transgressive cycle of the Zechstein Formation (Pharaoh et al., 2010).
A second period of tectonic activity was suggested by Geluk, 1999. Two new tectonic pulses were introduced, the Tubantian I & II, both active during the Zechstein period see table 1. The Tubantian I phase, occurred during the deposition of the Zechstein-1. This tectonic event was caused due to

rapid deposition of anhydrite on a differentiated basement, in combination with mild E-W extension. This resulted in several pull-apart basins and tilted fault blocks, which ran through the Variscan front. The topography during the ZEZ1W deposition was fault bounded, therefore the ZEZ1W filled the formed relief. Ultimately the produced relief was covered by the ZEZ1W Member (Geluk, 1999).

The second Zechstein tectonic pulse is the Tubantian II and occurred during the deposition of the Zechstein Upper Claystone formation. This phase involved uplift and erosion as a result of compressional forces. The result of this tectonic phase was the removal of a large part of the Zechstein 3 & 4 formations. This tectonic event affected mainly the southern onshore of the Netherlands (Geluk, 1999).

Table 1: Stratigraphy and tectonic pulses from the Permian to Triassic for the Netherlands. Source: Geluk., (1999).

Age	Epoch	Marine stage	NE European stages	Lithostratigraphy	Tectonic pulse	Tectonic phase
208			Rhaetian	Altena Group	~~	
			Norian	Upper Germanic Trias Group		
212					~~Early Cimmerian	
					~~	Cimmerian extension
222	Triassic		Carnian			
			Ladinian			
241			Anisian			
		Olenekian	Scythian	Lower Germanic Trias Group	~~Hardegsen	
					~~	
251		Induan				
				Zechstein	~~Tubantian II	
		Tatarian		Group	~~Tubantian I	
			Late Permian	Upper Rotliegend		
265		Kazanian		Group	~~Altmark II, III	Late Variscan extension
					~~Altmark I	
		Kungurian				
	Permian			*hiatus*		
					~~Saalian	
		Artinskian	Early Permian			
		Sakmarian		Lower Rotliegend (locally present)		
296		Asselian				

Triassic

Zechstein deposition ended with the withdrawal of the sea from the Northern and Southern Permian Basins at the end of the Permian and beginning of the Triassic. Figure 8 gives an overview of the plate tectonic setting during the Late Triassic. During the Triassic break-up of Pangea commenced with rifting between the Arctic-North Atlantic and between Greenland and Scandinavia, which is called the Kimmerian phase. The rift slowly propagated into to the central Atlantic domain, marking the future line of continental break-up. An eastern branch developed in the North Sea are during the Triassic, dissecting the Southern Permian Basin into several rifts. East-west extension had reached the southern North Sea during the Middle Triassic, however the rate of extension decreased southwards. At the end of the Late Triassic a period of tectonic quiescence occurred, however regional subsidence continued (Geluk, 2007).

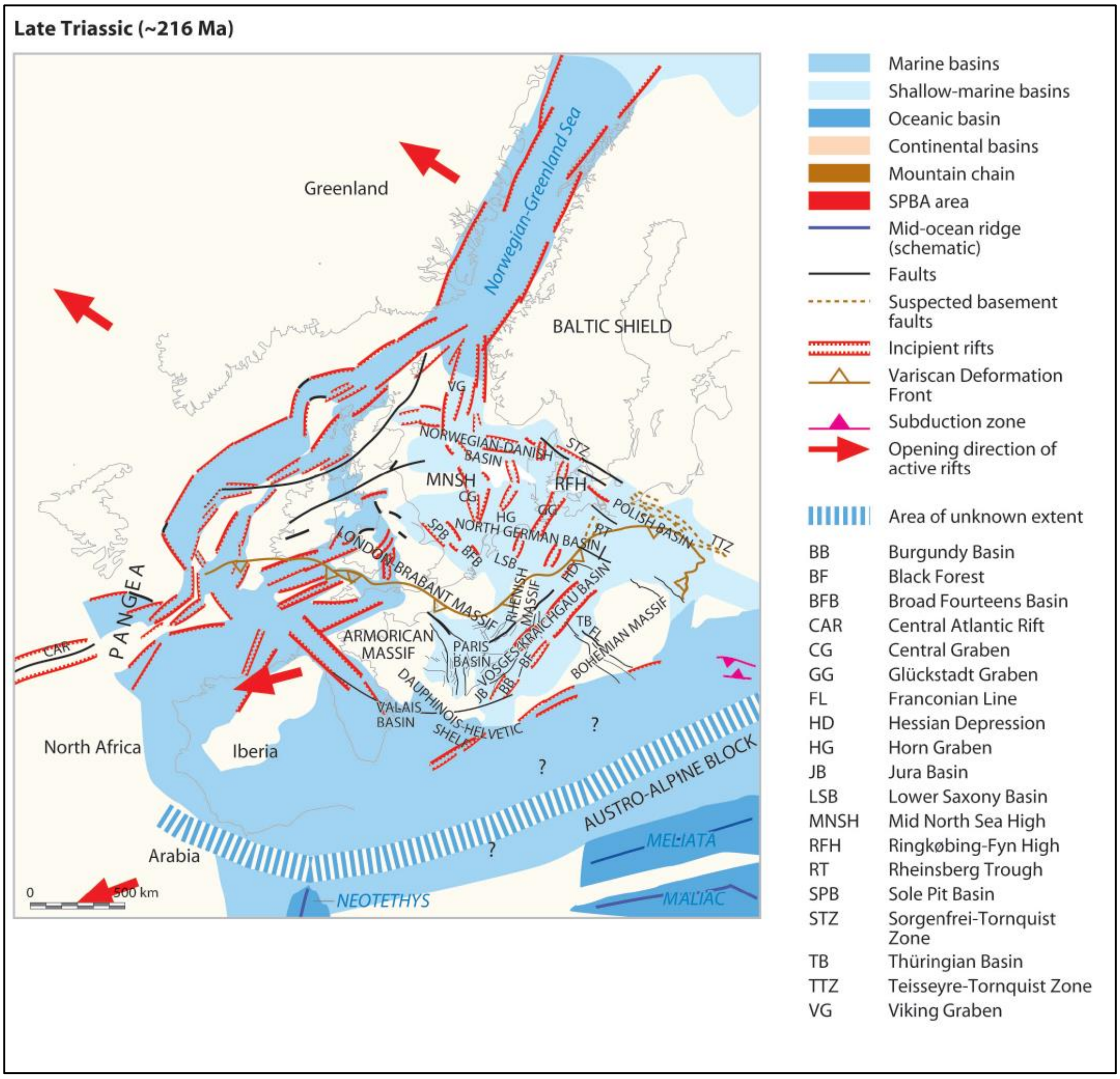


Figure 8: Structural overview map of the North Sea Area during the Late Triassic (Keuper, ~216 Ma) Source Southern Permian Basin atlas, pp 35.

With the withdrawal of the Zechstein sea from the Southern Permian Basin, sedimentation changed back to continental. In the Early Triassic fine grained lacustrine to marine clastics were deposited , forming the Lower Bundsandstein Formation. These deposits were followed by the Main Bundsandstein Formation, consisting of coarser fluviatile and aeolian clastics. Marine conditions took over in during the Middle Triassic, resulting in the deposition of the Röt and Muschelkalk Formations. The Muschelkalk is followed by the Keuper Formation, which contains finely grained coastal-plain to marine clastics and covers the complete Late Triassic (Van Adrichem Boogaert & Kouwe, 1993-1997).

The presence of thick salt deposits below the Triassic sediments and fault activity resulted into salt halokinesis. Salt behaves in a visco-plastic way, when it is buried below 500m, while other sediments show brittle deformation. Salt movement will initially be mainly lateral, forming so called salt-pillows, when the sedimentary cover is not yet broken. Halokinesis can be triggered due to long periods of extension, such as started during the Middle and Late Triassic. As a result of halokinesis the distribution and thickness of the Upper Germanic Trias Group is greatly affected by the salt movement (Geluk, 2007).

Jurassic

The main tectonic elements in the subsurface of the Netherlands developed during the Late Jurassic and Early Cretaceous, Late Kimmerian rifting. Figure 9 gives an overview of the plate tectonic configuration during the mid-Jurassic. In Triassic and Jurassic times the Netherlands structure changed from one single basin to an intricate pattern of smaller, fault bounded basins and highs, a multi-basinal pattern (Wong, 2007). The Early Jurassic was a period of relative tectonic quiescence and regional subsidence prevailed. In the Middle Jurassic the thermal Central North Sea dome developed, and much of the Dutch offshore was uplifted. Subsidence started again in Callovian and Oxfordian times, resulting in the crustal separation in the Central Atlantic and Tethys domains. With the crustal separation, rifting accelerated in the North Sea, creating for example the Viking and Central grabens and the Dutch Central Graben. In the southern part of the North Sea extensional basin with a NW-SE orientation developed, such as the Broad Fourteens, West Netherlands, Central Netherlands and Vlieland basins and Roer Valley Graben. The developed NW-SE orientation of the Mesozoic extensional basins in the South and West of the Netherlands was not conform with the assumed E-W direction, as observed in the northern part of the North Sea. The geometry of the southern basin was probably controlled by pre-existing structural elements, such as the those of the Caledonian Orogeny (De Jager, 2007 and Wong, 2007).

Salt halokinesis played a major role in the structuration and development of the subsurface of the Netherlands off and on shore. The Upper Jurassic is mainly found inside the extensional basin, outside those basins it is only found associated with salt induced rim synclines or transverse fault zones (Geluk, Paar and Fokker, 2007).

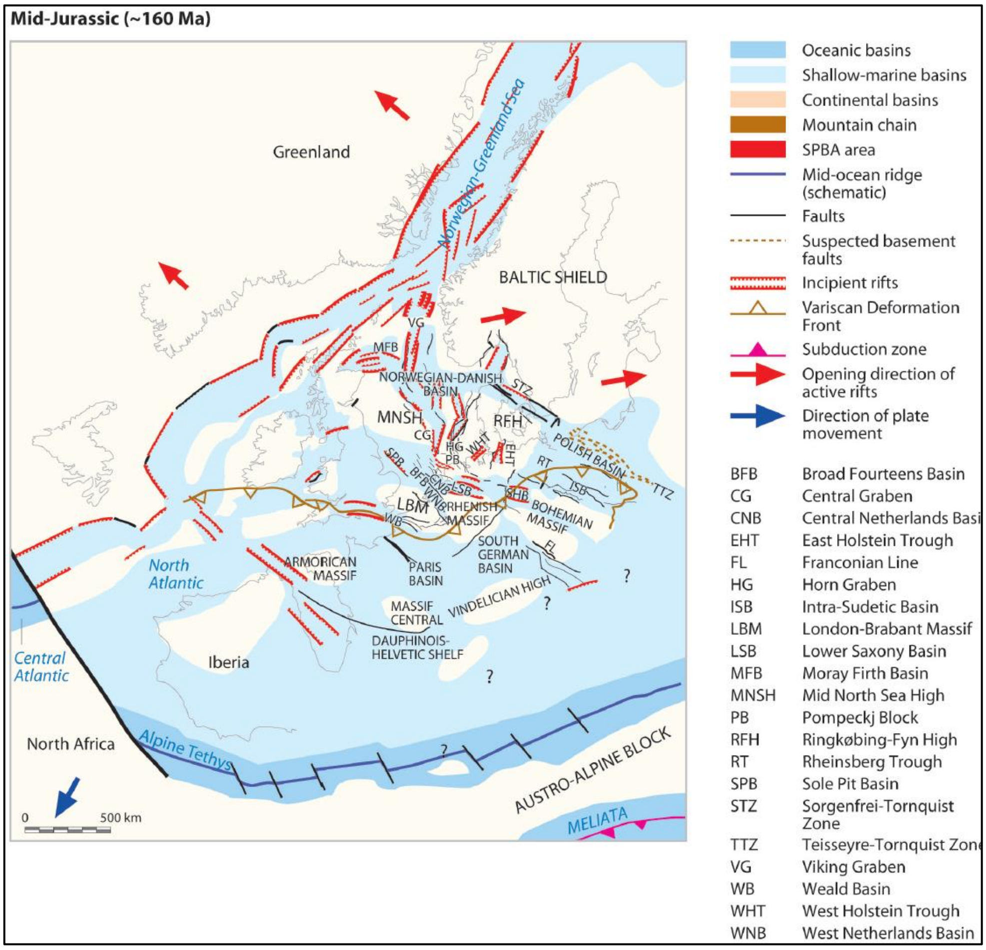


Figure 9: Mid Jurassic (~160 Ma) tectonic map of the North Sea. Source Southern Permian Basin Atlas pp 36.

The end of the Triassic was marked by a change in depositional setting. During the Permian and most of the Triassic deposition took part in an arid continental to highly restricted marine environment. From the latest Triassic into the Early Jurassic the environment changed to an open Marine system. In the open continental sea up to 1800m of fine-grained clastics of the Altena Group were deposited (Van Adrichem Boogaert & Kouwe, 1993-1997). At the end of the Early Jurassic the organic-rich shales of the Posidonia Formation were deposited. A period of uplift associated with thermal Central North Sea dome, resulted that sedimentation was only restricted to the rift basin. The developed NW-SE extensional basins were filled with locally more than 2500m of sediment, which belongs to the continental Schieland group, mainly marine Scruff Group and continental to restricted marine Niedersachsen group. The latter is dependent on which basin is involved. (Wong, 2007)

Cretaceous and Tertiary

After the opening of the North Atlantic, tectonic activity decreased in the area of the Netherlands and extensional stresses were mainly concentrated on the area between the British Iles, Norway and Greenland. The late Cretaceous was characterized by a period of regional thermal subsidence and rising sea levels. The entire area of the Netherlands was submerged by a shallow sea, depositing up to 1500m of chalk. The convergence of Africa and Arabia commenced during the Late Cretaceous, closing the Tethys oceanic basins. The gradual development of the Alpine orogenic system during the

Late Cretaceous and Paleocene, resulted in increasing stresses on its northern foreland. These stresses resulted in the inversion of the Mesozoic extensional basins. Inversion related uplift resulted in thinning and erosion of the Upper Cretaceous Chalk and Lower Tertiary clastics. Basin inversion was strongly modified by the presence of Zechstein Salt. In the West Netherlands Basin where no Zechstein salt is present, pre-existing faults were reactivated in a reverse manner, creating prominent structures as flower or pop-up structures. In the Dutch Central Graben, in which more than 1km of salt was deposited, the pre-existing faults were completely detached. This resulted in a broad uplift of deposits younger than the Zechstein (Herngreen & Wong, 2007).

Rifting in the Lower Rhine Graben propagated into the Netherlands during the Tertiary. Up to 2000m of Tertiary sediments were deposited in the down faulted Roer Valley Graben. Tectonic activity continued to the present day, as indicated by recent earthquakes along the main bounding faults. The south-eastern part of the Netherlands is being uplifted in conjunction with the uplift of the Rhenisch Massif. While much of the North Sea still subsides (Wong et al., 2007).

In Tertiary times the Fenno-Scandian Shield experienced a gradual uplift. As a consequence of the Eridanos delta developed, which resulted in an increased clastic influx into the North Sea. The delta system prograded westwards into the deeper waters of the North Sea Basin. Ultimately shallow water conditions were established throughout the southern North Sea area, and quaternary deposits reached up to ~1000m in the northern part of the Dutch offshore (Pharah et al., 2010).

3.1 Study area structural elements

The study area is characterized by several important structural elements, which are visible on seismic and have influenced the character of the Zechstein in many ways. The development of the area was probably controlled by earlier basement lineaments. Structural mapping (Wride et al., 1995) revealed 3 main fault directions: 1) NW-SE attributed to the Variscan fault belt, 2) E-W originated from pre-Variscan Carboniferous extension and 3) N-S trend that probably represent an early Caledonian or older fold axis (Wride, 1995).

Three major rift phases have been recognized in the North Sea Area as described by Wride, 1995. First Permian rifting, that is locally associated with Rotliegend volcanics. Second, Triassic to mid Jurassic and third Upper Jurassic to Tertiary rifting. The Elbow Spit High is the most important structural element in the study area, since it was already present before Zechstein deposition. The Elbow Spit platform is structurally linked to the Elbow Spit High and will be discussed separately. The Step Graben is the shallower equivalent of the Dutch Central Graben and borders the Study area to the East. Seismic has revealed a graben like structure in the northern part of the study area, called Outer Step Graben by Wride 1995. Figure 10 shows the different structural elements of the study area.

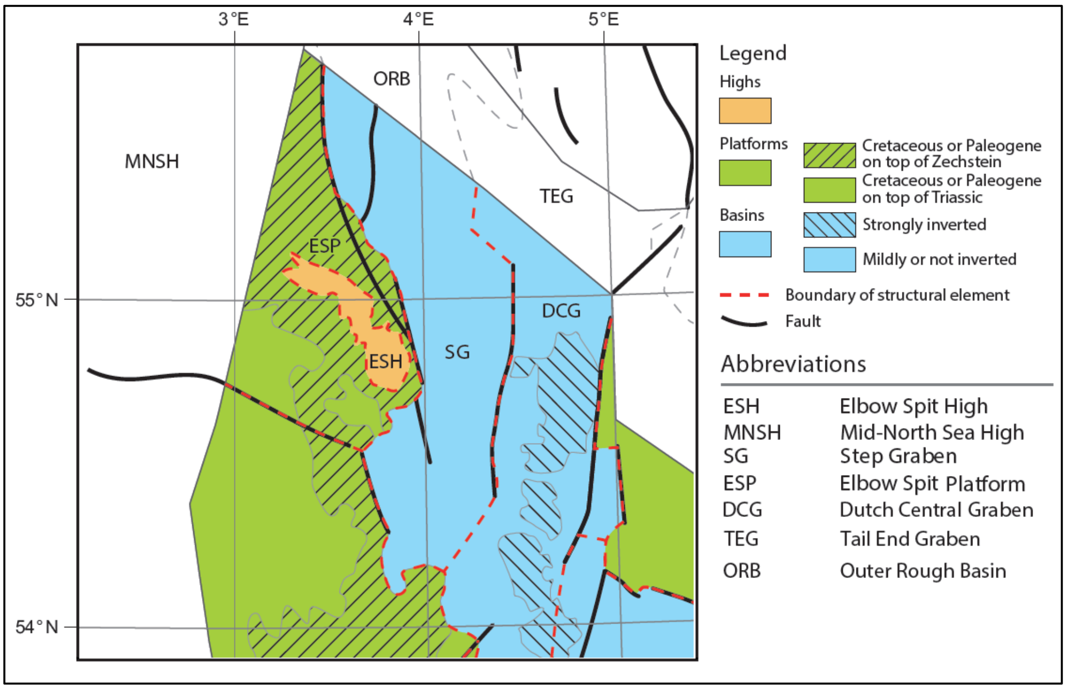


Figure 10: Late Jurassic – Early Cretaceous structural elements of the DEFAB area. Source Kombrink et al., 2012.

3.1.1 Elbow Spit High (ESH)

The Elbow Spit High is an area which was probably established in the Early Devonian and was present throughout the geological history of the North Sea. The Carboniferous in the ESH area is partly eroded or non-deposited and Upper Cretaceous sediments overlie Devonian and Carboniferous rocks. The nature of the ESH is probably related to an Early Devonian magmatic body, which explains the buoyant nature of the ESH. During the mid Kimmerian uplift, the ESH was located on the southern border of the Thermal Central North Sea Dome. Which resulted in the erosion of the entire Triassic and Jurassic. To the South-West the ESH gradually changes into the Elbow Spit Platform, while to the North-East the ESH is fault bounded to the Step Graben(Kombrink et al., 2012).

Several wells have drilled into the Elbow Spit High such as A17-01, E02-01 and E06-01. A17-01 reached the plutonic Caledonian basement on the Elbow Spit High, consisting there of an altered biotite-monzo-granite with a minimum age of ~346Ma (Van Adrichem Boogaert & Kouwe, 1993-1997).The well clearly shows the major unconformity associated with the Elbow Spit High, the Upper Cretaceous Ekofisk Formation lies directly ontop of the Late Devonian Lower Buchan Member, indicating the absence of Zechstein on top of the Elbow Spit High. The unconformity represents a time span of roughly ~310Ma. In well E06-01 the Zechstein-1 Carbonate Member is directly overlain by the Upper Cretaceous Ommelanden Formation. This probably indicates the erosion of the Triassic and Jurassic strata during the mid Kimmerian phase.

The seismic section in appendix 1 clearly shows the gradual dip of the onlapping reflectors from the South-West onto the Elbow Spit High. Below A17-01 a very transparent seismic section is present, which could be interpreted as the plutonic basement reached by A17-01. In well E02-01 the Ommelanden Formation is directly underlain by the Carboniferous Epen Formation. This confirms that the younger (than Devonian) stratigraphic units are onlapping onto the Elbow Spit high, from the South-West. The seismic section clearly shows the steep faults to the North-East of Elbow Spit High. In this area the Triassic is very well preserved and large salt domes are present. Further to the North-East the chalk is thickening, indicating that during the Cretaceous the Elbow Spit High was still a high.

3.1.2 Elbow Spit platform (ESP)

The Elbow Spit Platform can be seen as a continuation of the Elbow Spit High towards the North, South and West of the ESH. Together with the ESH, the ESP can be seen as the southern continuation of the Mid North Sea High. Kombrink et al., (2012) introduced the term Elbow Spit Platform, which suggests that the ESP is an actual platform, however the seismic in appendix 1 reveals that the Elbow Spit Platform is gently dipping towards the South-East. The term platform suggests that the structure is higher than the surrounding area and that the water depth is shallow in a Zechstein carbonate context. However Kombrink et al., (2012) introduced the term Elbow Spit Platform, because it is in closer agreement with other platform areas. A more accurate description for the Elbow Spit Platform could be the Elbow Spit Shelf. The ESP is characterized by the presence of Cretaceous and Triassic sediments on top of Permian rocks. Towards the East ESP is bounded by very well developed normal faults of the Step Graben, see appendix 1.

3.1.3 Step Graben

The study area is bounded towards the East by steeply dipping normal faults of the Step Graben. The Step Graben can be seen as a North-South trending complex terrace structure with lows and troughs, between the Elbow Spit High and the Dutch Central Graben. Deeper parts of the Step Graben often contain significant amounts of Triassic and Cretaceous sediments (Wride, 1995). Early Jurassic sediments were probably deposited in the area, however they were eroded during the mid Kimmerian phase. Late Jurassic sediments are still present in the area, whether in a very patchy manner (Kombrink et al., 2012). The transition into the Step Graben is also recognized by thick salt layers and the occurrence of salt domes along the normal faults.

The Dutch part of the Step Graben contains the Outer Step Terrace, Outer Step Trough, Step Low and Step Trough, see appendix 2. These lows are separated by highs such as the Step High, between the Step Low and Step Trough. The Step High is N-S trending major basement high (Wride, 1995).The eastern part of the Step Graben area will be discussed later in the report.

4.0 Zechstein lithological description

The Zechstein group in the Netherlands comprises 5 evaporite cycles ($Z_1 - Z_5$) all of formation rank. In the deepest part of the Southern Permian Basin up to 7 cycles are found. The names of the Zechstein Formations have been derived the German nomenclature, based on Zechstein outcrops near German villages. In each formation several lithological members are distinguished , however considerable facies variations may occur within each member. Table 2 provides a general overview of the formations and members found in the Zechstein Group and figure 11 gives a schematic overview of the ltihologies found in the Zechstein interval.

Table 2: This table gives a general overview of the Zechstein stratigraphy. Source for the presented Zechstein ages is Peryt et al., 2010 – Southern Permian Basin Atlas).

		Zechstein Group				
		Formation		**Member**		**Age (Ma)**
		Zechstein Upper Claystone	ZEUC	-	-	~253.7 to ~242.8
		Zechstein-5 Ohre	ZEZ5	Zechstein-5 Salt	ZEZ5H	~254.2 to ~253.7
				Zechstein-5 Salt Clay	ZEZ5R	
		Zechstein-4 Aller	ZEZ4	Zechstein-4 Salt	ZEZ4H	~254.9 to to ~254.2
				Zechstein-4 Pegmatite Anhydrite	ZEZ4A	
				Red Salt Clay	ZEZ4R	
		Zechstein-3 Leine	ZEZ3	Zechstein-3 Salt	ZEZ3H	~255.4 to ~254.9
				Zechstein-3 Main Anhydrite	ZEZ3A	
				Zechstein-3 Carbonate	ZEZ3C	
				Grey Salt Clay	ZEZ3G	
		Zechstein-2 Stassfurt	ZEZ2	Zechstein-2 Roof Anhydrite	ZEZ2T	~256.4 to ~255.4
				Zechstein-2 Salt	ZEZ2H	
				Zechstein-2 Basal Anhydrite	ZEZ2A	
				Zechstein-2 Carbonate	ZEZ2C	
Basal Zechstein Unit				Zechstein-2 Red-brown Salt Clay	ZEZ2R	
		Zechstein-1 Werra	ZEZ1	Zechstein-1 Anhydrite	ZEZ1W	~257.4 to ~256.4
				Zechstein-1 Carbonate	ZEZ1C	
				Coppershale	ZEZ1K	

The Zechstein sequences are the result of periodically flooding of the Zechstein Sea. Each Zechstein sequence consist of evaporites, carbonates and some minor claystone deposition. The evaporites consist mainly of anhydrite and rock salt (halite) and some minor bitter salts or Potash salt. Zechstein cycle boundaries are picked on maximum flooding surfaces, and can be approached with a genetic sequence stratigraphic model (Geluk, 2007). A typical Zechstein cycle is characterized by the following succession, from bottom to top: Claystone, Carbonate, Anhydrite, Halite and last Potash Salt. The Zechstein Formation is strongly affected by halokinetic movements, resulting in breaking and migration of Zechstein Members. The upper boundary of the Zechstein group has been put on the base of the Lower Germanic Trias Group. The Lower Germanic Trias Group is marked by a minor hiatus, representing the transition in depositional environment, from the laterally variable nature of the Zechstein into the well-correlatable Lower Triassic sediments. However as a result of halokinesis or erosion younger units may overlie the Zechstein Group. The lower boundary of the Zechstein Group in the Southern Permian Basin has been picked on the base of the Coppershale (ZEZ1K). This thin bituminous rich shale layer can be recognized throughout the basin. The ZEZ1K is also the result of the first Zechstein transgression (Van Adrichem Boogaert & Kouwe, 1993-1997). The Zechstein is present almost throughout the entire Southern Permian Basin. However it is missing on the London-Brabant Massif, the Ringkøbing-Fyn High, the Elbow Spit High, The Texel-Ijsselmeer High and some smaller unnamed highs. Figure 12 shows the distribution of the Zechstein throughout the Southern Permian Basin. Its absence on the highs is mainly the result of the Kimmerian uplift (Jurassic) and erosion and some of the highs were already elevated during deposition of the Zechstein.

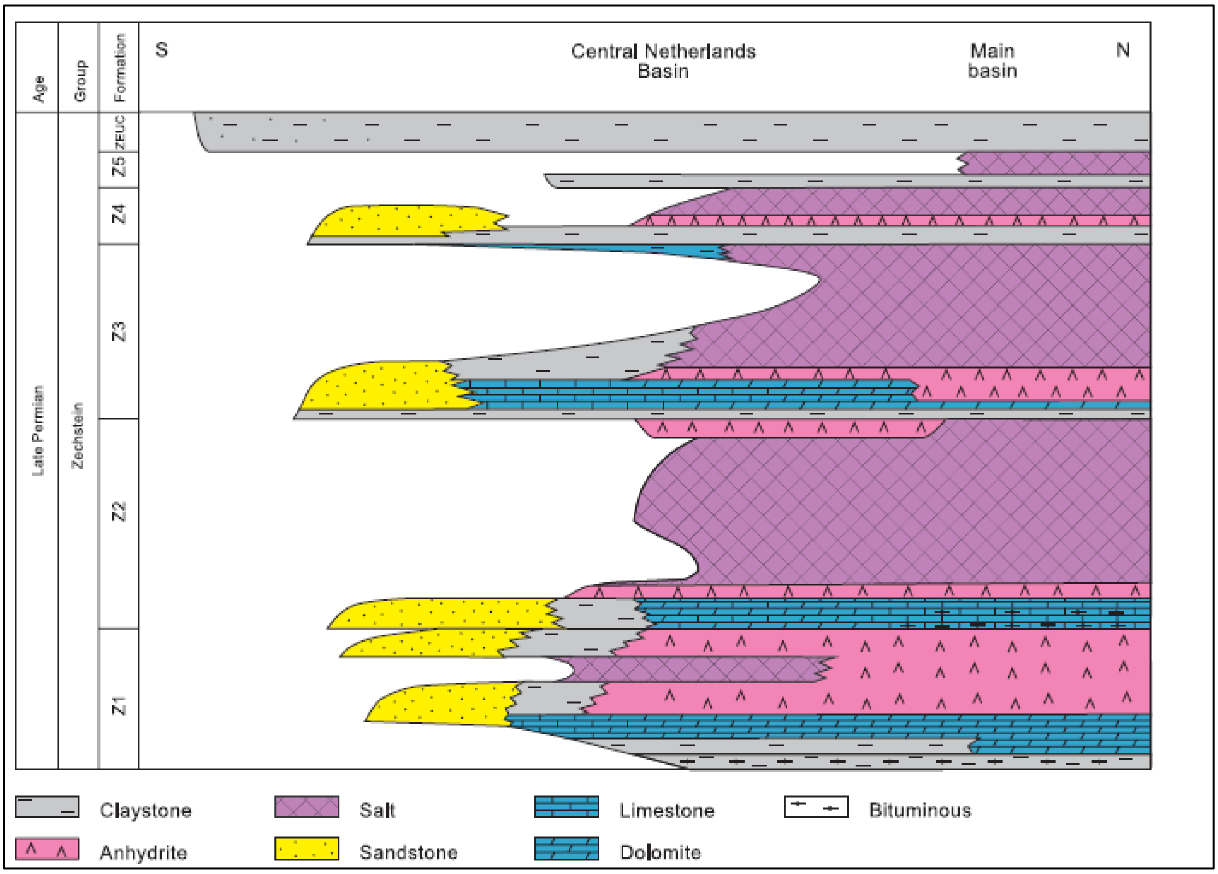


Figure 11: Schematic stratigraphic diagram for the Zechstein Group. Up to five Zechstein cycles are found in the Netherlands, each of formation rank. Source: Geluk, 2007.

The general depositional setting of the Zechstein Group can be described as a peri-marine to marine setting. During the first two Zechstein Formations, the Zechstein-1 Werra and Zechstein-2 Stassfurt Formation, the depositional setting varied from deep marine in the basin centre, to lagoon and sabkha/mudflat at the basin margins. The clastics found in the south-west part of the Southern Permian Basin were deposited in an estuarine setting. During the deposition of the Zechstein-2 halite Member (ZEZ2H) the topography in the basin was filled-in. And Zechstein-3 Leine Formation was deposited in a shallow marine-environment. Younger Zechstein cycles, the Aller and Ohre Formations, were deposited in a more hypersaline shallow-marine environment in the basin and no carbonates are present. The claystone and halite alternations are more typical of a playa lake depositional setting.

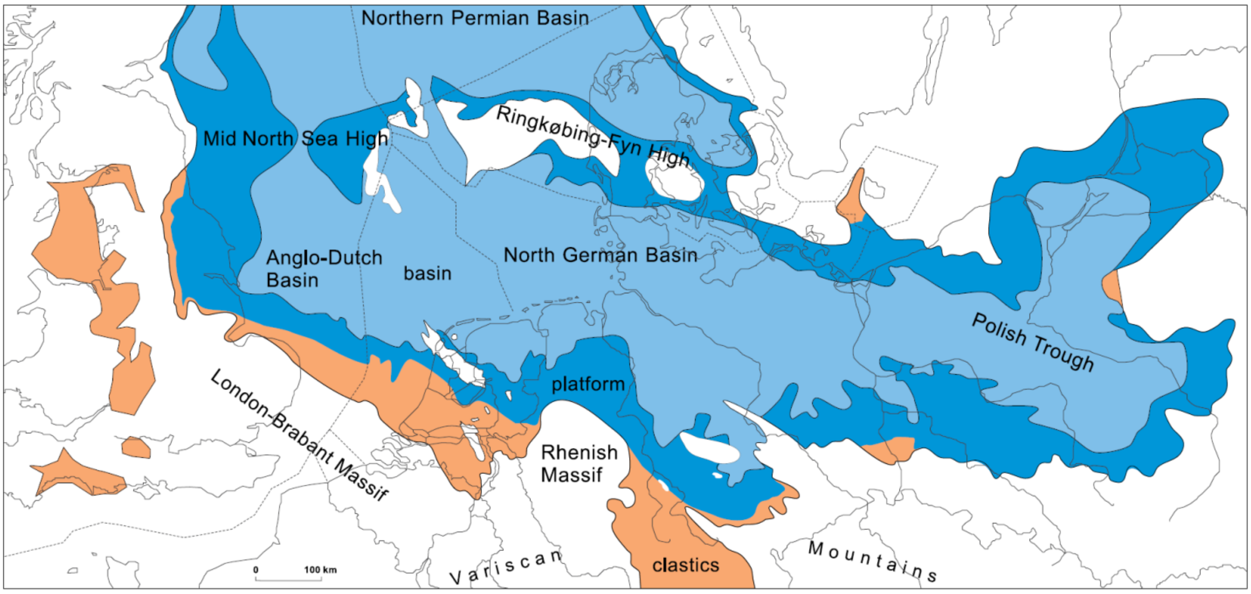


Figure 12: Present-day distribution of the Zechtstein-2 carbonate Member. White area's is non deposition of the Zechstein, light blue is basinal, dark blue is platform facies and orange corresponds with terrestrial deposits. (Source: Geluk, 2007 - Geology of the Netherlands)

4.1 Zechstein 1 cycle

The first Zechstein cycle or Werra Formation is subdivided by 5 lithological units: The Coppershale Member (ZEZ1K), Zechstein 1 Carbonate (ZEZ1C), Zechstein 1 Anhydrite (ZEZ1A), Zechstein Salt (ZEZ1H) and Zechstein Roof Anhydrite (ZEZ1T), see table 2.This formation can be found throughout the Southern Permian Basin, however variations in lithology and distribution do occur, for example ZEZ1H is only found in the deeper parts of the basin. And the ZEZ1C has a profound facies difference between basinal and platform setting.

Depositional setting

In late Permian times rifting in the northern part of the North Sea area resulted in a connection between the Southern Permian Basin and the Barents Sea. This connection resulted in an influx of water into the Southern Permian Basin. Under the prevailing dry climate an evaporitic environment was established resulting in widespread cyclic deposition of evaporites. The controlling mechanism for this cyclicity is the deglaciation and glaciation of Gondwana, resulting in a glacio-eustatic sealevel change (Ziegler, 1990).

The base of the ZEZ1 is marked by the Coppershale Member and can be found basin wide. The ZEZ1K was the first deposition following the transgression of the Zechstein Sea, which flooded the pre-existing low relief [Van de Sande et al., 1996]. The following ZEZ1C Member formed in oxygenated waters where the water-depth was low enough to establish carbonate build-ups. The distribution of the ZEZ1C is mainly controlled by the pre-existing relief present in the Southern Permian Basin.
The ZEZ1C grades up into the Zechstein-1 Anhydrite Member as a result of increased salinity throughout the basin. Gypsum precipitation was triggered by intense evaporation close to the sea-surface (Van der Baan, 1990). In shallow-water areas anhydrite precipitation occurred rapidly enough to build up to sea level, exceeding overall sea-level rise and subsidence. Figure 13shows the depositional model for the anhydrite precipitation, this figure illustrates the differences in development between basin and platform. In the Zechstein Sea a chemocline was established at

around 15m water depth, around this chemocline sulphate reducing bacteria proliferated. Gypsum crystals formed in areas with exceeding the ~15m water depth, were effectively reduced by the sulphate reducing bacteria. Anhydrite was able to reach the basin floor after storm events. During and after a storm the established chemocline was mixed throughout the water column, allowing the gypsum crystals to reach the basin floor. This depositional setting resulted in a large lateral differences in anhydrite precipitation rates, resulting in a marked relief difference of up to ~400m between basin and shallow-water areas. The environment during shallow-water anhydrite precipitation can be compared with a shallow-water sabkha environment. After the sulphate deposition ceased, the remaining peripheral sub-basins were filled with halite (T.J.A. Reijers, 2012)

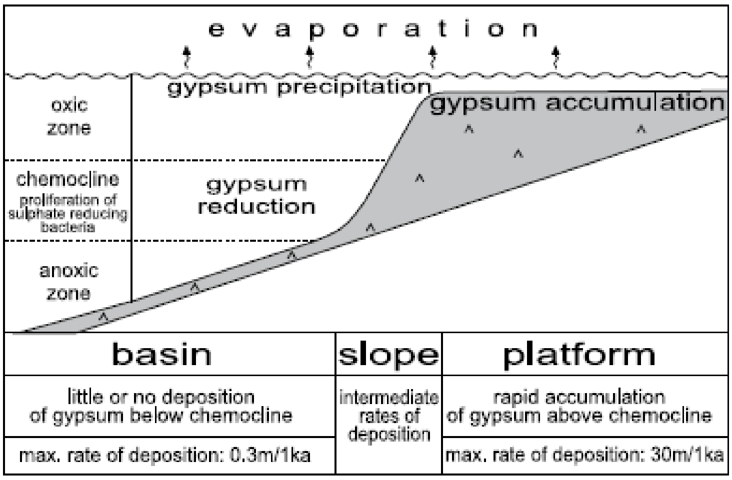


Figure 13: Overview of the depositional setting for the anhydrite member. There is a great difference between basin and platform anhydrite deposition. (Source: Van der Sande et al., 1990).

Lithological description

The Coppershale(or Kupferschiefer) Member is a finely laminated, brownish-black bituminous shale with a thickness of up to ~2 m thick and is characterized on wire-line logs by high gamma-ray and low acoustic velocity readings. The total organic content (TOC) is roughly ~5% and locally very rich in copper deposits (Reijers et al., 2012). The source rock potential of the ZEZ1K is quite low, as a result of its thickness (Taylor, 1998).

The Zechstein 1 Carbonate can be divided into two settings: platform/slope and basinal. The ZEZ1C associated with platform/slope can be up to ~200m thick and consist of marls and carbonates. Whilst the ZEZ1C associated with the basinal setting is only 8-10m thick. The basinal facies contains mainly secondary limestone and occasionally dolomite and is characterized by fine dark organic-rich laminations, and sometimes white anhydrite laminea. Another striking feature of the basinal facies is that it is devoid of any fossil. (Van der Baan, 1990)
Platform/slope setting can be further divided into the following facies: slope, shallow marine, restricted/unrestricted platform, deeper lagoon and arid flood-plain/playa facies. The deeper lagoon facies is characterized by a monotonous well-bedded dolomite mudstone, without any fossils. The unrestricted platform facies is build-up of a variety of carbonate rock types, including ooid-grainstones, pisoid-grainstones, intraclast-grainstones, bioclast-grainstones and grapestones. Restricted platform facies are composed of supratidal pavement breccias, storm layers, calcrete

hardpan crusts, thrombolites and beds of nodular anhydrite (Van der Baan, 1990). Arid floodplain/playa facies are recognized by a succession of red-brown and grey-green claystone and siltstones, sometimes intercalated with streaks of nodular anhydrite. Common features in these facies are sheet flood deposits and desiccation cracks. Laminated secondary limestone and dolomites, similar to the basinal facies, represent the shallow marine facies. However it differs from the basinal facies in containing fossils. Sedimentary structures are indicative for the slope facies, such as conglomeratic debris flows, slumps and slides. Lithologically the slope facies contains secondary limestone and dolomite (Van de Baan, 1990).

The Zechstein 1 Anhydrite Member is a thick white/grey deposit, which created a pronounced basin relief contrast. Anhydrite deposition in shallow waters resulted in a thick, up to 250m, succession. Whilst in deeper marine conditions anhydrite deposition was almost nil(T.J.A. Reijers, 2012). However storm related anhydrite is found in the deeper parts of the basin. This anhydrite is deposited due to mixing of the chemocline after a storm event, characterized by thin laminae of anhydrite (Van der Baan, 1990).

Zechstein 1 Salt is not widespread and is only found in peripheral sub-basins away from the main basin (T.J.A. Reijers, 2012). The Zechstein 1 salt deposition is characterized by translucent and crystalline halite.

Petroleum geological relevance

The Coppershale could function as a potential source, as the TOC is up to 5%. However there is not very much known about the source rock potential of the Coppershale. If the Coppershale is mature enough it could possible source the platform and slope facies of the Zechstein-1 Carbonate Member. The main reservoir rock in the Zechstein-1 Formation is found in the ZEZ1C Member, and mainly in the ZEZ1C platform dolomites. Several Zechstein-1 Carbonate fields are producing gas in the UK Southern North Sea. For example the Hewet field which shows a very heterogenous porosity distribution, indicating the complexity of carbonate reservoir rocks. Best porosities area found in the upper part of the Zechstein-1Carbonate platform. However in the Netherlands gas shows have been reported from basal Zechstein Carbonates, but porosity and permeability of these rocks is normally to poor for commercial production (Geluk, 2000). The Zechstein-1 Halite Member could act as a seal. However the ZEZ1H is not deposited everywhere, which makes the risk associated with this seal quite high.

4.2 Zechstein 2 cycle

The second Zechstein cycle or Stassfurt Formation is deposited after renewed transgression and flooding of the Zechstein Sea. The base of the Zechstein 2 cycle is marked by the basal Carbonate Member (ZEZ2C) or ‘main dolomite’, followed by the basal Anhydrite Member (ZEZ2A), the Zechstein 2 Halite Member (ZEZ2H) and Zechstein 2 Roof Anhydrite (ZEZ2T). There is a pronounced thickness contrast associated with the Zechstein 2 cycle. In the northern offshore of The Netherlands the Zechstein 2 cycle thickness can reach up to 700m, whilst in the southern part of The Netherlands it is only 50m thick. This is the result of large lateral differences in halite deposition. The southern limit of the ZEZ2C lies more to the North compared with the ZEZ1C, this is made visible in figure 14, which illustrates the facies distribution of the Zechstein 1 and 2 Carbonate Member. The topography present after the deposition of the ZEZ2A was to a great extend leveled out by the deposition of the

ZEZ2H. The upper boundary of the Zechtein-2 cycles lies below the Grey Salt Clay Member of the Zechtein-3 Formation. The Zechstein-2 Formation can be recognized as a complete evaporative cycle, as the top most recessive anhydrite member (ZEZ2T) is present.

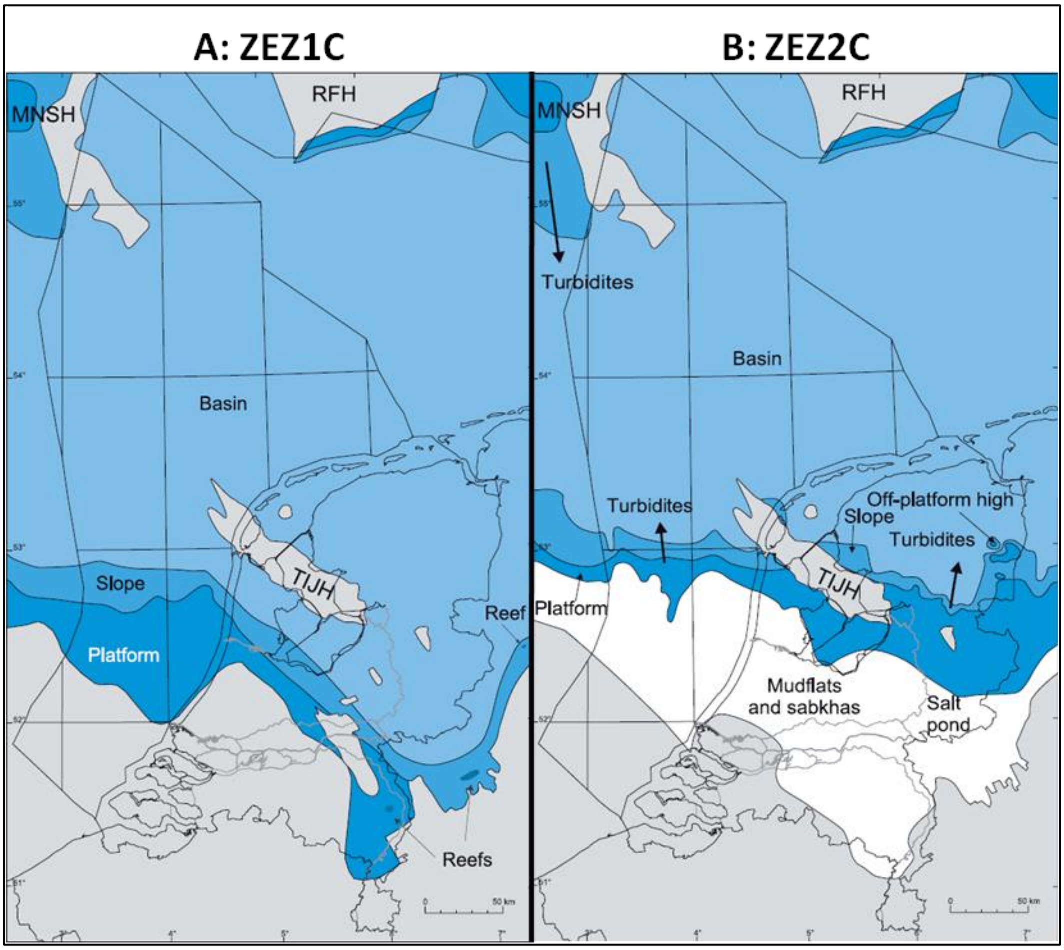


Figure 14: A) Facies map of the ZEZ1C Member. B) Facies map of the ZEZ2C Member. Facies map B shows that the Zechstein-2 carbonate is located more to the north compared with the Zechstein-1 carbonate.

Depositional setting

The second transgression, which resulted in re-flooding of the Zechstein Sea, did not reach as far as the first transgression, see figure 14. This renewed flooding of the Southern Permian Basin reduced the salinity and sedimentation changed from halite & anhydrite to carbonate sedimentation. The distribution of the ZEZ2C is mainly controlled by the pre-existing relief formed by the Zechstein-1 Formation, and mainly the Zechstein-1 Anhydrite Member. Figure 15illustrates how the shape of the ZEZ1A Member controls the distribution of the depositional setting (basin, slope and platform) of the Zechstein-2 Carbonate Member.

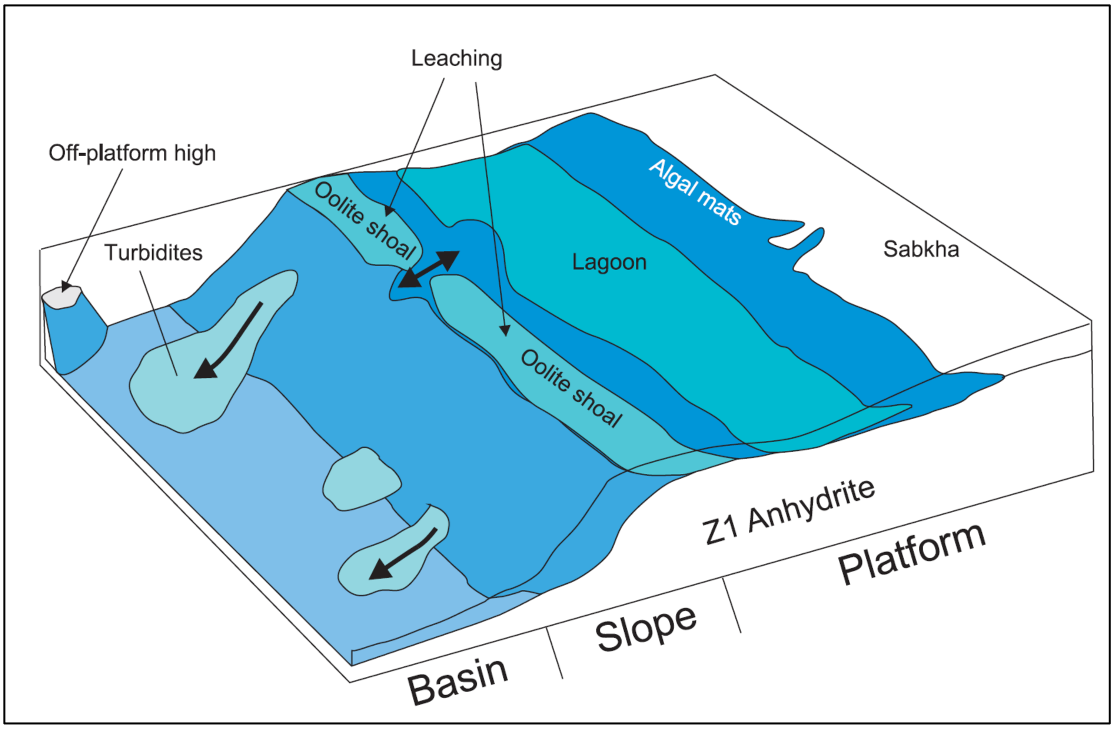


Figure 15: Depositional model for the Zechstein-2Carbonate Member. The distribution of the basin, slope and platform environment is mainly controlled by the distribution of the ZEZ1A Member. (source Geluk, 2007 – Geology of the Netherlands.)

When salinity increased, carbonate sedimentation changed into anhydrite precipitation. The depositional mechanism for the Zechstein-2 Anhydrite Member is the same as the model for the Zechstein-1 Anhydrite Member. The distribution follows again the pre-existing relief, formed by the ZEZ1A and ZEZ2C and in other areas with a shallow-water depth. Relative sea-level continued to drop and the increased salinity resulted in the precipitation of halite. The change from anhydrite to halite marked the end of the Basal Zechstein Unit (table 2). The ZEZ2H leveled out the existing relief in the Southern Permian Basin, resulting in a rather shallow, featureless basin. Figure 16 shows the evolution of the basin from start to end of the Zechstein-3 Formation.

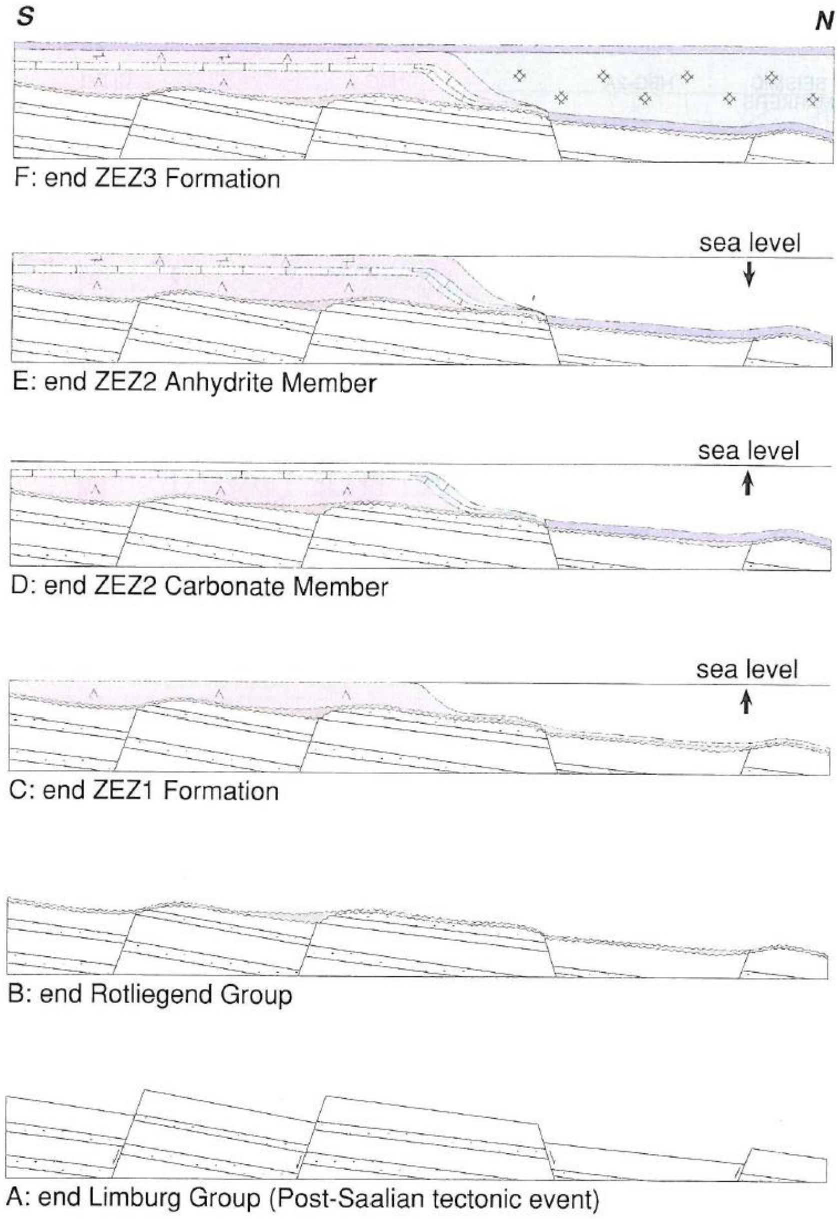


Figure 16: Schematic sedimentation history of the Basal Zechstein Unit. Vertical arrows indicate relative change in sea-level. A) Illustrates the topography at the end of the Limburg Group (or Post-Saalian tectonic event). B) Shows the deposition of the Coppershale Member, just after the first transgressive cycle. Panel C shows the deposition of the ZEZ1A, illustrating the influence of water-depth. Panel D represents the deposition of the Zechstein-2 Carbonate Member, after renewed flooding, and the influence of the ZEZ1 Formation. When relative sea-level dropped and salinity increase, anhydrite precipitation started, panel E. At the beginning of the ZEZ3 Formation the whole basin was filled with Zechstein-2 Halite, erasing all existing relief, panel F.

Lithological description

The Zechstein 2 Carbonate Member is very similar to the Zechstein 1 Carbonate Member, and can be divided into three facies: basinal, slope and platform (Geluk, 2007). The facies distribution of the ZEZ2C owes their areal distribution to the profile established by the ZEZ1A Member, see figure 15 & 16. The basinal deposits are up to 8-12m thick, finely laminated carbonates, with dark-colored bitumous laminea, also known as the 'Stinkkalk' or 'Fetid limestone'. The basinal ZEZ2C has up to 1.2% TOC, and is therefore a potential source rock(Geluk, 2007). The slope facies contains light-colored limestones and dolomites and re-deposited platform sediments. This facies can reach thicknesses up to ~200m in the eastern part of The Netherlands. Platform facies are made up of a complex oolitic, pelletoidal, bioclastic and pisolitic pack and grainstones, and finely laminated wackestones. As stated in the depositional model the shape and distribution of the ZEZ2C platform facies is controlled by paleogeography created by the ZEZ1A platforms.

The Zechstein 2 Anhydrite Member is a white to grey colored deposit, with a pronounced relief difference between basinal and platform settings. And is generally developed as a massive body of relatively pure anhydrite along the basin margins (Van Adrichem Boogaert & Kouwe, (1993-1997). In the deeper part of the basin the ZEZ2A is usually very thin, as a result of the chemocline which existed during deposition of the ZEZ2A.

The Zechstein 2 Salt Member consists of mostly (>95%) white translucent halite or 'rock salt'. The ZEZ2H thickness depends on the type of setting: platform, slope or basin. In basinal setting ZEZ2H thickness can reach up to ~600m, whilst in other setting the thickness is much smaller (Geluk, 2007) The ZEZ2H deposition filled the pre-existing relief in the Southern Permian Basin, which led to the pronounced thickness differences of the ZEZ2H.

The Zechstein 2 Roof Anhydrite Member is associated with the end of the Zechstein 2 salt deposition and marks the end of the Zechstein 2 cycle. The ZEZ2T is a thin and pure anhydrite unit, underlying the Grey Salt Clay Member. It thickness is usually up to an only a few meters. The Zechstein 2 Roof Anhydrite is only found in the central part of The Netherlands (Geluk, 2007).

Petroleum geological relevance

A possible source rock in the Zechstein-2 cycle could be the Zechstein-2 Carbonate basinal facies, or also known as the Stink-kalk. These rocks have source rock potential, with a TOC of up to1.2% (Geluk, 2007). Two Zechstein fields (Stadskanaal and Gieterveen) as well as a Zechstein discovery in the north-western offshore (E13-01) have oil shows probably sourced from the Zechstein-2 Carbonate basinal facies. The most import Zechstein reservoir rock is found in the Zechstein-2 Formation, the Carbonate Member. The best producing reservoir facies in this member is found in the slope deposits, however production still depends on the presence of fractures in the reservoir (Geluk, 2007). In the Netherlands producing Zechstein-2 Carbonate fields are found in the Drenthe area, such as the Emmen-field. The Zechstein-2 Formation also delivers an important seal, the Zechstein-2 Halite Member. The well-known Groniningen gas field is sealed by the salt of the Zechstein-2 Formation.

4.3 Zechstein 3 cycle

The third Zechstein cycle or the Leine Formation is the result of the result of renewed flooding of the Zechstein Sea. This third transgressive cycle starts with the deposition of the Grey Salt Clay (ZEZ3G), followed by the Zechstein 3 Carbonate (ZEZ3C), the Zechstein 3 Main Anhydrite (ZEZ3A) and ends with the deposition of the Zechstein 3 salt (ZEZ3H). The upper boundary of the Zechstein-3 Formation is put on the base of the Red Salt Clay of the Zechstein-4 Formation. The Zechstein-3 Formations is never developed as a complete evaporative cycle, as the top most anhydrites are absent. Figure 17 shows the distribution of the Zechstein-3 Formation through the Netherlands section of the Southern Permian Basin. When this facies distribution map is compared with figure 14, it becomes clear that the paleogeography of the Zechstein-3 Formation is more like a simple, ramp-type than the Zechstein-2 Carbonate (Geluk, 2000).

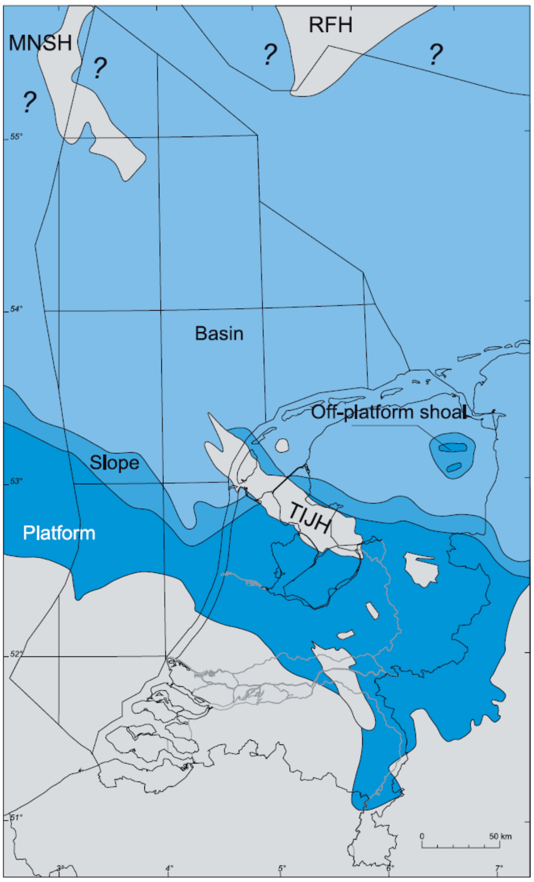


Figure 17: Facies distribution map of the Zechstein-3 Carbonate Member. Source Geluk 2000

Depositional model

The start of the deposition of the Zechstein-3 Carbonate Member started after flooding of the entire basin and records the most widespread transgression, with carbonates extending towards the margins of the basin(Geluk, 2000). The Zechstein-3 Carbonate Member varies a lot less in thickness than the ZEZ1C and ZEZ2C members. This is the result of the flattening of the basin, due to the ZEZ2H precipitation. And therefore the Zechstein-3 Carbonate Member does not show the same areal variation as the Zechstein-2 Carbonate Member. The fauna found in the Zechstein-3 Carbonate Member indicates that the salinity is slightly increased in the basin (Taylor et al., 1998). When relative sea-level dropped again sedimentation changed from carbonates to anhydrite. Which is only deposited on the northern parts of the Zechstein-3 Carbonate platform, slope and basin, see figure 18. Due to continued evaporation and relative sea-level drop, the precipitation of the Zechstein-3 Halite Member started.

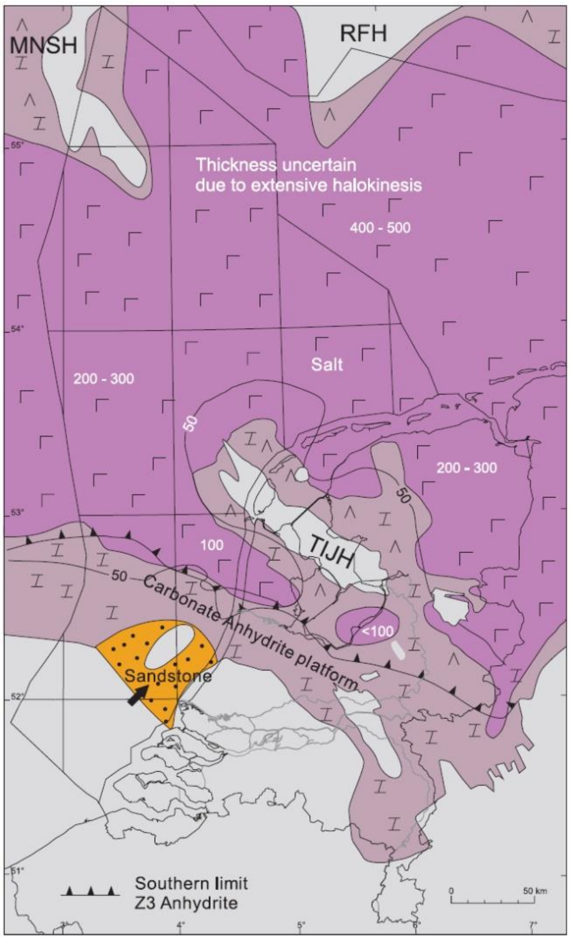


Figure 18: Facies and isopach map (in meters) of the Zechstein-3 Formation. It shows the maximum southern extend of the Zechstein-3 Anhydrite Member (Geluk, 2007 – Geology of the Netherlands).

Lithological description

Grey Salt Clay is an important regional marker, of thick, grey claystone, with a varying thickness of 5 to 10m.

The Zechstein 3 Carbonate Member facies development is not as well-developed as in the ZEZ2C, as result of the leveling out of the paleogeography by deposition of the ZEZ2H (Geluk, 2007). Again this carbonate member can be divided into three genetic facies: basin, slope and platform. The basinal facies contains a dark-colored limestone of a few meters thick, which is hardly distinguishable from the overlying ZEZ3A Member. Laminated and bioturbated carbonate mudstones, and silty dolomites represent the slope facies of the ZEZ3C. Compared to the slopes of the ZEZ1C and ZEZ2C the ZEZ3C slope is not as well-developed, it has a more gentle relief compared with the other two. Platform facies are recognized by the presence of grey microcrystalline dolomites and algal boundstones and are up to ~40m thick. Adjacent to the slope, platform facies contains oolitic and bioclastic-grainstones (Geluk et al., 2000).

The Zechstein 3 Anhydrite Member is a thick, up to ~100m, white/grey layer. As a consequence of Zechstein 2 salt movement, large Zechstein 3 carbonate slabs became embedded in the salt. These rafts form potential drilling hazards (Geluk, 2007).

The Zechstein 3 Salt can reach a thickness of up to ~300-400m and is divided into two units: 1)Basinal part, consisting of halite and 2) an upper part, containing two units of thick potassium magnesium salt layers (Geluk, 2007).

Petroleum geological relevance

The dark-colored basinal limestone of the Zechstein-3 Carbonate Member could function as a potential source rock, just as the basinal facies of Zechstein-2 Carbonate Member. However this is never tested and the TOC is also not known. Reservoirs in the Zechstein-3 Formation are found in the dolomitized platform facies of the Zechstein-3 Carbonate Member, and are mainly found in the western part of the Netherlands (Geluk, 2000).

4.4 Zechstein 4 cycle

The Zechstein 4 cycle or 'Aller Formation' can be subdivided into the Basal Claystone and Red Salt Clay (ZEZ4R), both characterized by widespread deposition throughout the basin. The Basal Claystone Formation is a maximum flooding surface and a therefore an important marker. The Red Salt Clay is composed of an anhydrite-bearing red claystone. These units are followed by the Zechstein 4 Pegmatite-Anhydrite (ZEZ4A) and the Zechstein 4 salt (ZEZ4H) (Geluk, 2007). The upper boundary of the Zechstein-4 cycle is put on the top of the Zechstein-4 salt Member. The Zechstein-4 Formation is an incomplete evaporation cycle, because the carbonate member and an upper anhydrite member are missing (Van Adrichem Boogaert & Kouwe, (1993-1997).

4.5 Zechstein 5 cycle

The occurrence of the Zechstein 5 cycle or 'Ohre Formation' is only limited to the north-east onshore and north-western offshore of the Netherlands. It can only be found where the Zechstein-4 Salt Member is fully developed (Van Adrichem Boogaert & Kouwe, (1993-1997).The Zechstein 5 cycle is composed of the Basal Claystone of several meters, followed by a roughly 15m thick halite member. This Zechstein Formation is presumably the youngest Zechstein evaporite cycle to be found in the Netherlands. This fifth evaporation cycle is incomplete, because the carbonate member is missing.

4.6 The Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation (ZEUC) is found throughout the Southern Permian basin and lies between the highest formation/member of the Zechstein Group and the base of the Lower Germanic Trias Group. In the fringe area of the basin this formation may even overlie the Upper Rotliegend Group (Van Adrichem Boogaert & Kouwe, (1993-1997)).The formation contains red and grey anhydritic claystones and sandstones. Its thickness varies roughly between ~10 to ~50m (Geluk, 2007).

4.7 Zechstein build-up distribution

The Zechstein distribution maps in figures14 &17 suggest that the Zechstein build-ups are only found to the southern part of the Southern Permian Basin and to the west of the Mid North Sea High in the UK sector of the North Sea. Deposition of Zechstein build-ups is closely related to water depth and local water depth is closely related to the structural setting in a specific area. For example in the NE Netherlands Zechstein platform and slope facies are deposited on the highs of the pre-existing relief that was inherited from the Saalian tectonic event, see figure 16. The pre-existing relief resulted in a shallow water depth on which anhydrite and carbonate platform developed.

5.0 Proven Zechstein platform areas

This section gives a short description of an existing Zechstein gas field and the carbonate platform area. The Zechstein field is located in the NE onshore Netherlands and the other Zechstein platform is located in Denmark, which is located along the northern margin of the Southern Permian Basin in Denmark. For both platforms a well description will be given. For the Collendoorn platform a seismic comparison with the E02-02 platform will be made.

5.1 Collendoorn field (Zechstein platform facies) – proven reservoir

The Collendoorn platform is located near the village of Collendoorn in the NE of the Netherlands, see figure 19 for the precise location and locations of other ZEZ2C gasfields. Van de Sande et al., (1996) published a detailed study on the Collendoorn gasfield and the Zechstein-carbonate platform in which the gas field is located.

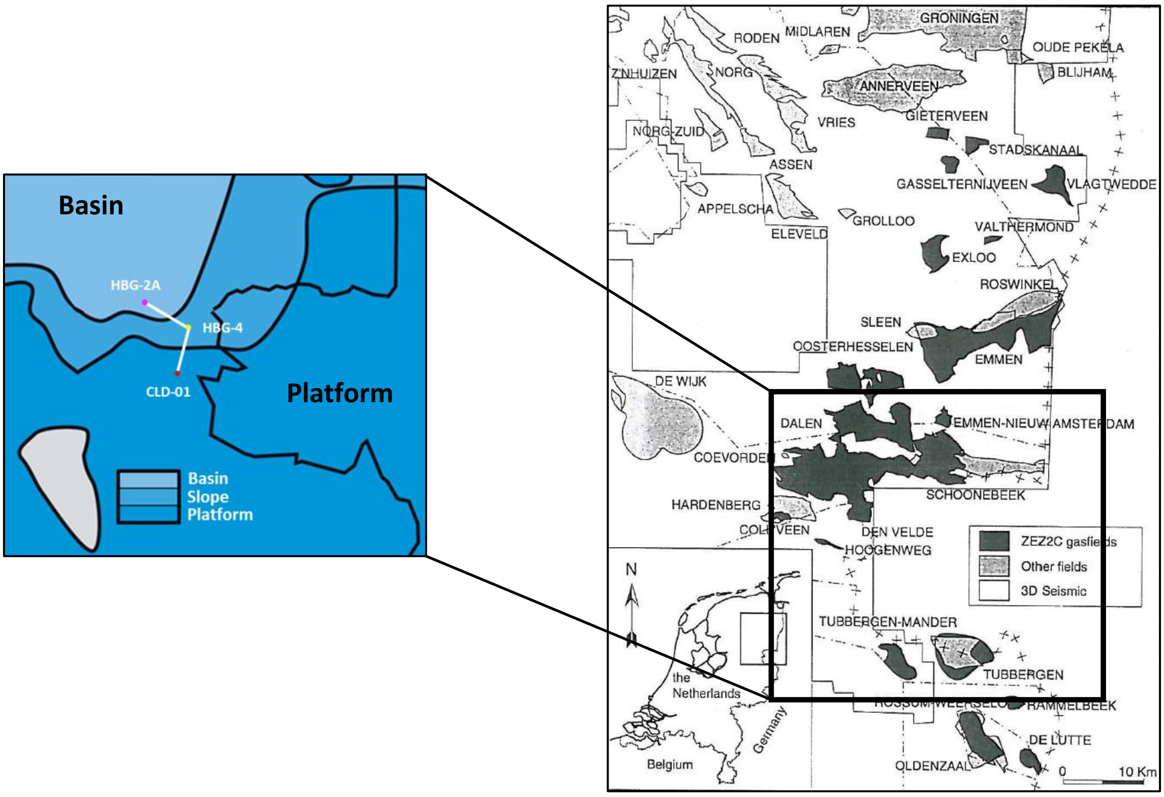


Figure 19: This figure shows the location of the seismic composite section and well log correlation panel through the CLD-01, HBG-04 and HBG-02A wells. Right panel shows the distribution of gas producing Zechstein fields in Drenthe. The square inset shows the position of the left panel, which shows the Zechstein facies distribution in this area.

A well log correlation panel from Van de Sande., et al (1996) can be found on the next page, see figure 20.This correlation panel shows the basin – slope – platform transition of the Zechstein-2 Carbonate Member through the CLD-01, HBG-2A and HBG-04 wells. Platform facies were found in the CLD-01 well. In the HBG-04 well slope facies were found and basinal facies in the HBG-02A well. Together with the well log correlation panel a seismic cross-section through these wells is presented in figure 21.

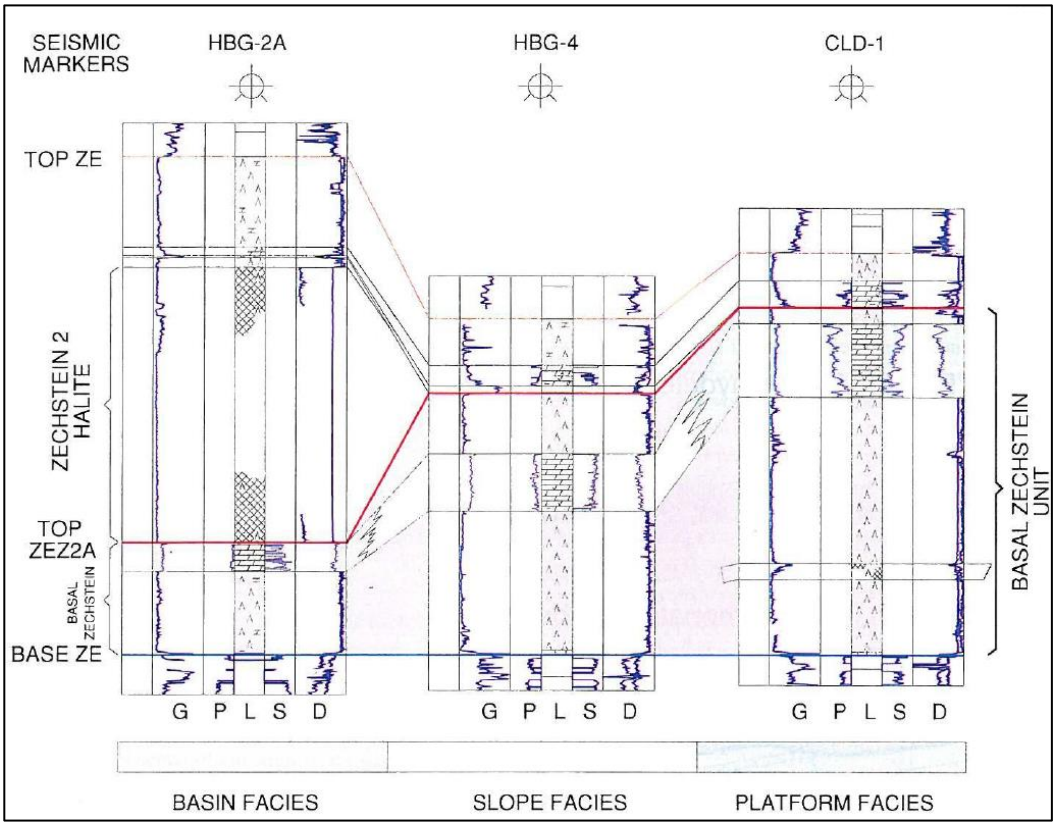


Figure 20: Well log correlation panel of the Basal Zechstein Unit found in wells CLD-01, HBG-04 and HBG-02A, showing gamma ray (G), porosity (P), lithology (L), gas saturation (S) and sonic and density (D). Source: Van de Sande et al., 1996.

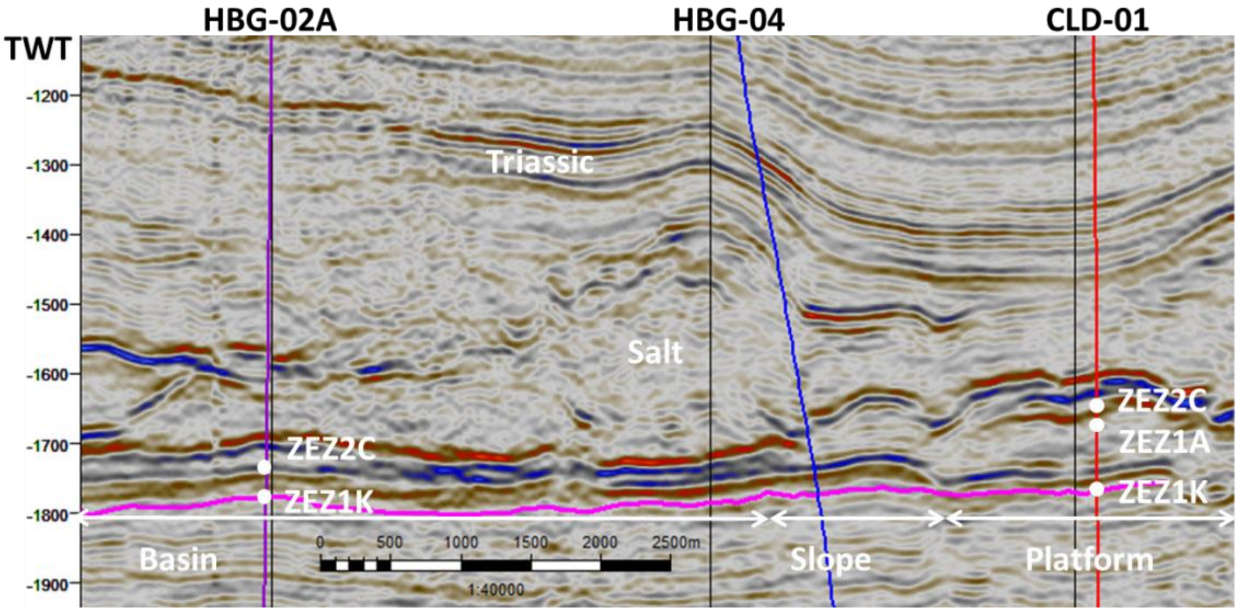


Figure 21: A seismic composite section through the CLD-01 (Red), HBG-04 (Blue) and HBG-02A (Purple) wells. The thin black lines are the corners of the composite line as shown in figure 1.

The well log correlation panel shows that Zechstein platform facies are characterized by thick Zechstein-1 Anhydrite deposits, which is overlain by a relatively thick Zechstein-2 Carbonate Member. Within the platform area no Zechstein-2 Halite deposits are present; as a result the

Zechstein-2 Carbonate Member is almost directly overlain by the Zechstein-3 Carbonate and Anhydrite Members. However there is a small interval of Zechstein-2 Anhydrite present between the carbonates of the Zechstein-2 and -3.

The thickest Zechstein-2 Anhydrite is found in the slope section of a Zechstein build-up. Also the best carbonate porosities are found in the slope facies. The transition from slope to basin is characterized by thinning of the Zechstein-1 Anhydrite and Zechstein-2 Carbonate Members. The Zechstein-2 Anhydrite Member is not found in the basinal section of the Zechstein. This is the result of the depositional mechanism for the anhydrite. In the deeper parts of the basin anhydrite dissolves again when it moves below the chemo-cline. Salt deposits are not found it the slope section of a build-up, however thick salt, primarily Zechstein-2 Halite, deposits is found in the basinal part. The well correlation panel shows that the Zechstein-3 Carbonate Member thins towards slope and basinal Zechstein, whilst the Zechstein-3 Anhydrite Member becomes thicker towards the basinal Zechstein.

The seismic cross-section (figure 3) though the Collendoorn platform shows the transition from platform – slope – basin. The platform clearly shows the thick Zechstein-1 Anhydrite Member as a quite transparent section, with on top the bright red loop of the Zechstein-2 Carbonate Member. The base Zechstein horizon has a low amplitude compared with the basinal Zechstein. The basinal Zechstein is characterized by thick transparent salt deposits. The thick Zechstein-1 Anhydrite Member is not present in this section. The entire Basal Zechstein Unit is very thin and is only visible as a combination of three bright loops.

5.2 Jutland Zechstein-2 carbonate

Figure 22 shows a cross-section that cuts through the following structural elements in the Danish onshore subsurface. From North to South the elements are: Ringkøbing Fyn High, Arnum Block, Zechstein platform break and Tønder Trough. The interpretation is that this structural cross-section shows similarity with the structural elements found in the NE Netherlands subsurface. The wells Tønder-2, Løgumkloster-1 and Arnum-1 found respectively Zechstein basin, slope/platform and platform facies. These well are plotted and roughly correlated in figure 23 (Stemmerik and Frykman, 1989).

The basinal well shows thick salt deposits from the Zechstein-2 Halite Member, which corresponds with the Na-2 member in the Tønder-2 well. The Tønder-2 well features a complete Basal Zechstein Unit that is a little less than 100m. The Basal Zechstein Unit is the thickest in Løgumkloster-1 well that most likely represent a slope or platform environment. The Zechstein-2 Halite Member is very thin compared with the basinal well. This is characteristic for Zechstein platform and slope deposits. The Arnum-1 Zechstein section is very thin. A possible explanation could be that the Ringkøbing Fyn High was a high during Zechstein deposition in the Southern Permian Basin, and that the Zechstein onlaps and pinches out onto the high.

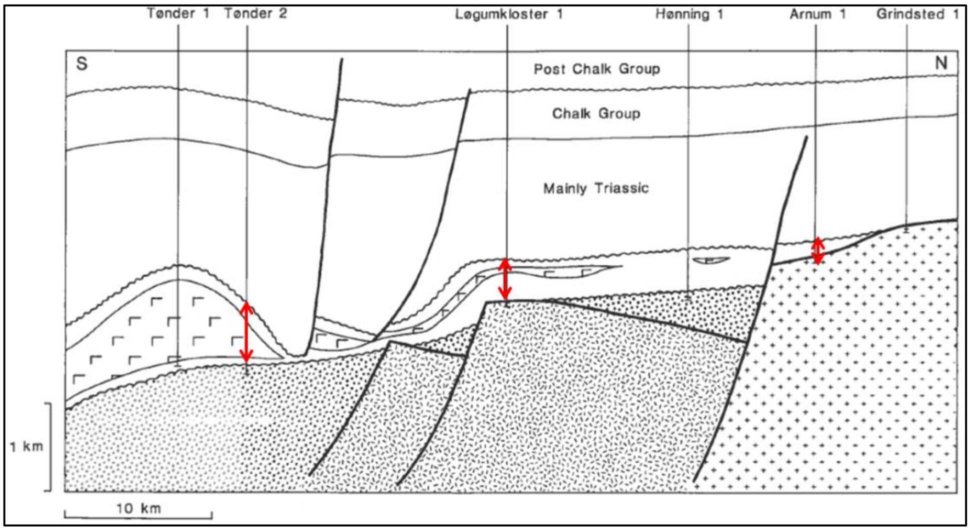


Figure 22: North-South cross-section from the Ringkøbing Fyn High (North) into the Southern Permian Basin (South). A schematic cross-section of the subsurface is presented in this panel. The well locations for the well correlation are also shown. Source: Stemmerik and Frykman, 1989.

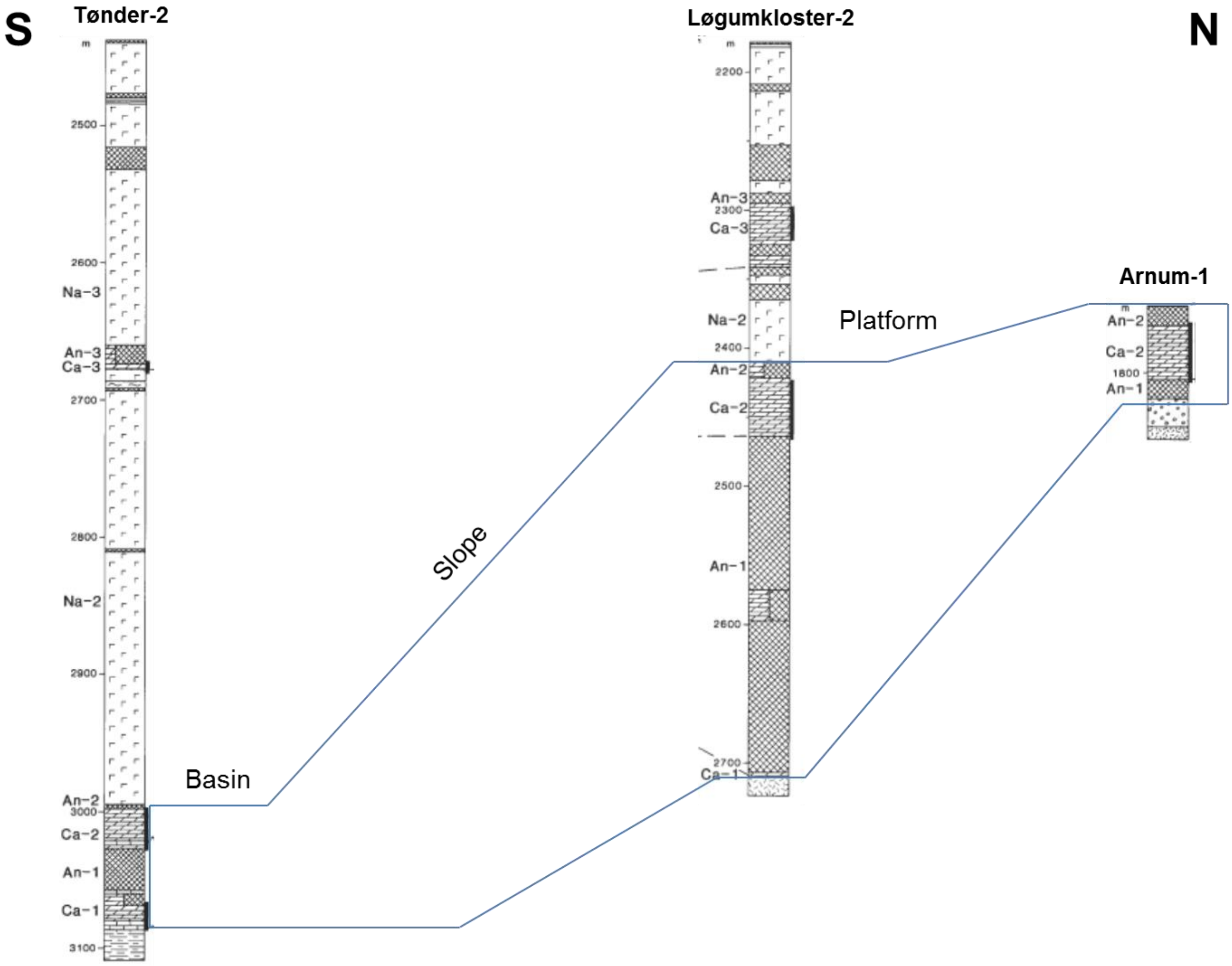


Figure 23: Well correlation panel, showing the Basin, slope and platform transition, as inferred from the stratigraphy. Source: Stemmerik and Frykman, 1989.

6.0 Possibilities for Zechstein build-ups in the northern Dutch offshore

The distribution of Zechstein build-ups is mainly controlled by local water depth found along the margins of the Zechstein Basin and above regional paleo-highs(Van der Baan, 1990). Regional paleo-highs, such as the Proto Texel-IJsselmeer High and East Netherlands High, created shallow water environments in which anhydrite platforms and carbonate build-ups could develop. Figure 16 and figure 24 show a diagrammatic cross-section of the development of shallow water anhydrite and carbonate platforms on top of a paleo-high.

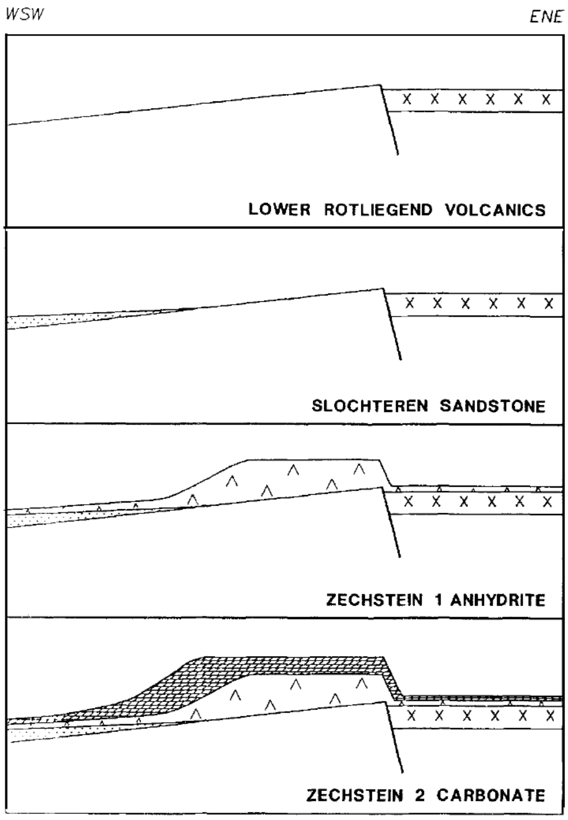


Figure 24: Figure: Illustrating the structural influence on Zechstein build-up development. Source Van der Baan, 1990.

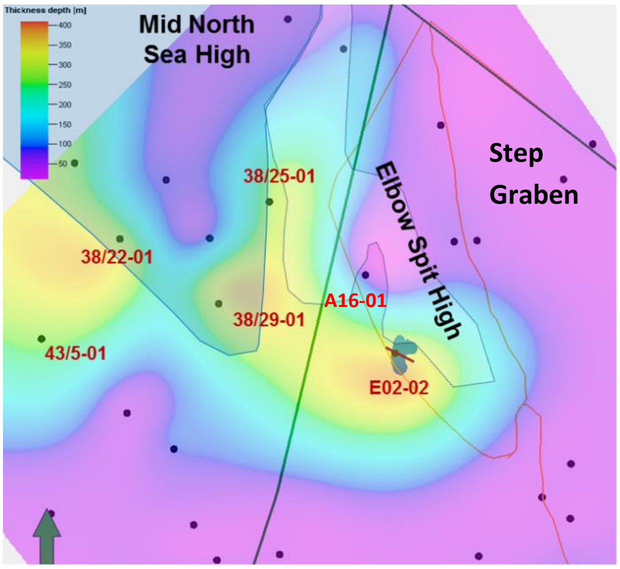
The Zechstein facies distribution maps(figure 14 and 17), suggest that in the Netherlands Zechstein build-ups are only found all along the southern margins of the Southern Permian Basin and are partially absent in the northern margin, in the Dutch and German sectors of the North Sea. Slope and platform facies have been drilled in the UK North Sea sector, well 38/25-1 at the western side of the Mid North Sea High. Figure 14 illustrates that Zechstein slope and platform facies are found along the northern fringe of the Southern Permian Basin in Germany and Poland.

Wride (1995) states that in the northern part of the Southern Permian Basin the Zechstein is subdivided into a complex of shallow and deep water evaporites. Zechstein facies in this area differ from basinal halites to shelf carbonates and/or anhydrites. The tectonic segmentation in the northern Dutch offshore, mainly in the A and B quadrants, appears to be influencing the Zechstein distribution. Wride (1995) concludes that "the structural segmentation of this area has been an influence on deposition and tectonics from the Zechstein to the Tertiary". This does not exclude the possibility of the Zechstein build-ups along the highs bordering e.g. Outer Step Trough or Step Low.

During the Zechstein period, the Elbow Spit High was probably submerged from the sea, as shown by the absence of any Zechstein deposits at the crest of this structure. This can be seen on seismic, on which it is visible that the Zechstein onlaps onto the Elbow Spit High (Appendix 3). The Elbow Spit Platform, which is a gentle slope towards the South-West, was probably below sea-level. Zechstein anhydrite-carbonate build-ups could develop along the margins of the Elbow Spit Platform, were the water depth was shallow enough to sustain reefal build-ups, in a similar way along the southern fringe of the SPB. Salt accumulated further out in the basin where the basin was deeper, and was not deposited along the shallow basin margins.

6.1 Zechstein well review in the Dutch northern offshore

In 2013 EBN performed a well review of the Zechstein carbonates in the northern Dutch offshore. The study confirmed that many wells in the study area were drilled in basinal facies with low porosity and few fractures. However, some wells close to the Elbow Spit High and MNSH clearly show positive indications for Zechstein platform facies (e.g. oölitic and sucrosic), recorded in cuttings and (sidewall) core descriptions. A petrophysical evaluation was performed on some of the wells with Zechstein-2 carbonate and showed an average porosity of ~15% in well E02-02. This compares very well with Zechstein-2 carbonate reservoirs in platform-slope facies onshore Denmark and onshore Netherlands (EBN 2013, unpublished).



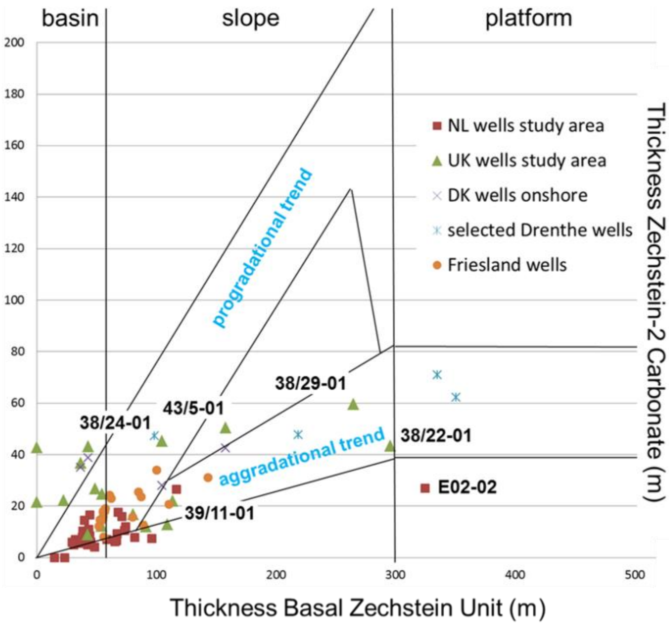


Figure 25: Left: Well based thickness map of the Basal Zechstein Unit in the MNSH area. The thickness clearly increases along the flank of the MNSH and the ESH. Black dots indicate wells drilled into the Zechstein, red labels indicate wells with (recorded) positive indicators for carbonate platform facies. The carbonate build-up drilled by well E02-02 is indicated by a blue polygon. Right: Correlation between Zechstein-2 Carbonate thickness and total thickness of the Basal Zechstein Unit for the regional well dataset, following the approach by Van de Sande et al. 1996. Many of the wells in the study area and onshore DK and NL plot in the slope part of the chart. Note that the Drenthe dataset used in Van de Sande et al. is not plotted entirely in this chart. Figures from Jaarsma et al., 2014

The left panel of figure 25 shows the thickness of the Basal Zechstein Unit in the Mid North Sea High area. The thicknesses (in meters) are based on well data from the study area in the Netherlands and UK. The map clearly shows an increase in thickness along the southern margin of the Elbow Spit High and Mid North Sea High. The well control East of Elbow Spit High is very low, therefore it cannot be ruled out that platform and slope facies exist East of the Elbow Spit High.

The right panel of figure 25 shows the correlation between Zechstein-2 carbonate thickness and total thickness of the Basal Zechstein Unit, for regional dataset used in the well review study. The diagram is based on the approach of Van de Sande et al., 1996, were on the vertical axis the ZEZ2C thickness is plotted and on the horizontal axis the total thickness of the BZU. The figure shows that most of the wells in study area plot in the slope and basinal part of this chart. Well E02-02 is the only well that lies in the platform part of the chart, which implies a thickened Basal Zechstein Unit (EBN Jan Schneider, unpublished).

Well A16-01

This well is located closed to the South-West margin of Elbow Spit High, see figure 1 and 25. This well found 92 meter of Zechstein deposits, consisting of dolomite, anhydrite, the Coppershale and Weissliegend. Within the dolomite stromatolite facies are found, see figure 26. This core-slab shows the laminated structure that is often found in stromatolites. Stromatolites are found in shallow water environments such as carbonate platforms. The schematic Zechstein platform cross-section, which can be found in appendix 4, published by Slowakiewicz et al., (2013) shows the possible locations for shallow water stromatolites on a Zechstein platform. The total thickness of the dolomite deposits is roughly 45m of which 25m show good reservoir characteristics. The averaged porosity found within the 25m is roughly 22-23%, which is an excellent porosity.

Figure 26: Core-slab from well A16-01 showing the laminated structure, that is interpreted as stromatolite facies.

Well E02-02

Seismic data suggests a Zechstein build-up is present at the location of well E02-02; in this report the platform is referred to as the" E02-02 platform". An East-West seismic cross-section through well E02-02 clearly shows the platform-slope-basin transition of the E02-02 platform, see figure 3. Well E02-02 was an exploration well to the Zechstein carbonates, within the Zechstein minor gas reading were recorded (~0.01%). The well found roughly 27m of the Zechstein-2 Carbonate Member. A sidewall sample was taken from the Zechstein-2 Carbonate Member in well E02-02, this sidewall sample was described, after a modified Dunham classification, as an anhydrite-rich microbial-algal wackestone. This suggests that the depositional setting was a shallow basinal setting, probably on a platform. The presence of evaporite minerals, mainly anhydrite, supports a shallow-water depositional setting (PanTerra GeoConsultants, 2014).

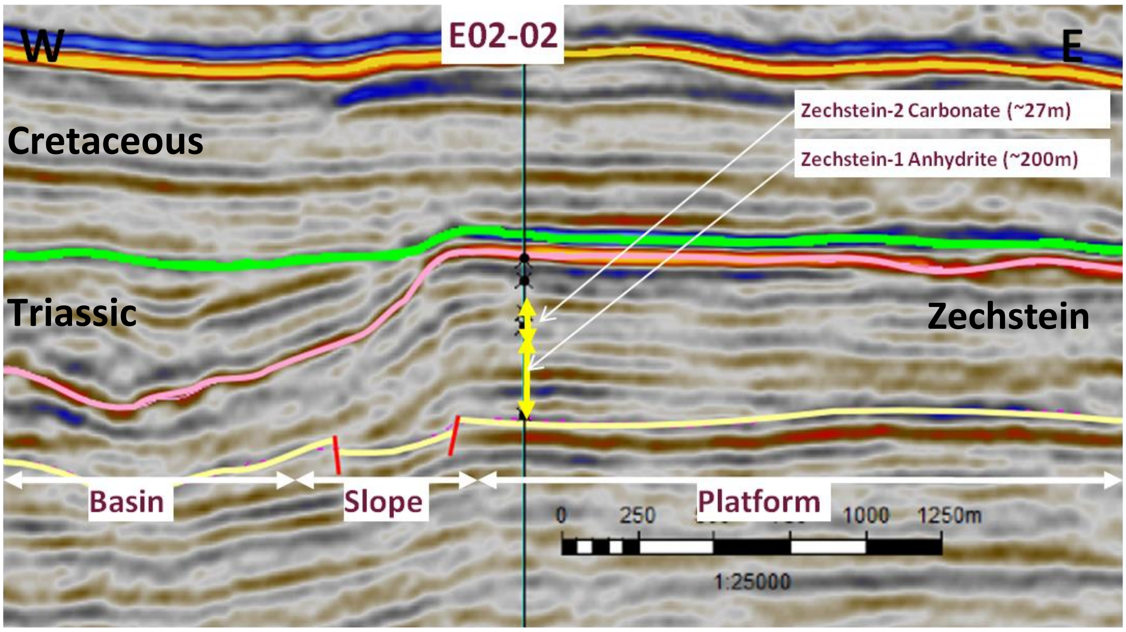


Figure 27: East-West seismic cross-section through E02-02.The seismic and well data indicate that the well was drilled close to the edge of a Zechstein-2 build-up. Thickness of the ZEZ2C ~27m and ~217m for the ZEZ1A. (seismic data courtesy Fugro).

Other wells

The map in figure 28shows the location of the other wells that are assessed during the “Zechstein well review”. The most important wells in this section are the English 39/11-01 and 39/07-01, the Dutch A14-01, A05-01 and German A06-03 wells.

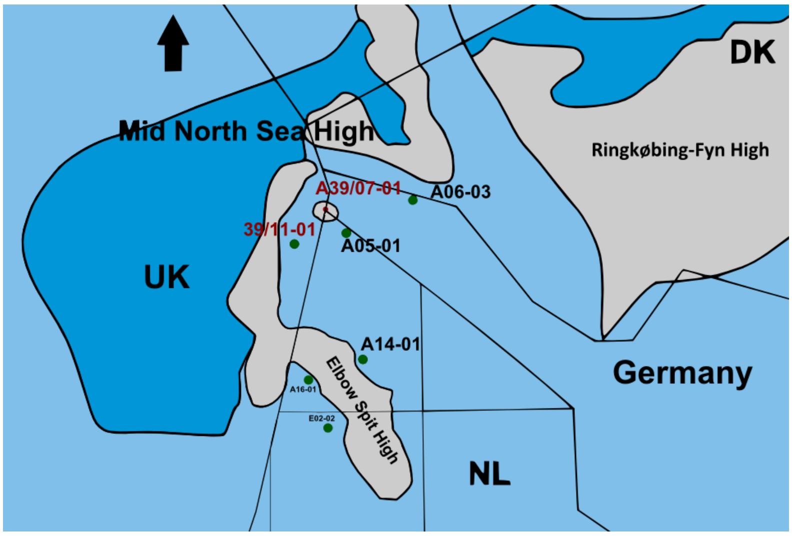


Figure 28: Map overview illustrating the well locations of the other wells assessed in the report. Green dots are wells with positive Zechstein platform indications, whilst red dots show only tight basinal facies.

The UK well 39/11-01 well showed a Zechstein section of only 32m, consisting only the Basal Zechstein Unit. Seismic has shown that the Zechstein in this area is truncated by younger formations, comparable with the E02-02 platform. Well 39/07-01 does not show any Zechstein. A possible for the absence of Zechstein deposits could be that the area were 39/07-01 is located was a high during Zechstein deposition. This can be illustrated by seismic that shows that the area is bounded by faults, creating a high. Another possibility that also explains the thin Zechstein section in well 39/11-01 could be that erosion of the Zechstein occurred during the Mid-Kimmerian Unconformity (Kombrink et al., 2012). Eroding the Zechstein along the eastern margin of the Mid North Sea High.

The Dutch wells A14-01 and A05-01 both show thick anhydrite deposits. Thick anhydrite deposits are usually indicative for shallow water environment, since anhydrite dissolves below a certain water depth (Van der Baan, 1990). Well A05-01 drilled through roughly 472m of mainly anhydrite deposits, occasionally interbedded with carbonate layers. A striking detail is that Zechstein salt deposits is virtually absent in this well. The Basal Zechstein Unit in well A14-01 in roughly 70m thick and consists mainly of anhydrite. The Anhydrite is interbedded by three small roughly 15m thick carbonate banks. The thick anhydrite deposits are usually only found in areas that have had a shallow water depth, suitable for anhydrite precipitation and preservation as well as carbonate deposition.

6.2 Conclusions

The well review of the Zechstein carbonates in the Dutch northern offshore confirms the possibility for the presence of Zechstein build-ups along the southern margin of the Elbow Spit High. This is very well possible because the Elbow Spit High was surfaced above sea-level, creating a possible shallow water setting along its margins. Well A16-01 proved the presence of shallow water stromatolites with very high porosities along the South-West margin of the Elbow Spit High. Well E02-02 was drilled on a Zechstein build-up, located at the southern probable shallow water margin of the Elbow Spit High. The E02-02 build-up was confirmed by a sidewall core analysis. Therefore, it is possible that similar structures are present in the vicinity of this well and along the southern margin of Elbow Spit High.

North of the Elbow Spit High, in the area of the Step Graben (see figure 2), only 4 wells have drilled into the Zechstein, all drilled basinal facies. The structural elements present in this area are similar to the structural elements located in the Dutch onshore. Both areas contain fault-bounded depressions and uplifted fault blocks. If the timing was correct, then it is possible that Zechstein build-ups could have developed on the paleo-highs in the northern Dutch offshore.

Therefore it cannot be ruled out that Zechstein platform and slope facies exists in the Northern Dutch offshore. This is investigated by detailed seismic mapping of the Zechstein in western part of the DEFAB area.

7.0 Methods

This chapter describes the methodology used in this study to investigate the presence of Zechstein carbonate platform or build-ups in the Dutch northern offshore. Information on Zechstein carbonates is found in literature, analogues in the NE Netherlands and well data. Only 6 wells have a full dataset comprising sonic and density logs, checkshots and TD below base Zechstein. Table 3 gives an overview of the selected wells. The methods used in this study are: 1) generation of synthetic seismograms "synthetics" on hypothetical and real wells, 2) seismic interpretation, 3) time-depth conversion. These methods have been applied in Petrel 2012.5. An overview of the data-set can be found in figure 29.

Table 3: Overview of the selected wells for the Zechstein study. Log and checkshot information were downloaded from the DEFAB dataset and website www.nlog.nl. The well-logs of E12-03 and F07-02 do not cover the entire Zechstein stratigraphy. They are missing the upper Zechstein stratigraphy.

Well	Sonic (DT) [μs/ft]	Density (RHOB) [g/cm³]	Checkshots	Well logs contain complete Zechstein	TD below base Zechstein
A15-01	X	X	X	X	X
E02-02	X	X	X	X	X
E09-01	X	X	X	X	X
E12-03	X	X	X	-	X
F04-02-A	X	X	X	X	X
F07-02	X	X	X	-	X

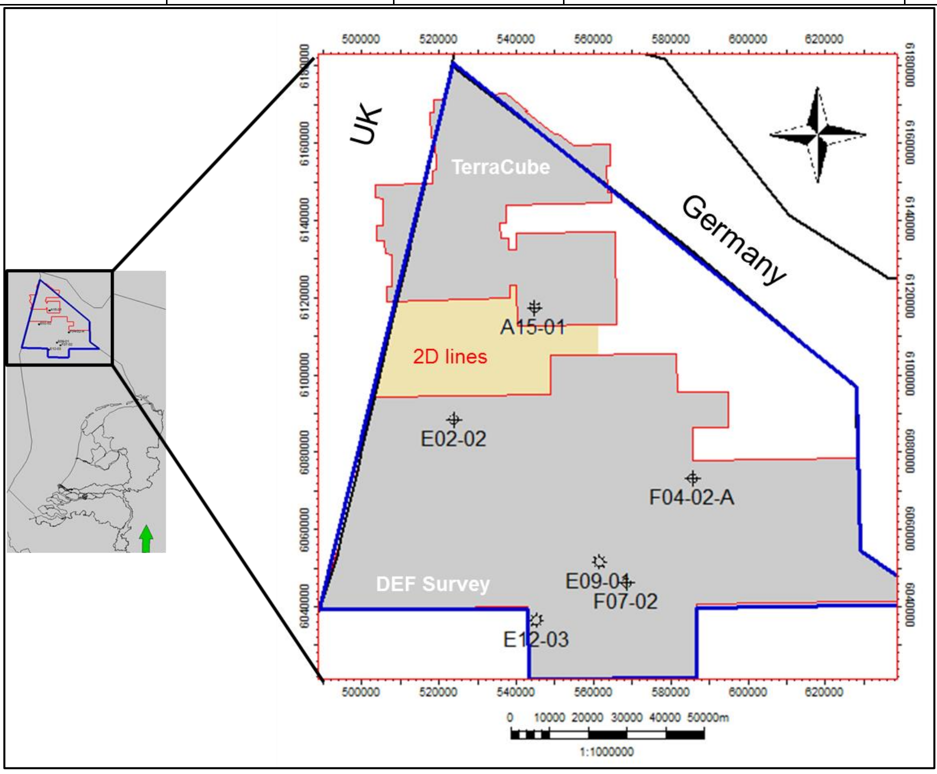


Figure 29: Outline of the DEFAB area, in blue, in combination with the data-set. The lower grey area corresponds with the 3D seismic DEF survey and the upper grey area with the merged 3D TerraCube. The area in beige is only covered with 2D lines. The wells suitable for the generation of synthetics are indicated on this map.

7.1 Seismic interpretation

Seismic interpretation was done in the Dutch northern offshore, available were the two 3D seismic cubes and the 2D lines covering the remaining area. The DEF survey covers the D, E and F blocks in the Netherlands offshore and was completed in 2012 by Fugro. The survey is covering over 8.000km^2 from the UK to the German offshore border with10ms recording time. The second 3D seismic cube used in this study is the TerraCube offshore 3D cube, which covers the A and B blocks in the Dutch North Sea. The TerraCube comprises of several merged 3D surveys. This merge caused seams between the different 3D cubes and shows differences in imaging due to differences in acquisition and processing of various input surveys. The 2D lines and several areas in the TerraCube have limited seismic quality, see figure 30.

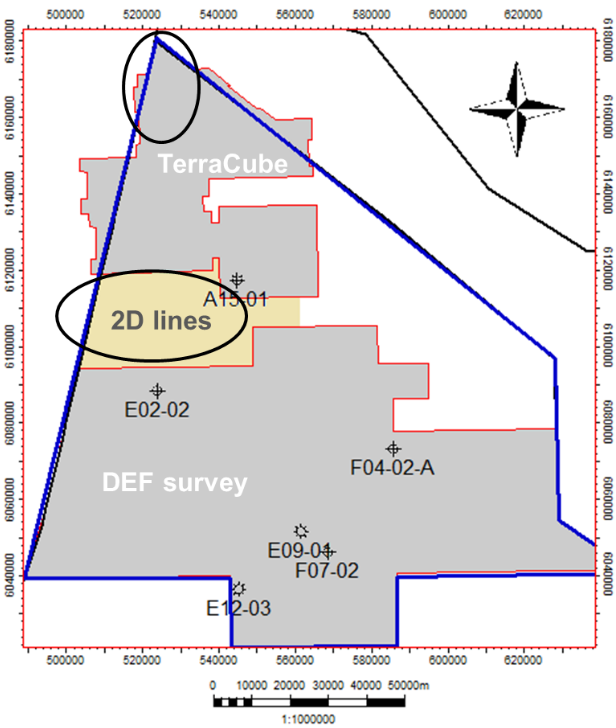


Figure 30: Outline of the seismic data, the black circles represents areas with limited seismic quality. The seismic interpretation in these areas has a larger uncertainty compared with the other areas.

The detailed interpretation of the base and top Zechstein was guided by the regional DEFAB base and top Zechstein interpretations. The gridlines for the Triassic horizons, base Chalk, base North Sea Super Group and Mid North Sea Unconformity were available from the DEBAB data-set as well and used for reference.

In order to tie the wells to the seismic a depth – time conversion was carried out on the selected wells. Checkshot data was available from the DEFAB database and TNO website www.nlog.nl. The depth – time converted wells & associated well-tops were used as starting point for the detailed seismic interpretation.

Zechstein thickness map& base Zechstein amplitude map

After the top and base Zechstein horizons had been interpreted on seismic, base and top Zechstein surfaces were created by gridding the interpretation using the convergent interpolation algorithm. These surfaces were used to calculate the Zechstein thickness in the DEFAB area. Subsequently all negative values in the thickness map were set to zero and a polygon was created to mask the area with no Zechstein. The Zechstein amplitude map was generated by extracting the seismic amplitude from the full-stack reflectivity cubes, along the base Zechstein horizon.

7.2 Synthetics

Synthetics were created for 2 hypothetical wells, for which synthetic well-log data was created using values from real wells. Synthetics were created for the 6 selected wells in the DEFAB area. More details about the synthetics and the seismic characterization of the Zechstein can be found in the chapter: “Seismic characterization of the Zechstein”.

7.3 Time – depth conversion

Time-depth conversion for the overburden was performed using a hybrid velocity model derived from the VelMod-2 project (Dalfsen et al., 2007) and the customized DEFAB velocity model (EBN internal). The conversion of the top and the base Zechstein time maps was done in different ways. The Top Zechstein was converted as base Lower Germanic Trias Group, using the hybrid model. The Base Zechstein was converted in an indirect way, using the Zechstein thickness map.

Top Zechstein

The V_0 map for the base North Sea Supergroup was taken from the DEFAB data-set. The underlying V_o maps up to the base Lower Germanic Trias Group were derived from the VelMod-2 project. The function used for the time-depth conversion was $V=V_0+K*Z$, where V_0 represents the V_0 surfaces and K is a constant deducted from the VelMod-2 project (Dalfsen et al., 2007). The K values can be found in table 4. These K-values are the result of linear regressions for the K-values of VELMOD-1 per layer and per region performed by Dalfsen et al., 2007.Well-tops were used to calculate the difference (residuals) between the well-tops and time-depth converted surfaces. In table 5 an overview of the residuals is given for the top Zechstein surface. A correction surface was created from the residuals using the convergent interpolation algorithm. The surface is shown in appendix 5, and illustrates that the miss-fit between the well-tops and time-depth converted surface increase towards the North. This indicates that the top Zechstein surface in the northern part of the study area is slightly too low. This correction surface was applied to the top Zechstein surface in order to correct the mismatch between the well-tops and the depth-converted top Zechstein surface. This correction method avoids the creation of bulls-yes around the wells. Table 6 shows the difference between the converted top Zechstein surface and well-tops. The calculated difference between well-top and converted top Zechstein is for all wells below 10%, which is deemed acceptable for the purpose in this study.

Table 4: K-values for the lithostratigraphic layers used inthe time-depth conversion.

Layer	K value
North Sea Group	0.288
Chalk Group	0.882
Rijnland Group	0.492
Schieland Group	0.959
Altena Group	0.45
Upper Germanic Trias Group	0.362
Lower Germanic Trias Group	0.362

Table 5: Residual table before correction top Zechstein.

Top Zechstein	Well	Residual	Well	Residual
	A08-01	360.28	E04-01	38.42
	A11-01	219.21	E06-01	44.74
	A14-01	154.55	E09-01	79.33
	A14-02	125.33	E12-03	47.25
	A16-01	81.60	F01-01	48.64
	A17-01	-269.37	F04-01	-29.18
	E02-01	21.95	F04-03	102.13
	E02-02	30.16	F07-02	-25.48

Table 6: Overview of the difference between calculated Z values time-depth corrected surface and z values well-tops. It is assumed that a difference below 10% is acceptable.

	Z Surface	Z well tops	Difference	%
A11-01	-3125,25	-3071,07	54,2	1,8
A14-01	-2458,2	-2409,95	48,3	2,0
A14-02	-2637,32	-2530,6	106,7	4,2
A16-01	-2182,66	-2103,8	78,9	3,7
E02-01	-1966,63	-1961,36	5,3	0,3
E02-02	-1955,76	-1942,37	13,4	0,7
E04-01	-1554	-1558	-4,0	0,3
E06-01	-2064,12	-2060,8	3,3	0,2
E09-01	-2243,54	-2262,65	-19,1	0,8
E12-03	-2538,12	-2506,78	31,3	1,3
F04-01	-3193,24	-3135,1	58,1	1,9
F04-03	-3423,82	-3318,23	105,6	3,2
F07-02	-2171,81	-2351,34	-179,5	7,6

Base Zechstein

The base Zechstein surface is time-depth converted using the Petrel calculator function, both the Zechstein thickness and top Zechstein surface maps are used in the process. The Zechstein thickness map was converted to depth in the Petrel calculator. The following function was used, which was presented in the VelMod-2 project:

$V_{int} = 4500$ for TWT ≥280ms

$V_{int} = 5500 - 6.67 * TWT$ for TWT ≤280ms

This method to convert the base Zechstein is preferred, since there are large velocity differences within the Zechstein. The sonic velocity for Zechstein salt is slower compared to the Zechstein carbonates and anhydrite members. The Zechstein thickness is used to distinguish between the salt sonic velocity and carbonate/anhydrite velocity. It is assumed that a Zechstein thickness below 280ms correlates with thickened Zechstein carbonate/anhydrite deposits and thus faster sonic velocities. The Zechstein thicknesses above 280ms are assumed to correlate with thick salt deposits, which have a slower sonic velocity.

The 6.67 constant was derived in the VelMod-2 project by Dalfsen et al., (2007). The resulted thickness map in depth was added to the top Zechstein in order to calculate the depth converted base Zechstein map. The Petrel time-depth conversion only accepts one sonic velocity and this would create a very large uncertainty in the time-depth converted Zechstein maps.

8.0 Results

The results in this report are split into three sections 1) Seismic characterization and 2) Seismic interpretation, 3) velocity model and the observed low amplitude areas based on the base Zechstein amplitude map. The section seismic characterization describes the Zechstein seismic using hypothetical synthetics, well synthetics and seismic sections. This chapter can be read separately from the report. The high resolution top and base Zechstein maps (in time and depth) can be found in appendix 6&7. The top and base Zechstein maps based on the 2D lines are not interpreted in such great detail as the DEF and TerraCube maps, since the 2D seismic quality is quite poor. The Zechstein thickness map, based on the top and base Zechstein depth maps can be found in appendix 8.The base Zechstein amplitude map will be used to identify base Zechstein lo amplitude areas that probably correlate with Zechstein build-ups. The identified areas are first discussed for the DEF survey and second for the TerraCube.

9.0 Zechstein seismic character in real data

9.1 Petrophysical description

The Zechstein group contains several sequences of carbonate, anhydrite and salt deposits that display significant acoustic impedance contrasts. When the individual thickness of each Zechstein member is above seismic resolution, it should be possible to see quite some detail in the seismic. However this is not always the case, and therefore some Zechstein members cannot be detected on seismic. In this section an attempt will be made to characterize the individual Zechstein members in a Petrophysical way. Two composite schematic synthetic seismograms have been made: one for the Zechstein in a basinal setting and one for a platform setting.

Density and sonic velocity

Table 7 and appendix 9 give an overview of the key rock properties of the Zechstein group that influence the seismic character. Density values are in [g/cm^3] and sonic velocity values are in [m/s]. The density and sonic velocity values are derived from wells that are suitable for the generation of synthetic seismograms. The values are averaged over the stratigraphic interval that corresponds with the Zechstein member; stratigraphic information is from the DEFAB database. The averaged values for each Zechstein member are plotted in a velocity vs. density graph, in combination with literature data and averaged values for each individual well, see appendix 10. This is done in order to check whether or not the values are representative for each lithological unit. The visible outliers are then removed. A possible source for the outliers could a wrongly interpreted stratigraphic boundary. A stratigraphic boundary that is too high or low could result in averages of density or sonic that is contaminated with values from an overlying or underlying Zechstein member. Another possible explanation could be a measurement error of the logging tool. In order to keep the petrophysical description of the Zechstein general, the outliers are removed from the dataset.

The averaged values for density are compared with literature data from '*Fundamentals of well-log interpretation Vol.1 O. Serra*'. It is clear that the Zechstein-1 and -2 Formations compare very well, whilst the ZEZ3C and ZEZ3A densities are much lower than the literature data. This could be the result of a shortage of data for the ZEZ3A and ZEZ3C members, see appendix 10, which could result in a very poor averaged value for both Zechstein members. The sonic velocity values for all averaged Zechstein members are much lower than the literature data. It should be stated that the literature values for both density and sonic should contain a range of values and not one sinlge point. Due to the fact that sonic velocity increases with an increasing density, and since density usually increases with depth due to compaction, also sonic velocity increases with depth. An important exception are salt layers/domes, of which the density barely increases with depth. The values for the Zechstein-2 Halite Member compare very well with the literature data. Another explanation for the discrepancy between literature and well data could be that the Members in the well data do not contain e.g. pure anhydrite but also contain other lithologies. That results in higher or lower petrophysical values.

Table 7: Overview of density and sonic values for the Zechstein Members and literature values for each lithology found within the Zechstein. See appendix 9 for the density and sonic graph for each individual Zechstein member. Literature data source: *Fundamentals of well-log interpretation Vol.1 O. Serra.*

		Density [g/cm3]	Sonic [m/s]
Member	Zechstein Upper Clay	2,50	3645
	Zechstein-2 Anhydrite	2,81	5222
	Zechstein-3 Carbonate	2,61	4606
	Zechstein-2 Halite	2,16	4472
	Zechstein-2 Anhydrite	2,93	5859
	Zechstein-2 Carbonate	2,72	5548
	Zechstein-1 Anhydrite/Werra	2,91	5985
	Zechstein-1 Carbonate	2,74	5410
	Coppershale	2,51	3964
Literature	Clay	2.4 - 2.7	
	Carbonate	2.71 - 2.75	6350
	Dolomite	2.87	7007
	Anhydrite	2.96	6096
	Halite	2.17	4549

Acoustic Impedance

The acoustic impedance (Z) of a lithological unit is the product between both density in [g/cm^3] and sonic velocity in [m/s]. The difference in acoustic impedance between two lithological units determines the visibility of the boundary between those rocks. Thus if for example the ZEZ2A (highest density and sonic velocity) is overlain by the ZEZ2H (lowest density and velocity), the observed acoustic impedance contrast will be very high. Figure31 gives an overview of the computed acoustic impedance values, based on the averaged density and sonic velocity values.

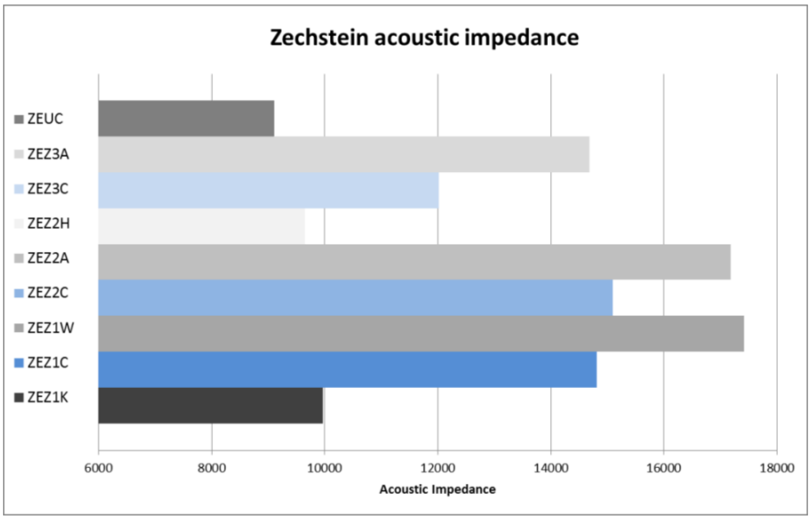


Figure 31: Zechstein acoustic impedance for each individual Zechstein member, based on the averaged density and sonic velocity values.

Ideal synthetic seismograms

In the following section an attempt has been made to generate two ideal synthetic seismograms for the Zechstein. Figure 32 shows the locations of the ideal wells, the first synthetic was made for a basinal Zechstein setting, with very thick salt and a thin Zechstein Basal Unit. The second synthetic was based upon a Zechstein platform. The values for the acoustic impedance were based upon the averaged density and sonic velocity of each Zechstein Member. The density and sonic values are for the overburden are based on the Triassic Main Claystone Member; density is 2.48 [g/cm^3] and sonic is 87 [µs/ft]. And the density and sonic for the underlying layer is based on the Upper Silverpit Formation; density 2.5 [g/cm^3] and sonic [µs/ft]. It should be stated that the thicknesses of each Zechstein member are averaged thicknesses, based on the actual data.

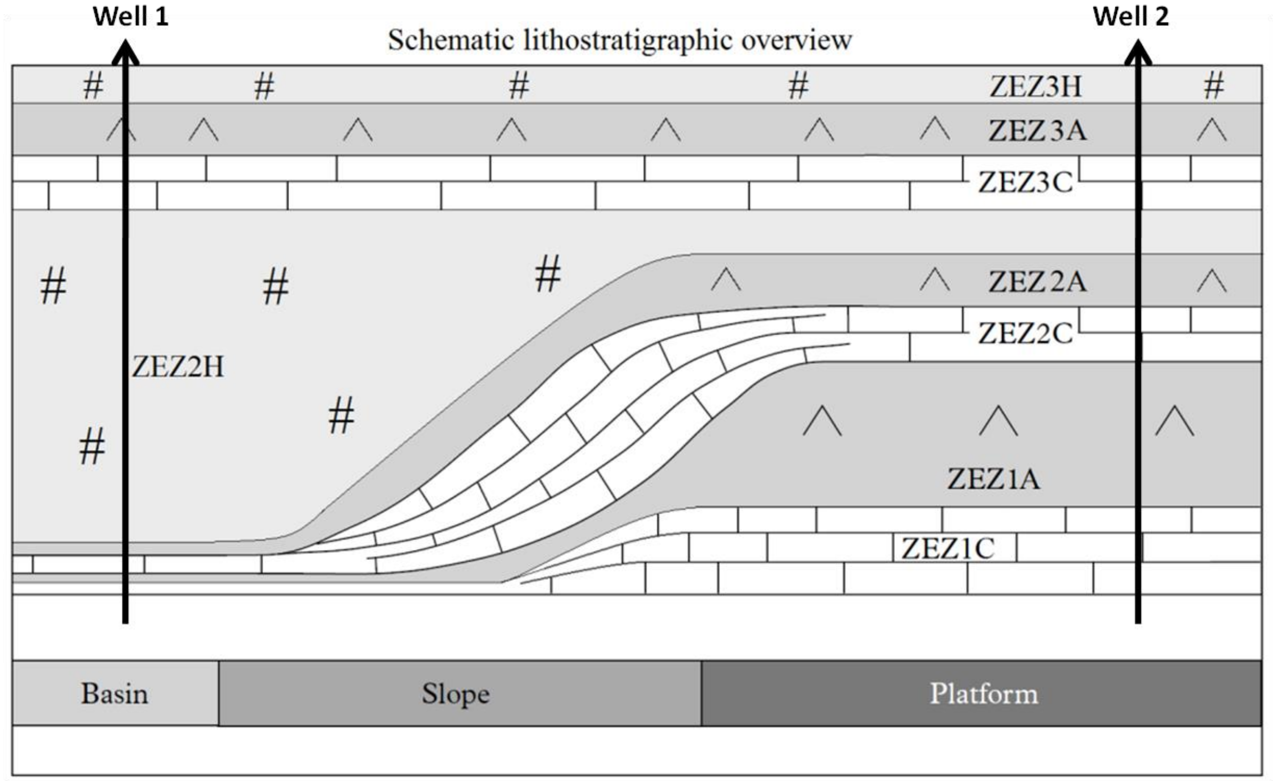


Figure 32: Schematic cross-section through the Zechstein, showing the ideal well locations. Picture modified after Geluk, 2000.

The wavelet used for the synthetics is an Tapered Sinc wavelet, which is based on the wavelet extracted from the DEF survey. The frequency high and low cut of the Tapered Sinc is to be similar to the DEF wavelet, low frequency cut is 20Hz and high frequency cut is 60Hz.

The vertical resolution is the minimum separation between two seismic reflectors, that can be regongized as separate interfaces. The seismic resolution has been established to be: VR = ¼ wavelength. With the average frequency of 40Hz and an average sonic velocity whithin the Zechstein of ~5000 [m/s], the wavelength (V/f) is around ~125m. Which results in a vertical resolution of rougly 30m, hence the seismic data will not resolve thicknesses lower than 30m.

Ideal basinal well

This ideal well was placed in the basinal setting of the Zechstein group, thus thick salt and thin carbonate/anhydrite layers. The thicknesses of individual members were based on literature data and real well data. Table 8 gives an overview of the chosen thicknesses with the source on which the data is based.

Table 8: Zechstein well tops and thicknesses as used for the ideal basinal well.

Hypothetical Zechstein Basin			
	Well Tops [m]	Thickness [m]	Thickness based on
Overburden	*0*	*2000*	
ZEUC	2000	25	*Geluk, 2007 - Geology of the Netherlands*
ZEZ3H	2025	238	*Type section Van Adrichem Boogaert & Kouwe, 1993-1997*
ZEZ3A	2263	30	*Well E02-02*
ZEZ3C	2293	4	*Strozyk et al., 2012 and well E02-02*
ZEZ2H	2297	450	*Type section Van Adrichem Boogaert & Kouwe, 1993-1997; Geluk, 2007*
ZEZ2A	2747	5	*vd Sande, 1996*
ZEZ2C	2752	10	*vd Sande, 1996*
ZEZ1A	2762	5	*Same as ZEZ2A*
ZEZ1C	2767	7	*vd Sande, 1996*
ZEZ1K	2774	2	*vd Sande, 1996*
Underburden	*2776*	*100*	
Zechstein Thickness		**776**	

The thicknesses of the ZEZ3H and ZEZ2H members are based on a combination between the type sections of both Zechstein members as described by Van Adrichem Boogeart & Kouwe, 1993-1997 and Geluk, 2007. For example the thickness of the ZEZ2H in the type section is 236m, while Geluk, 2007 states that the maximum thickness of the ZEZ2H is ~600m. Therefore a thickness of 450m is chosen, which lies roughly in the middle. In Geluk, 2007 the thicknesses of the ZEUC is given to be between 10-50m. For the ideal well, the thickness is set to 25m, which lies roughly in the middle. The thicknesses of the Basal Zechstein Unit members are all based on the values given by Van de Sande, (1996). Both the ZEZ3A and ZEZ3C are both on a combination between Strozyk et al., 2012, Van Adrichem Boogeart & Kouwe, 1993-1997 and well E02-02. Which resulted in values very similar to well E02-02. The overburden is set to 2000m (same as well E02-02), in order to simulate the real depth of the Zechstein in the DEFAB area.

Appendix 11 shows the generated synthetic for the ideal basinal well. The first two columns from the left show the density and sonic graphs based on the averaged well data. The third column is the acoustic impedance, which is calculated during the synthetic generation process. The fourth column shows the wiggle trace of the synthetic, a colored peak corresponds with a soft kick in acoustic impedance; positive amplitude. The fifth column is the same as the wiggle trace only with corresponding seismic colors. Hard kicks are characterized by a red fill, while soft kick is filled with blue. The lithology on which the synthetic is based is illustrated in the schematic cross-section on the right side of the figure.

The synthetic seismogram shows three important features of a basinal Zechstein section: the seismic character of the Basal Zechstein Unit, the Zechstein-3 rafts and top of the Zechstein. The Base of the Zechstein is characterized by a high positive amplitude loop, directly followed by a high amplitude negative loop. This interval corresponds with the Basal Zechstein Unit, the top is defined by a hard kick and the base by soft kick. The individual Zechstein members in this interval are too thin to be detected on seismic. The total thickness of the BZU is 29m, which is lower than the seismic resolution. Therefore the whole BZU interval can be seen as one unit with a relative high acoustic impedance, compared with the overlying salt. The petrophysical properties of salt result in a relative low acoustic impedance compared with the underlying BZU. This difference in lithology and petrophysical properties resulted in the profound hard kick at the top of the BZU.

The second important feature in this hypothetical synthetic section is the seismic character of the Zechstein-3 Anhydrite and Carbonate. Both members are completely encased in salt, which result in a very distinctive seismic character. Anhydrite has a higher density and lower sonic slowness than salt, the acoustic impedance of the anhydrite member is higher, which results in a hard kick followed by a soft kick. Therefore the top of this interval corresponds with a high amplitude negative loop, a hard kick. While the base of the raft is defined by a high amplitude positive loop. Both loops are primarily defined by the Zechstein-3 Anhydrite Member, since the ZEZ3C Member is too thin to be detected on seismic. And due to the thickness of the ZEZ3A Member, close to the seismic resolution, the side-lobes of both loops interfere, enhancing each other. In other words, the positive side-lobe of the top ZEZ3A enhances the positive amplitude loop of the ZEZ3A base, and vice versa.
If the Zechstein-3 Carbonate is thick enough to be resolved on seismic, the top will be defined by a decrease in acoustic impedance, thus positive amplitude loop. The base will be characterized again by a decrease in acoustic impedance; salt has a lower acoustic impedance compared with carbonate. Thus the top and base of the ZEZ3C will be defined by a positive amplitude loop.

The top Zechstein in this hypothetical well is set to be the Zechstein Upper Claystone (ZEUC). The ZEUC is in this section only 25m thick and falls below the seismic resolution. However the base of the ZEUC is the top of the ZEZ3H, which is defined by a hard kick. The density of the ZEZ3H is lower than the ZEUC, while the sonic velocity in the ZEUC is higher compared with the ZEUC. The difference in sonic velocity between the salt and clay units resulted in the increase in acoustic impedance between the ZEUC and ZEZ3H Members. If the ZEUC is thick enough, thicker than 30m, the top would be characterized by an increase in acoustic impedance, a negative loop. However the amplitude of the loop should be low, due to the small difference in petrophysical properties between the ZEUC and the overlying Main Claystone Formation. In appendix 11 a small negative amplitude loop is visible near the top of the ZEUC; this could correspond with the top Zechstein in this synthetic seismogram. However it is more likely that this negative loop is an enhanced side-lobe of the high amplitude negative loop of the top ZEZ3H.

It should be stated that the seismic character of the top Zechstein is highly dependent on the overlying lithology. In this case the overlying lithology is the Triassic Main Claystone Formation, while in the area of E02-02 the overlying lithology is the Vlieland Claystone Formation. It is even possible that the ZEZ3H is covered by younger Zechstein Members such as the ZEZ4A or the ZEZ5A. The acoustic impedance contrast between the ZEUC and the anhydrite member is in this case much larger, and would result in a negative loop with a very high amplitude. The interface between the anhydrite and the underlying ZEZ3H would be characterized by a decrease in acoustic impedance, and result in a positive amplitude loop.

Ideal Zechstein platform well

The ideal platform well is a well through a Zechstein build-up, thus thick anhydrite and carbonate layers, and absence of any salt, see Figure32. The thickness of each individual Zechstein member was based on literature and well data. Table 9 shows an overview of the chosen thicknesses for each Zechstein member.

Table 9: Zechstein well tops and thicknesses as used for the ideal platform well.

Hypothetical Zechstein Platform			
	Well Tops [m]	**Thickness [m]**	**Thickness based on**
Overburden	*0*	*2000*	
ZEUC	2000	25	*Geluk, 2007 - Geology of the Netherlands*
ZEZ3A	2025	40	*Well E02-02*
ZEZ3C	2065	20	*vd Sande, 1996 and Well E02-02*
ZEZ2A	2085	80	*Well E02-02*
ZEZ2C	2165	80	*Reijers, 2012*
ZEZ1A	2245	175	*Reijers, 2012 and well E02-02*
ZEZ1C	2420	30	*Well E02-02, Geluk, 2000 and vd Sande, 1996*
ZEZ1K	2450	2	*vd Sande, 1996*
Underburden	*2452*	*100*	
Zechstein Thickness		**452**	

Well E02-02 has had the strongest influence on the thicknesses of the Zechstein members in this ideal well. The ZEUC thickness is 25m thick, the same as in the basinal setting. The Zechstein-3 Anhydrite Member is in this ideal well 40m thick, and is based on well E02-02, in which the ZEZ3A is 36m thick. The underlying ZEZ3C is thicker in the platform section than in the basinal section. In this ideal well the thickness is set to correspond the maximum thickness, ~40m, given by Van de Sande, (1996) and a minimum thickness, ~3m, from well E02-02. The thickness of the ZEZ2A is based on well E02-02.Zechstein-2 Carbonate thickness values were based on a combination of the article of Reijers, (2012) and well E02-02. The ZEZ2C in well E02-02 is ~27m thick, while in Reijers, 2012 a maximum thickness of 120m is given. The thickness of the ZEZ1A is combination between Well E02-02, Geluk, (2000) and Van de Sande, (1996). The thickness in well E02-02 is very thin, only a few meters. Geluk, (2000) states that the maximum thickness of the ZEZ1C can reach up to 80m, while Van de Sande, (1996) describes the ZEZ1C as a usually thin layer. Therefore the thickness of the ZEZ1C is picked at 30m. The Coppershale thickness is the same as in the basinal section, because the ZEZ1K is deposited on very regional scale.

Appendix 12 shows the generated synthetic for the ideal platform well. The first two columns from the left show the density and sonic graphs based on the averaged well data. The third column is the acoustic impedance, which is calculated during the synthetic generation process. The fourth column shows the wiggle trace of the synthetic, a colored peak corresponds with a soft kick in acoustic impedance; a positive amplitude. The fifth column is the same as the wiggle trace only with corresponding seismic colors. Hard kicks are characterized by a red fill, while soft kick is filled with blue. The lithology on which the synthetic is based is illustrated in the schematic cross-section on the right side of the figure.

The ideal platform synthetic will be described from bottom to top. The synthetic show that the base Zechstein is defined by a decrease in acoustic impedance, illustrated by a high amplitude positive loop. This soft kick in acoustic impedance is defined by the interface between the base ZEZ1C and the underburden. The ZEZ1K is not resolved on the synthetic, because it thickness falls below seismic resolution. The ZEZ1C has relative high density and low sonic velocity, compared with the underburden. This large difference results in the large difference in acoustic impedance and thus the large positive amplitude loop in the wiggle trace. The side-lobes of the base Zechstein loop are the result of the high amplitude loop of the base Zechstein. These side-lobes are characterized by a negative amplitude loop.

The ZEZ1C top is a positive amplitude loop. The amplitude is not as high as the base of the ZEZ1C, due to the smaller difference in acoustic impedance between the ZEZ1C and ZEZ1-anhydrite Member. The ZEZ1A interval is recognized by high density and low sonic slowness values. These petrophysical properties result in a very high acoustic impedance associated for the ZEZ1A interval, and thus a positive amplitude loop at the base of the ZEZ1A and a negative amplitude loop at the of the ZEZ1A Member. If the thickness of the ZEZ1C Member falls below the seismic resolution, the positive amplitude loop at the base of the ZEZ1C will become even larger and the amplitude of the side-lobes will become larger. This result in a very distinctive set of loops. The high positive amplitude loop will be bordered by two high amplitude negative side-lobes.

The interface between ZEZ1A and ZEZ2C is defined by an increase in acoustic impedance; however the difference in acoustic impedance is not as large as between the ZEZ1C and the underburden. Therefore the amplitude of the associated loop is not as large compared with the ZEZ1C/underburden loop. This is the resulted since difference in petrophysical properties between ZEZ2C and ZEZ1A is not as big as the difference between ZEZ1C and the underburden. The same can be applied for the top of the ZEZ2C. The interface between the ZEZ2C and ZEZ2A is defined by a decrease in acoustic impedance. And a relative small positive amplitude loop, comparable with the negative amplitude loop at the ZEZ2C base.

The thickness of the ZEZ3C is 20m and falls therefore below the seismic resolution. However the synthetic does show two loops that are probably associated with the ZEZ3C Member. A very high amplitude negative loop characterizes the top ZEZ2A, due to the large difference in petrophysical properties between the ZEZ3C and ZEZ2A interval. The density of ZEZ2A is higher and the sonic velocity is much lower than of the ZEZ3C. This difference results in a large increase in acoustic impedance, and therefore a very high amplitude negative loop in the synthetic wiggle trace. The top of the ZEZ3C is defined by a high amplitude positive loop, soft kick, due to a decrease in acoustic impedance. The seismic character of the ZEZ3C is probably the result of an interplay between the ZEZ2A, ZEZ3C and ZEZ3A Members. The high amplitude negative loop associated with the ZEZ3C base is probably defined by the increase of acoustic impedance between ZEZ2A and ZEZ3A. Normally two low amplitude positive side-lobes are expected with this in high negative amplitude loop. However the upper side-lobe has a much larger amplitude compared with the lower side-lobe. This can be explained by the decrease in acoustic impedance between ZEZ3A and ZEZ3C, which should result in a positive amplitude loop. This loop is should not be visible on the seismic: it falls below seismic resolution. However it probably enhances the upper side-lobe of the ZEZ2A and ZEZ3A loop, creating the high amplitude positive loop. A closer look at the top ZEZ3C loop reveals that the peak of the loop does not coincide with the top ZEZ3C. This confirms the explanation above.

The top of the ZEZ3A is defined by an increase in acoustic impedance, due to the large petrophysical differences between the ZEZ3A and ZEUC. This results in a high amplitude negative loop, with two corresponding side-lobes. The ZEUC, which is set to correspond with the top Zechstein in this ideal well, falls below seismic resolution. However a small negative loop is visible close to the top of the Zechstein. This loop is probably enhanced by the side-lobes of the top ZEZ3A.
In this case the Zechstein is overlain by the Triassic Main Claystone Member and the ZEUC falls below seismic resolution. In other cases the Zechstein may be overlain by a different lithology and the ZEUC may be even thicker or even absent, as in well E02-02.

Top Zechstein is defined in these ideal wells by the Zechstein Upper Clay Formation. This is however a shale, which could be easily eroded. The overlying formation is defined by the Triassic Main Claystone Formation or by the Cretaceous Vlieland Claystone. Shale can be easily eroded; therefore caution should be taken with the use of the observed seismic character from the top Zechstein. If for example the top Zechstein is eroded or an alternative layer overlies the Zechstein, the acoustic impedance contrast could be very different.

9.2 Conclusions on the petrophysical description

It can be concluded that due to the pronounced lithological and petrophysical properties, the Zechstein seismic behavior can be very well predicted. The anhydrite members with high density and high sonic velocity always produce an increase in acoustic impedance for their top, and always a decrease in acoustic impedance for their base. While the density and sonic velocity of the carbonate member usually produces the opposite. The overall density and sonic velocity of the BZU in the basinal setting is higher than the surrounding layers. This results in the very characteristic negative loop, hard kick, followed by a positive loop. Top Zechstein seismic character is very dependent on the overlying lithologies and whether or not the ZEUC is present.

9.3 Zechstein well synthetics

This section gives a short introduction on the creation and use of synthetic seismograms ("synthetics") and the used parameters for the process. Next, several wells are introduced and a short description of the generated synthetics is given. Using the synthetics, conclusions are drawn on the seismic character of each individual Zechstein member.

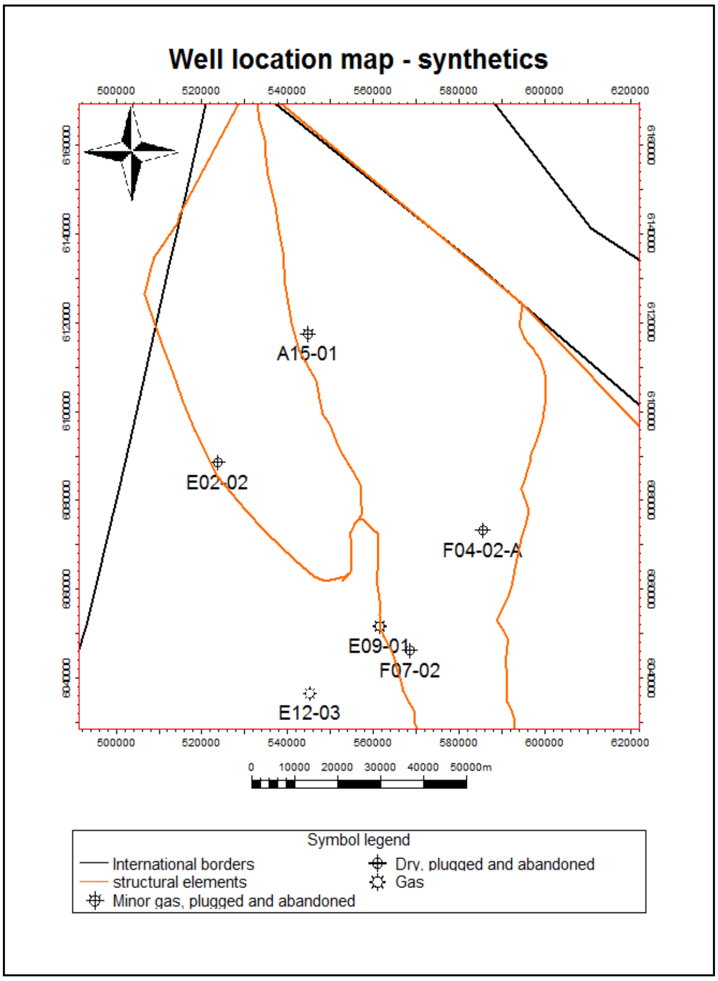


Figure 33: Map showing the locations of the wells, which are used for the generation of the synthetic seismograms.

Synthetic seismograms

A synthetic seismogram is the result of forward modeling of the seismic response along a borehole. The seismic response is based on the (changes in) acoustic impedance of the lithologies, which is calculated with the following equation:

$$Z = v * \rho$$

Where, Z = Acoustic impedance
v = Velocity [m/s]
ρ = Density [kg/m^3] or [gr/cm^3]

The velocity is derived from sonic slowness measurements; the density is derived from density logs like neutron density.

The acoustic impedance is used to calculate the reflection and transmission coefficients along an interface with acoustic impedance contrast. The reflection coefficient is calculated by:

$$R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)}$$

Where, R = Reflection coefficient
Z_1 = Acoustic impedance of first lithology
Z_2 = Acoustic impedance of second lithology

The calculated reflection coefficient is then convolved with a wavelet, which results in a synthetic seismogram along the wellbore.

In the seismic data used in this study an increase in acoustic impedance (hard kick) corresponds with a positive reflection coefficient, and is displayed as a trough. While a decrease in acoustic impedance (soft kick) corresponds with a negative reflection coefficient, and is displayed as a peak.Figure 34 illustrates the seismic convention used in this project.

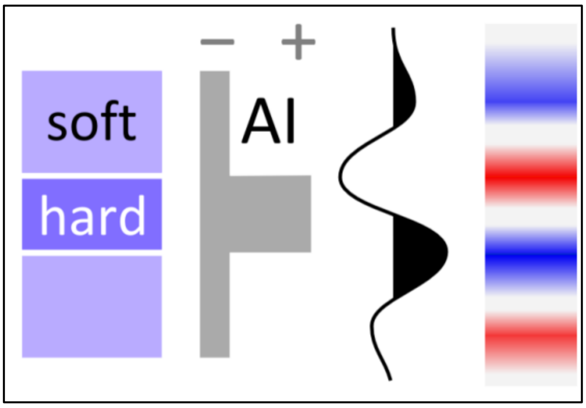


Figure 34: Seismic convention used in this project. An increase in acoustic impedance (AI) is displayed with a trough and the color red. A decrease in acoustic impedance is displayed with a peak and the color blue.

Seismic well tie (classic)

The synthetics in this project were created in Petrel2012.5 E&P software. This software gives the possibility for interactive sonic calibration, wavelet extraction and building, as well as interactive stretching and squeezing of time-depth curves. Before a synthetic can be generated, the sonic log must be calibrated with checkshots. Calibrating a sonic log corrects the log velocities using checkshot data, thereby calibrating the sonic log in seismic travel time. In order to calibrate the sonic log, the log is checked for any gaps in the data. Missing values are interpolated, in order to fill the lack of data. The sonic log is despiked, when necessary. Despiking the sonic log is used to remove spike values, as these error readings will accumulate down through the well when integrating the sonic values. They must be removed before the sonic correction is applied.

Multiple wavelets were investigated for the synthetic generation process. The first investigated wavelet is extracted from the DEF survey, see figure 35.The shape of this extracted wavelet is the of a minimum phase wavelet, which is an asymmetric wavelet with most of the energy in the first part of the wavelet. The extracted wavelet has an automatically assigned time-shift, in order to match the synthetic with the seismic cube. This time-shift is unwanted, because the wavelet will be used in other seismic cubes. Due to these two reasons this wavelet is not suitable for the seismic evaluation of the Zechstein. The second wavelet is also extracted from the DEF survey, however the extraction window is set within the Zechstein interval, see figure 35. The shape of the wavelet corresponds better with the shape of a zero phase wavelet, however there are multiple peaks and troughs visible. This wavelet contains as well an automatic time-shift and because of this and the multiple peaks and troughs the second extracted wavelet is discarded as well.

Petrel offers the possibility to create a wavelet in the wavelet builder. Figure 36 illustrates the zero phase Ricker wavelet, that will be used in the Zechstein seismic character evaluation. This wavelet corresponds with the following convention, a hard-kick corresponds with a negative amplitude, see figure 34. Its frequency spectrum is set to mimic the frequency of the extracted wavelet, and thus the seismic resolution.

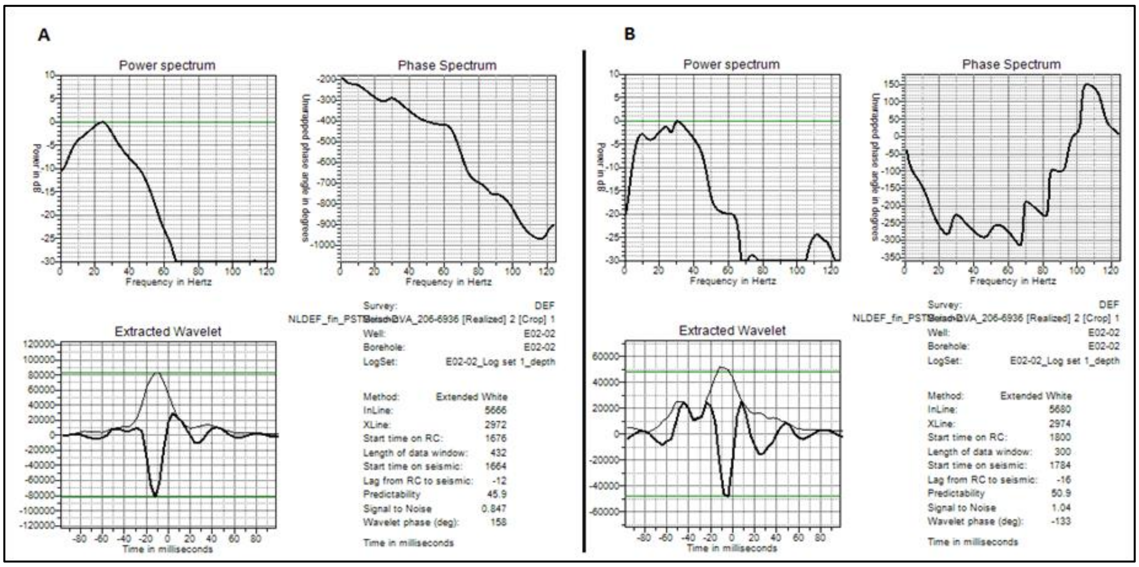


Figure 35: A) wavelet extracted from DEF-survey. B) Wavelet extracted within the Zechstein interval in the DEF-survey. Both wavelets are not suitable for the Zechstein seismic character evaluation.

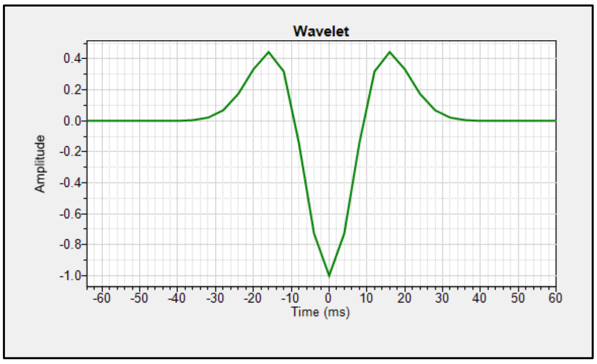


Figure 36: Left panel shows the location of the wells used for the synthetics. Right panel shows the Zero-phase Ricker wavelet, which is used in the synthetic process.

The DEFAB area contains 224 wells, including side-tracked wells, of which 171 are not penetrating the Zechstein-2 Carbonate Member according to DEFAB stratigraphy. From the remaining 53 wells, 6 wells were selected according to the availability of sonic & density logs through the Zechstein and checkshots. A complete overview of the investigated wells can be found in appendix13. In table 10 … an overview of the used wells and corresponding well-logs is given; and in figure 33an overview of the well locations is presented.

Table 10: Overview of the used well for the synthetic seismic evaluation. Wells are selected on the presence of sonic & density logs, checkshots and if the well logs are available for the complete Zechstein section, or only hitting the base of the Zechstein.

Well	Sonic (DT) *[µs/ft]*	Density (RHOB) *[g/cm³]*	Checkshots	Well logs contain complete Zechstein	Base Zechstein
A15-01	X	X	X	X	X
E02-02	X	X	X	X	X
E09-01	X	X	X	X	X
E12-03	X	X	X	-	X
F04-02-A	X	X	X	X	X
F07-02	X	X	X	-	X

E02-02

Well E02-02 is a non-deviated well located on the south-western margin of the Elbow Spit High, see figure 33, defined as an exploration wildcat well. E02-02 was drilled in 1990 and TD'd at 2647m MD. The objective of the well was to drill an exploration well to the Zechstein carbonates. After well completion and test results showed that the well was dry, it was plugged and abandoned. Some traces of gas were found, however the amount was far too little, ranged between 0 – 0.04% at the boundary between Cretaceous and Permian. The average total gas readings were 0.01%. The highest values occurred as fairly isolated peaks in the Upper Zechstein.(Final Well Report, E02-02, 1990).

The total drilled section of well E02-02 is 2647m thick, of which 364m in the Zechstein. The well encountered 3 Zechstein Formation, comprising 6 members. From top to bottom this will be, 36m of Zechstein-3 Anhydrite, 3m Zechstein-3 Carbonate, 79m Zechstein-2 Anhydrite, 27m Zechstein-2 Carbonate, 217m Zechstein-1 Anhydrite and 2m Zechstein-1 Carbonate. Zechstein section is lacking any Zechstein halite member. Appendix 14 shows the stratigraphic coverage of the well-logs.

Synthetic

Appendix15 shows a well section of well E02-02, it shows the gamma ray log, density log, sonic log, acoustic impedance log, generated synthetic and the seismic survey along the borehole. The synthetic seismogram, as presented in figure 5, will be discussed from top to bottom. The synthetic shows that the top of the ZEZ3A member corresponds with a hard kick (increase in acoustic impedance). This corresponds with the transition from the "softer" Vlieland Claystone to the "harder" Zechstein 3 Anhydrite member. This corresponds with a negative amplitude, illustrated with a red reflector. The following member in the Zechstein stratigraphy will be the ZEZ3C. The acoustic impedance shows that the ZEZ3C top should correspond with a soft kick, illustrated with a decrease in acoustic impedance, this is visible in the synthetic seismogram as a blue reflector or positive amplitude.

The synthetic seismogram does not show the transition from ZEZ3C to the ZEZ2A. A possible explanation for this could be that the ZEZ3C layer is too thin for the seismic resolution and is therefore not detected on both seismic and synthetic. The top of the ZEZ2A is visualized by a blue reflector, a soft kick.

The next reflector in this section is the transition from ZEZ2A to the ZEZ2C, this transition is characterized by a decrease in acoustic impedance and thus a blue reflector. The transition from ZEZ2C to the ZEZ1W member is characterized with an increase in acoustic impedance and a red reflector. In contrast with the ZEZ3C/ZEZ2A transition, the ZEZ2C/ZEZ1W boundary is visible. This has probably to do with the thickness of the ZEZ2C member and therefore the seismic resolution.

The last transition in the Zechstein Formation is the boundary between ZEZ1W and the ZEZ1C (and possible ZEZ1K). This boundary is represented by a decrease in acoustic impedance and therefore a blue reflector. An overview of the Zechstein reflectors is given in table1.

Table 11: Schematic overview of the encountered soft and hard kicks in the E02-02 well.

KNNC		Hard Kick
ZEZ3A		
ZEZ3A		Soft Kick
ZEZ3C/ZEZ2A		
ZEZ2A		Soft Kick
ZEZ2C		
ZEZ2C		Hard Kick
ZEZ1A/W		
ZEZ1A/W		Soft Kick
ZEZ1C/ROCL		

E09-01

The exploration well E09-01 is a deviated well on the western margin of the Step Graben, in the E-block of the Dutch sector of the North Sea, see figure 33. E09-01 is drilled in 1980 and has a measured depth (MD) of 3401m, the true vertical depth (TVD) is 3397m. The objective was to test the Rotliegend sandstones. Result of the exploration well was gas, however this was found in the ZEZ2C. A production test was performed on the ZEZ2C M, which resulted in a flow of ±300.000m3/day consisting mainly of N2 (±85%). And after this the well was plugged and abandoned(well report E09-01, NAM, 1980). The total drilled section of well E09-01 is 3401m, of which 500m in the Zechstein. However it should be mentioned that 380m of this section is the Zechstein-2 Halite Member. The Zechstein stratigraphy encountered can be found in appendix 16. In total this well counts 9 Zechstein Members. The available well-log for this well are the gamma ray, density and sonic logs. Appendix 16 gives an overview of the well-logs and their stratigraphic coverage.

Synthetics

Appendix 17presents the synthetic and well section of well E09-01, this well section shows the gamma ray, density, sonic, acoustic impedance logs, and the generated synthetic seismogram and the actual seismic survey along the borehole. The upper most Zechstein well-top in this well is the

Zechstein Upper Claystone Formation (ZEUC). The top of the ZEUC corresponds with a blue reflector in the seismic, soft kick in acoustic impedance. A closer look at the acoustic impedance log shows that there is hardly any evidence for a decrease in acoustic impedance, see appendix 17.
The boundary between ZEUC and ZEZ3A is characterized by a red seismic reflector, hard kick in acoustic impedance. The well-tops of Zechstein Grey Salt member (ZEZ3G) and ZEZ2H fall together in one seismic reflector, which is hardly visible on seismic or synthetic seismic. In well E09-01 a ~380m thick interval of ZEZ2H is found. In this interval the very dim seismic reflectors are present. However the Zechstein 2 salt interval is often very deformed, due to salt movement, resulting in a very chaotic yet transparent image on seismic, and Sonic values are often very constant.
The well tops below of the Basal Zechstein Unit, below the salt, are all within an interval of ~40m, which is probably below the seismic resolution. The transition from ZEZ2H to the ZEZ2A Member is characterized by a blue reflector, which indicates a soft kick. This compares quite well with the seismic along borehole. The ZEZ1K and ZEZ1C Members correspond with a single bright reflector in the synthetic seismogram. The same reflector is visible in the seismic along borehole, however not as bright as in the synthetic. A schematic overview of the encountered differences in acoustic impedance is given in table 12.

Table 12: Schematic overview of the encountered soft and hard kicks in the E09-01 well.

RBSHM ZEUC		**Soft Kick**
ZEUC ZEZ3A		**Hard Kick**
ZEZ3A ZEZ3G/ZEZ2H	Vague blue	**Soft Kick?**
ZEZ2H ZEZ2A/ZEZ2C		**Soft Kick**
ZEZ2A/ZEZ2C ZEZ1C/ZEZ1K		**Hard Kick**

F04-02-A

The F04-02-A was a wildcat well drilled in 1980, on the border between the F/4 and F/5 block in the Dutch North Sea, see figure 33. The main objective of this well was to drill into a Rotliegend horst block between two N-S trending faults with a well-defined dip closure to the South and dip and fault closure to the north. Secondary objectives were in the Zechstein carbonates, Upper Carboniferous sandstones and Middle Bunter sandstone. Total drilled section is 4656m measured depth. The well was dry, and is therefore plugged and abandoned.

The Zechstein encountered in the F04-02-A well consisted of a thick, uniform development of halite. Interbedded with some minor anhydrite and subordinate carbonate lithologies apparent towards the base of the succession. The total Zechstein thickness is up to ~400m, consisting of 5 Zechstein Formations, see appendix 18. The Zechstein interval mainly consists of halite from the ZEZ2H, ZEZ3H and ZEZ4H Members, with a total thickness of up to 339m. The available well-logs for the F04-02-A well are the gamma ray, sonic and density logs. Appendix 18 gives an overview of the available well-logs and their stratigraphic coverage, focused on the Zechstein interval.

Synthetics

Appendix 19shows the generated synthetic seismogram of well F04-02-A and the extracted seismic along borehole, together with the used wire-line logs. The first well-top in this well is the ZEUC, and coincides roughly with a red seismic reflector, increase in acoustic impedance. However the ZEUC well-top is very close to the ZE4H well-top, therefore it is not clear whether or not the ZEUC produces the red reflector. This corresponds very well with the extracted seismic.
The second reflector shown in the synthetic seismogram is the reflector produced by the transition from the ZEZ4H Member to the ZEZ4A/ZEZ3H Members. This transition is characterized with a blue reflector, which also corresponds nicely with the extracted seismic. The seismic resolution is too little in order to distinguish between the ZEZ4A and ZEZ3H Members.
The synthetic shows that the transition from the ZEZ3H Member to the ZEZ2H Member corresponds with a faint blue reflector. This coincides quite well with the extracted seismic, however the reflector in the extracted seismic is much brighter compared to the synthetic.
The Basal Zechstein Unit (BZU) is only 51m thick and is characterized in the synthetic as one bright red reflector, underlain by bright blue reflector. This corresponds well with the extracted seismic along the F04-02-A borehole. The seismic resolution is probably too poor to distinguish between the individual well-tops in the Basal Zechstein Unit. A schematic overview of the synthetic and corresponding kicks in acoustic impedance is presented in table 13...

Table 13: Schematic overview of the encountered soft and hard kicks in well F04-02-A. BZU is Basal Zechstein Unit. In this schematic overview the BZU is considered to be one formation, due to its thickness of only 51m, which is too little for the seismic resolution.

RBSHM		Hard Kick
ZEUC/ZEZ4H		
ZEZ4H		Soft Kick
ZEZ4A/ZEZ3H		
ZEZ3H	Vague	Soft Kick
ZEZ2H	blue	
ZEZ2H		Hard Kick
BZU		

A15-01

The exploration well A15-01 is located in the A quadrant of the Netherlands sector in the North Sea, see figure 33. In a structural context the A15-01 is located in the Step Graben and East of the Elbow Spit High. Drilling started in 1977 and drilled a section of 3912m measured depth (MD), there is no significant deviation for this well. The main objective of this exploration well was to investigate Zechstein and Rotliegend reservoir formations. Oil and gas-shows were found in the Basal Zechstein Unit. The well was dry and is therefore plugged and abandoned (Drilling report A15-01).

The total drilled section of well A15-01 is 3912m, of which 246m Zechstein. The Zechstein section in this well comprises of the Zechstein-1 Formation, including the ZEZ1K, ZEZ1C and ZEZ1A Members, the Zechstein-2 Formation, including theZEZ2C, ZEZ2A and ZEZ2H Members. The top of the Zechstein section is defined by the Zechstein Upper Claystone Formation. The ZEZ2H Member is the thickest

Zechstein member in this section, with a thickness of 149m. The ZEZ1A Member has a thickness of 41m, this is odd because the ZEZ2A Member usually has a comparable thickness. Younger Zechstein Formations such as the ZEZ3 and ZEZ4 Formations are missing in this well section. An overview of the encountered stratigraphy in the A15-01 well is presented in Appendix 20, which shows the available well-logs focused on the Zechstein for well A15-01.

Synthetic

Appendix 21shows the generated synthetic for the well A15-01, as well the extracted seismic along borehole. The upper most Zechstein Formation in this well is the ZEUC, which corresponds with a faint blue reflector in the synthetic. The same reflector in the extracted seismic is as well a soft kick, only a bit brighter. The synthetic shows that there is not a clear transition from ZEUC to ZESAU. The extracted seismic shows a red reflector below the well-top of the ZEZSAU. The third main reflector in the synthetic is a combination of the ZEZ2A, ZEZ2C and ZEZ1A/W Members; the total thickness is probably too low for the seismic resolution. This reflector is characterized by a bright red reflector, comparable with the extracted seismic. However the reflector in the extracted seismic is a bit dim, compared with synthetic. The boundary between ZEZ1A/W and the combination of ZEZ1C, ZEZ1K and ROCL is a bright blue reflector, exactly the same as in the extracted seismic. Table 14gives a schematic overview of the most important recognized reflectors in well A15-01.

Table 14: Schematic overview of the encountered soft and hard kicks in A15-01.

RBSHM ZEUC	(blue)	Soft Kick
ZEUC ZESAU	(light red)	Unknown
ZESAU ZEZ2A, C and ZEZ1W/A	(red)	Hard Kick
ZEZ1W/A ZEZ1C, ZEZ1K, ROCL	(blue)	Soft Kick
	(red)	Hard Kick

E12-03

The E12-03 well is drilled in the E-block, located South of the Elbow Spit High and West of the Step Graben, see figure 33. Drilling commenced in 1991 and was completed in the same year, having reached a total measured depth of 3865m. The well is slightly deviated and the true vertical depth is 3862m. The main objective was to drill into the Westphalian. A gas bearing formation was struck in the Westphalian Limburg Group(End of drilling report, Elf Petroland).

The total thickness of the drilled section was 3865m, of which 577m Zechstein. The Zechstein in this well contains 505m of salt from the ZEZ2H Member. The other 72m comprises the ZEZ1K, ZEZ1C, ZEZ1A, ZEZ2C, ZEZ2A and the ZEUC. The carbonate member thickness in this well is only a couple of meters. The available well-log for this well are the gamma ray, sonic and density logs, see appendix 22. However the sonic and density logs do not cover the complete Zechstein Formation. The ZEUC

Formation of the Zechstein is not covered, therefore the generated synthetic will only cover an incomplete part of the Zechstein.

Synthetic

Appendix 23 shows the generated synthetic for the E12-03 well. This synthetic is not complete for the Zechstein, because the sonic and density logs are missing for the upper most part. This affects only the ZEUC and ZEZ2H well tops. The Basal Zechstein Unit is too small for the seismic resolution, and is characterized by one bright red reflector, which compares very well with the extracted seismic.

F07-02

Well F07-02 was an exploration well located 180km north-northwest of the Den Helder, in the F7 block, see figure 33. The well was situated in the south-east of the Elbow Spit High and west of the Dutch Central Graben, in the Step Graben. The main objective was to drill into the Carboniferous aged Westphalian sandstone, and the second objective was the Lower Permian aged Slochteren sandstone Formation. Total drilled section was 4200m measured depth (MD), true vertical depth (TVD) was 4188m. Although not an objective of the well, traces of oil were recorded in the Zechstein-2 Carbonate Member, between 3260m and 3269m MD. Net thickness of the interval is 8.5m, porosity of 6% and a water saturation S_w of 80%. Throughout the Zechstein Group small gas traces were measured. The F07-02 well was plugged and abandoned as a dry hole (End of well report, Hamilton Oil Company LTD, 1993)
The total Zechstein thickness is up to 905m measured depth, of which 856m of Zechstein salt. The Basal Zechstein Unit is only 38m thick, the individual layers are probably too thin compared to the seismic resolution. The complete Zechstein stratigraphy and corresponding thicknesses can be found in appendix 24 show the available well-logs for F07-02. The sonic and density logs are only available for the Basal Zechstein Unit, both of them are missing for the ZEUC and the complete Zechstein salt interval.

Synthetic

Appendix 25 illustrates the generated synthetic for well F07-02. The left seismic trace corresponds with the synthetic and the right seismic trace is the extracted seismic along borehole. The synthetic for this well is incomplete, as result of the incomplete sonic and density logs. The synthetic show two very clear reflectors for the ZEZ2A, ZEZ2C and ZEZ1A/W, and the second reflector for the ZEZ1C, ZEZ1K and ROCL. The ZEZ2A, ZEZ2C and ZEZ1A/W are characterized by a very bright reflector, comparable with the extracted seismic. The ZEZ1C, ZEZ1K and ROCL reflectors are characterized with a bright blue reflector which compares very well with the extracted seismic.

9.4 Discussion & Conclusions

With the use of the generated synthetics it is possible to evaluate the seismic character of the Zechstein. The following Zechstein members will be discussed in the next section: ZEZ1K, ZEZ1C, ZEZ1A/w, ZEZ1C, ZEZ2A and the Basal Zechstein Unit will be discussed as a whole. Further the Zechstein Salt, ZEZ3C, ZEZ3A and the ZEUC.

Zechstein-1 Coppershale (ZEZ1K)

The Coppershale, with a thickness of ~2m, is not visible as an independent reflector on any of the generated synthetics. Therefore the Coppershale cannot be evaluated as a single reflector, and shall be discussed as a part of the Basal Zechstein Unit.

Zechstein-1 Carbonate Member (ZEZ1C)

The Zechstein-1 Carbonate Member is in none of the synthetics visible as a single independent reflector. Therefore the ZEZ1C will only be discussed as a part of the Basal Zechstein Unit.

Zechstein-1 Anhydrite Member (ZEZ1A)

Well-top of ZEZ1A is visible as a single reflector in wells E02-02 and A15-01, in other wells the ZEZ1A member is too thin. Therefore the seismic character of the ZEZ1A will be based on wells E02-02 and A15-01. In E02-02 the ZEZ1A interval shows decreased sonic values and increased density values, compared with the over and underlying Zechstein members. The top of the ZEZ1A is the base of the ZEZ2C, this boundary is marked with a bright red reflector. This is the result of an increase in acoustic impedance, acoustic impedance in the ZEZ2C is lower than in the ZEZ1A. The base of the ZEZ1A is the top of the combined interval of ZEZ1C and the ROCL, which is defined by a blue reflector. And is the result of a sharp drop in acoustic impedance.

In well A15-01 the ZEZ1A interval also shows decreased values for the sonic and increased values for the density logs. The overlying ZEZ2A and ZEZ2C Members are too thin to make a distinction on seismic scale. Therefore it is most likely that the top of the ZEZ1A is a combination of the ZEZ2C, ZEZ2A and ZEZ1A, which corresponds with a bright red reflector. The base of the ZEZ1A is also a combination of reflectors, which are not detectable on this seismic resolution.

Based on the two synthetics, E02-02 and A1502, it is possible to state that the top of ZEZ1A is a hard kick, red reflector and the base of the ZEZ1A corresponds with a soft kick, blue reflector.

Zechstein-2 Carbonate Member (ZEZ2C)

The ZEZ2C is thick enough to be detected on seismic in well E02-02. The sonic log of the ZEZ2C shows an increase in sonic values for this interval, while the density is lower compared with the overlying/underlying members. This results that the acoustic impedance of the ZEZ2C is a lot smaller. This contrast in acoustic impedance results in a soft kick for the top and a soft kick for the base of the ZEZ2C. Other wells show that the Zechstein-2 Carbonate Member is associated with increased sonic and decreased density values, see figure 37. Therefore it is possible to conclude that the ZEZ2C Member will be associated with a soft kick at the top and a hard kick at the base.

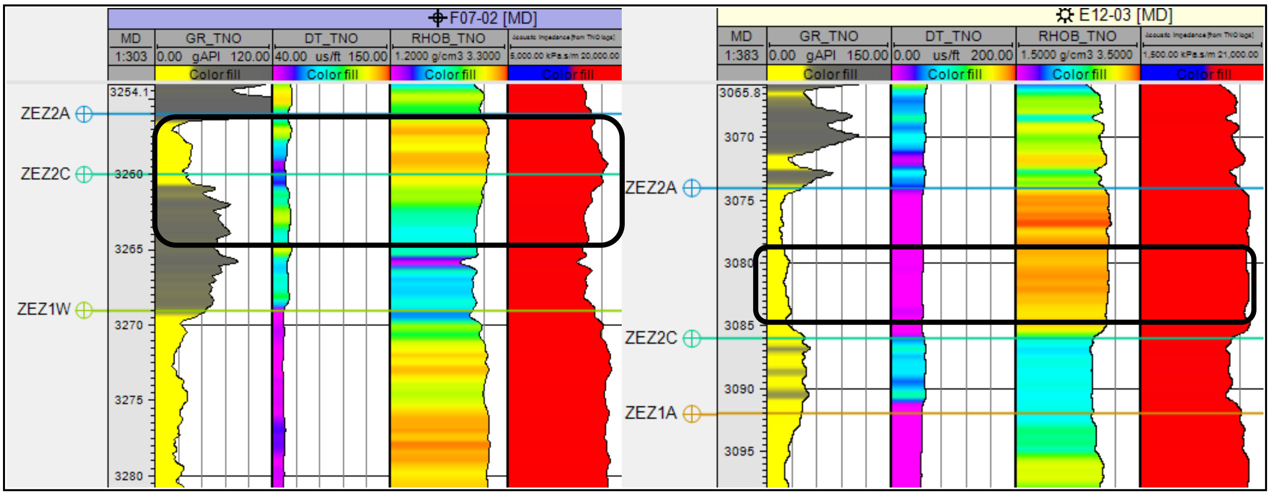


Figure 37: Two well section panels focused on the Zechstein-2 Carbonate Member. Circled areas are the ZEZ2C intervals, with increased sonic and decreased density values.

Zechstein-2 Anhydrite Member (ZEZ2A)

The well E02-02 is the only suitable well for the seismic evaluation of the ZEZ2A. The Sonic values compared with the overlying and underlying members are decreased, while the density values are increased compared with the neighboring members. These characteristic values for the ZEZ2A are also visible in other wells, such as the E12-03 well, see figure 38.

The above results in a soft kick, for the base of the ZEZ2A. The top of the ZEZ2A has not a clear reflector, this is the effect of the thin ZEZ3C layer between both anhydrite members. The thin carbonate layer falls below the seismic resolution, and as a result both anhydrite layers seen as one thick anhydrite package. The top of the ZEZ2C is characterized by a blue reflector, which is probably the result of the interplay between the thin ZEZ3C and top ZEZ2A. One should expect a hard as top ZEZ2A, due to the increase in acoustic impedance between the ZEZ3C and the ZEZ2A. It can be stated that the base of the ZEZ2A Member corresponds with a soft kick, blue reflector, and the ZEZ2A top should be represented as hard kick, and thus a red reflector. However this is very dependent on the overlying Zechstein member. If the ZEZ3C is thick enough to be datable on the seismic, than the top of the ZEZ2A will become much more prominent.

Zechstein Salt

The Zechstein Group is known for its thick packages of salt, such as the ZEZ2H and ZEZ3H. On well-logs salt is recognized for its very low sonic values, which usually distorts the seismic image of underlying formations. The well section of F04-02-A gives a good overview of the petrophysical charactistics of the Zechstein salt, see figure 10. The synthetic suggests some seismic reflectors in the salt interval, however it is not clear whether this is true or not. This could be the result of heterogeneities in the Zechstein salt.

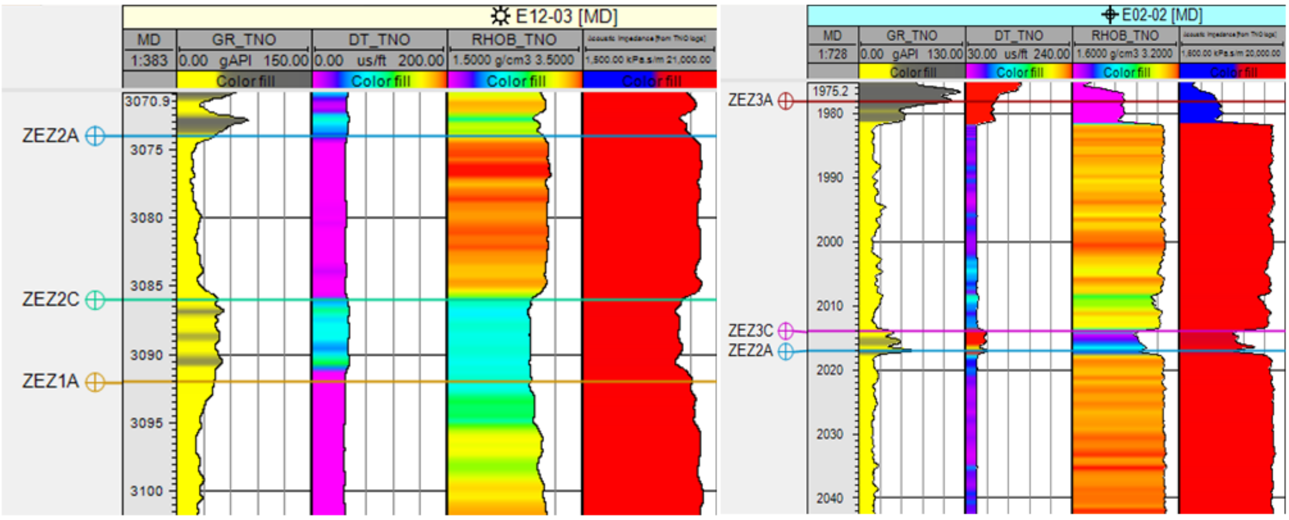


Figure 38: Part of the well section panels for wells E02-02 and E12-03, which are focused on the ZEZ2A Member. This interval shows a clear decrease in sonic values and a clear increase in density values.

Zechstein-3 Carbonate Member (ZEZ3C)

The Zechstein-3 Carbonate is not seismically detectable on any of the generated synthetics. Therefore it is only possible to do a theoretical seismic evaluation of the ZEZ3C. Figure 39 shows a zoomed in section of the well E02-02 showing the interval containing the ZEZ3C. The interval containing the ZEZ3C has elevated sonic values and lower density values, this result in a decrease in acoustic impedance compared with the over- and underlying Zechstein members. Normally this would result in a soft kick (blue reflector) at the top and a hard kick (red reflector) at the base of the ZEZ3C.

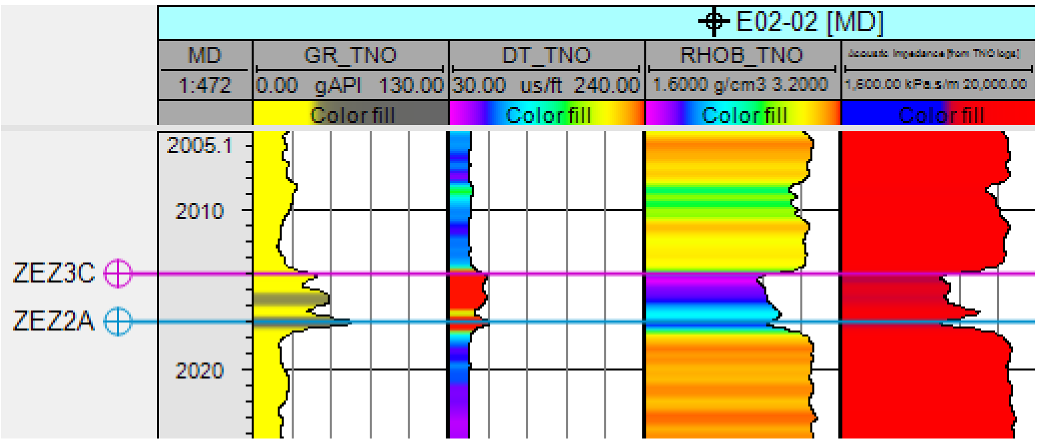


Figure 39: Well section of E02-02, zoomed into the ZEZ3C. Illustrating the increased sonic values and decreased density values, which result in a decrease in acoustic impedance compared with the over- and underlying members.

Zechstein-3 Anhydrite Member (ZEZ3A)

The synthetics of wells E09-01 and E02-02 are suitable for the seismic characterization for the ZEZ3A Member. E09-01 show that the curves of the sonic and density logs are very erratic of nature, which result in a very irregular acoustic impedance curve, see figure 40. It should be expected that the ZEZ3A interval has elevated density and decreased sonic values, just as observed in the ZEZ2A interval. Well E02-02 does show that the sonic and density values are respectively decreased and increased, compared with the over- and underlying stratigraphic units, see figure 40. This result in a bright red reflector (hard kick) for the top of the ZEZ3A in wells E02-02 and E09-01. However well E02-02 shows that there is a small offset between the ZEZ3A well-top and the increase in acoustic impedance and the position of the reflector. This could indicate that the well-top of ZEZ3A is slightly too high. The base of the ZEZ3A is not as good visible as the top of the ZEZ3A. E02-02 indicates that the base of the ZEZ3A should correspond with a blue reflector, soft kick. This is expected, when the underlying Zechstein member is the ZEZ3C Member, which has a lower acoustic impedance than the ZEZ3A.

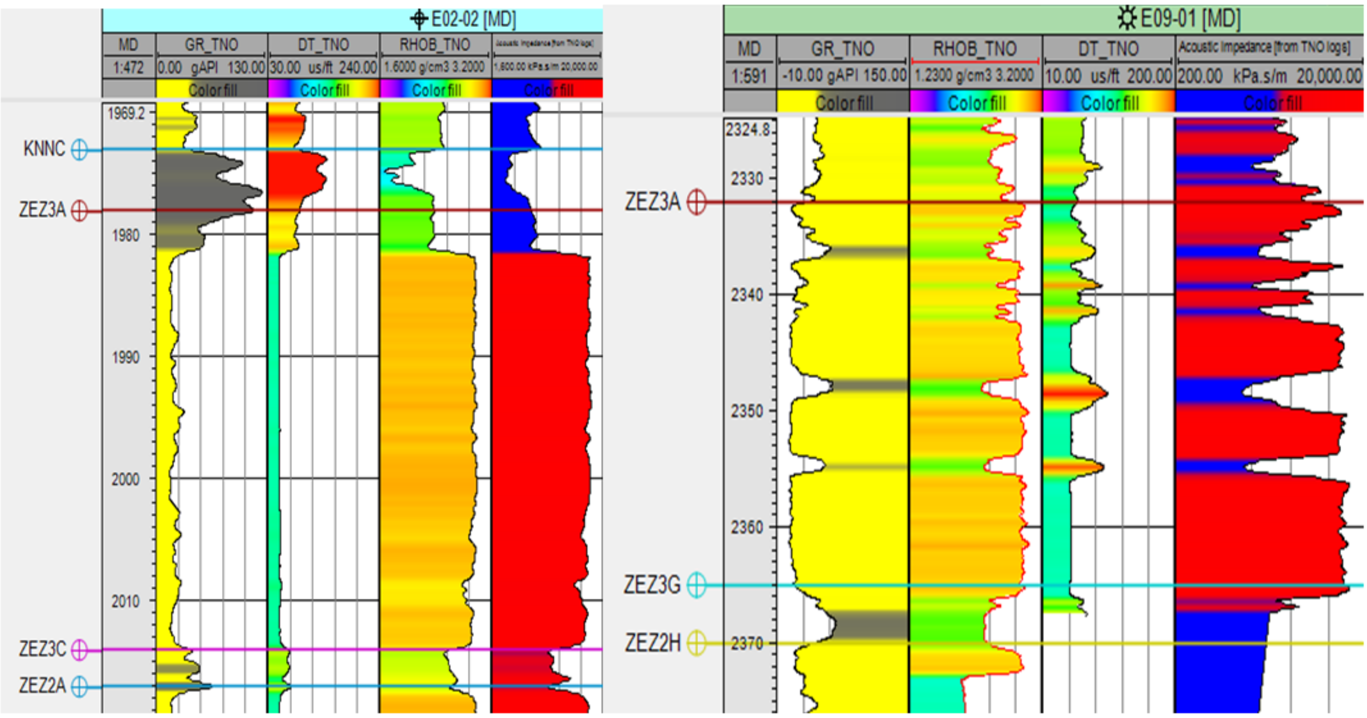


Figure 40: Left panel well E02-02, showing a regular ZEZ3A logs for the sonic and density. E02-02 also shows the potential offset in position of the ZEZ3A well-top. The right panel shows the E09-01 well section, with the corresponding erratic sonic and density well-logs.

Basal Zechstein Unit (BZU)

The Basal Zechstein Unit comprises of the ZEZ1K, ZEZ1C, ZEZ1A, ZEZ2C and the ZEZ2A Members, all the members lie beneath the thick Zechstein-2 Halite. Wells E09-01, E12-03 and F04-02-A were suitable for the seismic characterization of the Basal Zechstein , as a single unit. It was useful to describe the BZU as single unit, because in most of the wells the single members of the BZU are too thin to be recognized on seismic.

In well E09-01 the BZU is 41m thick and shows an overall decrease in sonic values, and an increase in density values. This resulted in elevated values for acoustic impedance, which is reflected in the synthetic seismic as a hard kick, for the lower part of the BZU. However this reflector is not as bright as in the extracted seismic. The lower boundary of the BZU shows a decrease in acoustic impedance, which is not reflected in the synthetic seismic. This can be explained due to the presence of the hard kick induced by the lower part of the BZUZ. It is possible that this hard kick shadows the weaker soft kick induced by the lower boundary of the BZU. Well E12-03 which contains a 45m thick BZU section, and is represented by a very thick, bright red reflector, which is possible the result of the decreased sonic and increased density values. The upper and lower boundary of the BZU is represented by two blue reflectors, of which the lower is much brighter than the upper reflector. Compared with the extracted seismic, the synthetic seismogram correlates very well, see figure 41. The F04-02-A well shows the same characteristic for the BZU as well E12-03. Thus a bright red reflector for the whole BZU, and bounded by two blue reflectors. The lower blue reflector is much brighter than the upper blue reflector, see figure 41. From the above it can be concluded that the BZU corresponds with a bright red reflector, bounded by two blue reflectors.

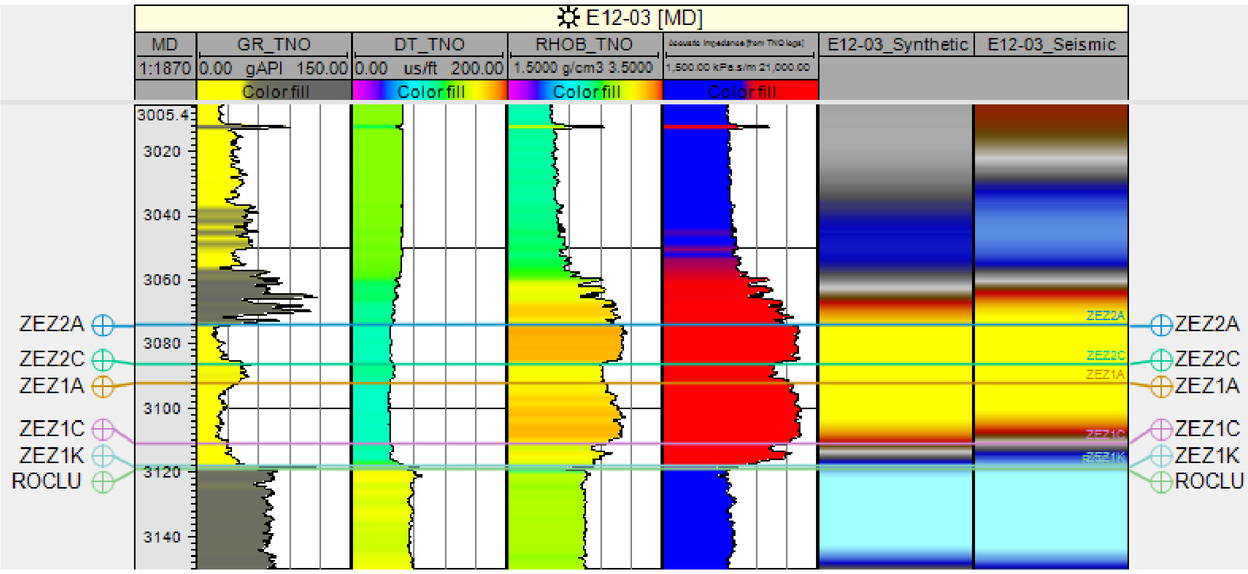


Figure 41: Well section of the E12-03 well focused on the BZU. The synthetic and extracted seismic compares very well in this well section.

9.5 Zechstein seismic character on seismic

The Zechstein seismic character is different in varying parts of the basin. Deeper areas are often characterized by thick halite deposits with associated halokinesis, while along the basin margins little or no salt is present. A very characterizing feature in the deeper parts of the basin are the ZEZ3A/C rafts, which are completely encased in Zechstein salt. The Zechstein-3 hard rock layers were deposited throughout the entire basin, as a result of the existing paleo-relief. This is the result of the Zechstein-2 salt, which covered all the existing relief in the Southern Permian Basin. Therefore the Zechstein-3 Carbonate and anhydrite Members show less variation in thickness, which indicates a more gentle relief (Geluk, 2000). The Zechstein-3 hard rock layers were deposited on top of the Zechstein-2 salt and covered by salts of the ZEZ3H Member. This resulted that the brittle Zechstein-3 layers were completely encased with salt, while the Zechtein-1/2 and Zechstein-3/4 Formations were mechanically coupled to respectively the underburden and the overburden.

This configuration has led to the formation of the Zechstein-3 rafts. The driving factor behind the formation of the Zechstein-3 rafts was the difference in density. The Zechstein-3 hard rock layers which have a higher density, respectively ~2.81 [g/cm^3] for anhydrite and ~2.61 [g/cm^3] for carbonate, than the surrounding salt, which has a density of ~2.1 [g/cm^3]. The difference in density results in an unstable situation, salt is lighter and wants to move upwards, while the denser ZEZ3A/C wants to sink below the salt. This results in the breaking and folding of the Zechstein-3 hard rock layers and the formation of rafts. The rafts show a large variety of locally restricted and strongly varying deformation features, like boudinage and folding (Strozyk et al., 2012). The ZEZ3A/C rafts are well imaged on seismic, due to the high acoustic impedance contrast between salt and the rafts. However if the thickness of the ZEZ3A/C stringer falls below 30-35m the raft is not visible (Strozyk et al., 2012). On seismic the ZEZ3A/C rafts are characterized by first a bright red reflector (hard kick), directly followed by a bright blue reflector (soft kick), see figure 42. The following section will discuss the Zechstein seismic character in combination with the Zechstein-3 rafts.

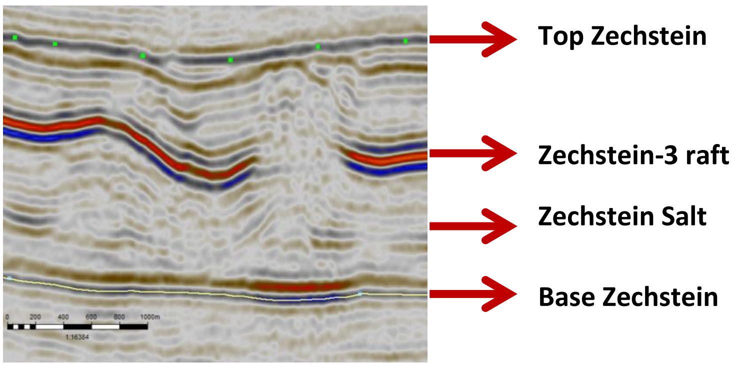


Figure 42: Typical Zechstein section in the deeper part of the basin, showing base and top Zechstein, ZEZ3A/C rafts and salt.

Seismic character

The following observations on the Zechstein seismic character are based on the seismic cross-section that can be found in appendix 26, which shows a E-W cross-section. The cross-section is inline 4960 through the DEF survey and shows the base and top Zechstein and base Chalk horizons. The cross-section can be split into three parts, each part illustrates a different seismic character of the Zechstein.

The first part is recognized by the ZEZ3A/C rafts which are completely encased in Zechstein salts. The Zechstein-3 Carbonate and Anhydrite Members are completely broken-up and folded, creating anti- and synclines. The rafts are very well visible on seismic as a red reflector, corresponding with a hard kick, followed by a blue reflector, which is a soft kick. This sequence is similar to the seismic succession found in the ideal basinal well. The geometry of the Zechstein-3 does not follow the geometry of the top or base of the Zechstein.

Top and base Zechstein in this section are not as bright as the raft, however both are very well visible on seismic. Top Zechstein corresponds with a soft kick, blue reflector, which is probably the result of a decrease in acoustic impedance from the overlying formation into the Zechstein Salt. This does not correspond with the ideal basinal well. A possible explanation could be that the overlying lithology has a higher acoustic impedance. This results in a soft kick at the interface between both lithologies, and this a blue reflector instead of a bright red reflector. The base of the Zechstein is characterized by first high amplitude negative loop directly followed by positive amplitude loop. This sequence is very similar to the base of the ideal well and to the Zechstein base of synthetic E12-03. This indicates that the BZU is too thin to be detected on seismic, and cross-section is in a basinal Zechstein setting.

Within the Zechstein some other faint reflectors are found, however these are not as bright as the top/base of the Zechstein and are equally folded as the Zechstein-3 rafts. Base Zechstein is characterized with a soft kick, blue reflector. The BPU and Carboniferous layers below the Zechstein group are very good visible on this seismic section.

The second part of the cross-section is recognized as a thick chaotic section. Top Zechstein in this section is as low amplitude soft kick, directly followed by a high amplitude hard kick. This is similar to the synthetic of the ideal basinal well. Where the top Zechstein was also directly followed by a high amplitude negative loop, hard kick. The Zechstein base of this section is very poorly visible, and corresponds with a low amplitude soft kick. In this section there are no visible rafts and the underlying Carboniferous is very poorly visible on the seismic section, whilst in section 1 the Carboniferous layers and BPU are very good visible on seismic.
A possible explanation for the difference of seismic visibility could be due to a processing mistake/artifact. This is supported by the fact that the Carboniferous layers are very well visible in section 1 and not at all visible in section 2, whilst they are certainly present in section 2.

The third section from the cross-section in appendix 26 is characterized by a Triassic pod, which has sunken into the Zechstein. In this section there is very little salt presence and the top Zechstein is very poorly visible on seismic. While the base Zechstein is very good visible on the seismic. The Zechstein base in this section is characterized by first a negative loop, hard kick, and directly followed by a positive loop, soft kick. This sequence is very similar as the sequence found in the ideal basinal synthetic. The internal structure of the Zechstein in this area is quite chaotic, besides some brighter reflectors, which could correspond to the Zechstein-3 rafts.

Appendix 27 shows another E-W cross-section through the DEF survey, which corresponds with inline 5674. This cross-sections shows the Zechstein-2 platform which was drilled by well E02-02. The well shows that the top of the Zechstein in this build-up corresponds with the Zechstein-3 Anhydrite Member. In this sections no salt is present, and the layers in the build-up corresponds with the Basal Zechstein Unit + Zechstein-3 Carbonate and Anhydrite Members and the intra-Zechstein reflectors are very well visible. The top corresponds with a high amplitude hard kick, red reflector, the ZEZ3A, whilst the base corresponds with a low amplitude soft kick. This is comparable with the ideal platform well synthetic. However the amplitude of the base Zechstein in this seismic section is much lower compared with the synthetic.

The Zechstein-3 Anhydrite and Carbonate Member in this section have the same shape as the older Zechstein members. The ZEZ3A and ZEZ3C follow the ZEZ2C build-up structure, transition from platform slope to basin. The top Zechstein is unconformable overlain by the Cretaceous Vlieland Claystone Formation. While to the west the Zechstein is overlain by an older formation, this interval seems to onlap onto the slope of the build-up and is cut-off by the Vlieland Claystone Formation. The base of the onlapping unit seems to correspond with the base of a Triassic pod to the west of this section, see appendix 28.

9.6 Discussion & Conclusions

The sections above show that the Zechstein seismic character can be very different over a small lateral extend. If the section 1 and 4 are compared with each other, it became clear that the amplitude of the base Zechstein is much higher in the basinal setting (~15.000) than in the platform setting (~5000). The amplitude of the base Zechstein could be influenced by the presence of salt and/or intra-Zechstein layers. There could be a possible relationship between the presence of thickened intra-Zechstein layers, as seen in E02-02 platform and the amplitude of the base Zechstein. In the next section an attempt will made to create an extracted base Zechstein amplitude map from the seismic data.

Another important observation is that the characters of the Zechstein-3 anhydrite and carbonate rafts are different in varying setting. For example in a basinal setting the ZEZ3 rafts are completely encased in salt and are heavily folded and faulted; the raft is the only bright reflector in the salt. In a shallow setting, the ZEZ3 rafts are not folded and show a more gentle continuing behavior, as observed in the E02-02 platform area. The ZEZ3A and ZEZ3C in the E02-02 platform area follow the structure of the older Zechstein units, probably due to the lack of salt. The ZEZ2H Member in the E02-02 area could be nod-deposited or migrated away from the structure. If salt was deposited and migrated away, the ZEZ3A and ZEZ3C member was draped over the ZEZ2C build-up. Resulting in the characteristic basin, slope and platform structure of the ZEZ3A/C members, while they were deposited in non-such manner. Therefore the shape of the ZEZ3A and ZEZ3C could be indicative for the presence of ZEZ2C build-ups. This method is probably only applicable along the margins of the basin were no salt was deposited or migrated away.

9.7 Base Zechstein amplitude map

The observed base Zechstein amplitude differences could indicate the presence of a Zechstein build-up. The amplitude differences could be used for a very rough first order exploration tool for the Zechstein, however the actual seismic should always be taken into account. Low amplitude base Zechstein could be an indicator for the presence of a thickened Basal Zechstein Unit. However it is known that the seismic reflectors below a salt dome are also dimmed, as a result of extremely thick salt.

In order to test the correlation between base Zechstein seismic amplitude and the presence of Zechstein build-ups, the seismic amplitude is extracted from the base of the known Zechstein carbonate build-up, namely the E02-02 platform.

Figure 43 shows the extracted amplitude map from the base Zechstein below the E02-02 platform. The purple area in this figure corresponds with the area with a low amplitude. A polygon is roughly drawn around the purple area in order to compare the platform outline derived from the amplitude map with the top Zechstein map.

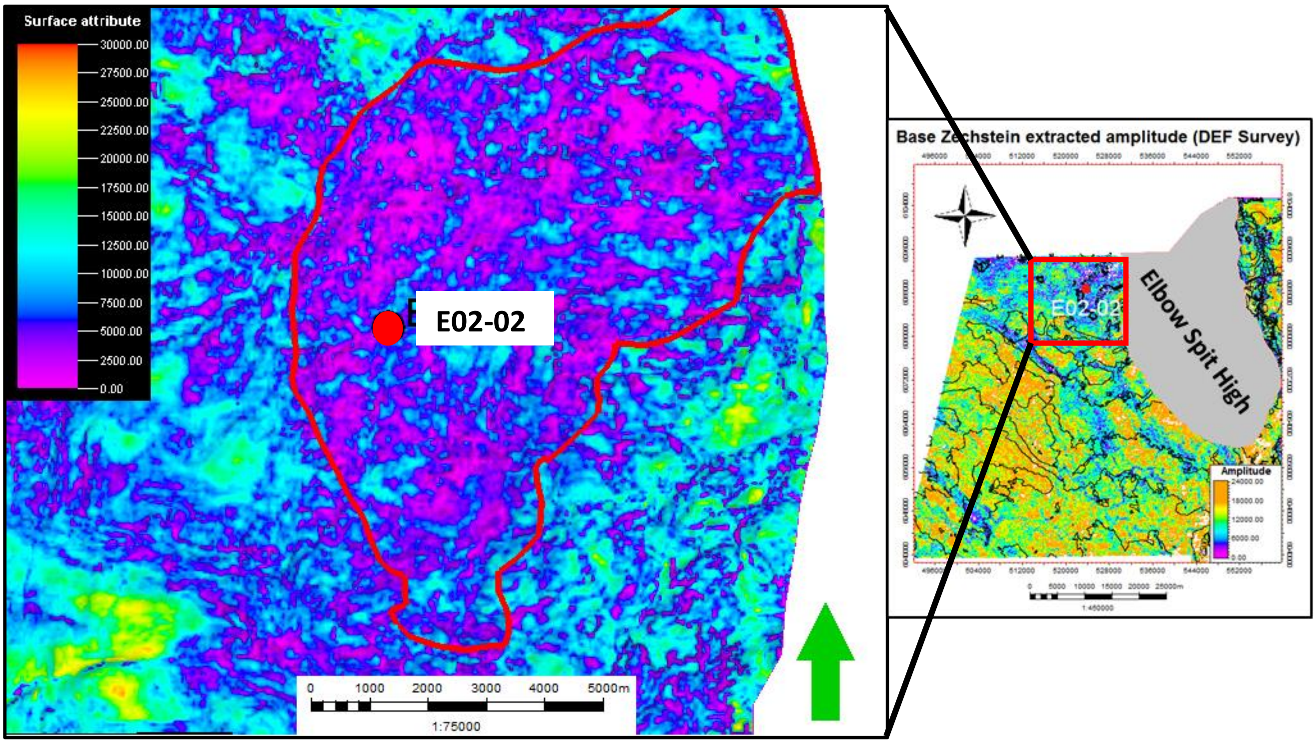


Figure 43: Base Zechstein amplitude map below the E02-02 platform. Purple colors indicate low amplitude values. Red outline correspond with the rough outline of the low amplitude areal.

Figure 44shows the actual extend of the E02-02 platform in combination with the low amplitude area outline. There is a small mismatch between the outline of the low amplitude area and the actual size of the reef. The low amplitude area is slightly larger, therefore it is possible to state that there is a limited correlation between the low amplitude area and the actual reef size. In the second result section an amplitude extraction for the entire base Zechstein map will be presented. This extracted amplitude map will be used in order to identify possible Zechstein build-ups in the study area.

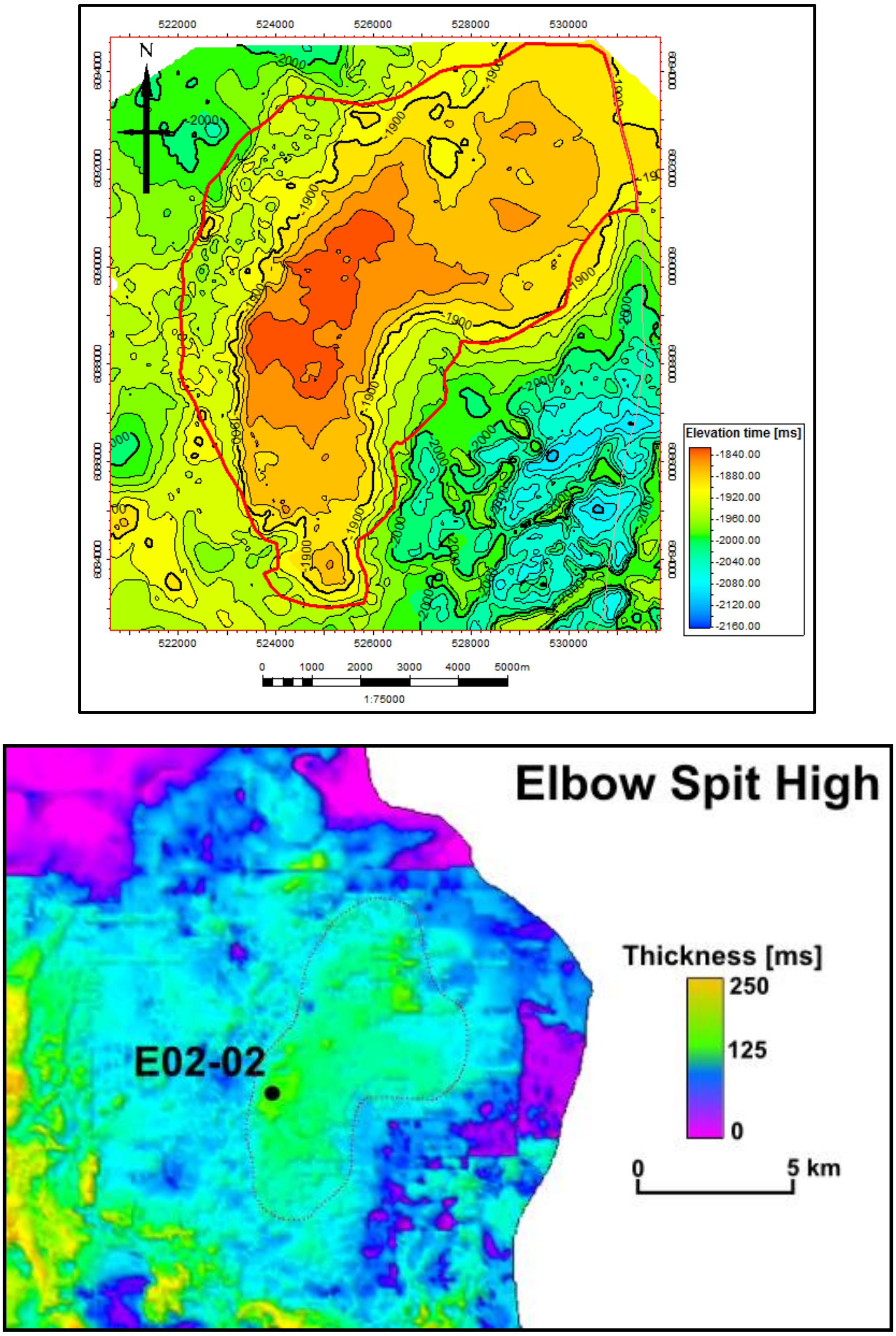


Figure 44: Upper panel) Top platform E02-02 map together with the low amplitude area outline. Lower panel same E02-02 platform illustrated in a thickness map.

9.8 Conclusions

The main conclusions from the Seismic characterization section are:

1. The Zechstein lithologies display several pronounced differences in acoustic impedance. This results in a very characteristic sequence of hard and soft kicks. The top of anhydrite layers are always hard kicks, while the top of the carbonate members are often associated with soft kicks. Zechstein base in both basinal and platform setting is always a soft kick. Base Zechstein in a basinal setting is recognized by a high amplitude negative loop followed by a high amplitude positive loop. In the platform setting base Zechstein can be recognized by a positive loop, surrounded by two negative amplitude side-lobes.
2. The seismic character of the top Zechstein is very dependent on the kind of lithology that overlies the top Zechstein and whether or not the Zechstein Upper Claystone is present.
3. The seismic sections showed different Zechstein seismic character in varying parts of the basin. From these sections it became clear that the structure of the rafts from the ZEZ3 Formation could be indicative for possible build-ups.
4. The amplitude of the base Zechstein can be used as a screening tool for the exploration of potential Zechstein build-ups. Where low amplitude area could indicate possible Zechstein platforms.

The remainder of this report contains information that is (temporarily) confidential.