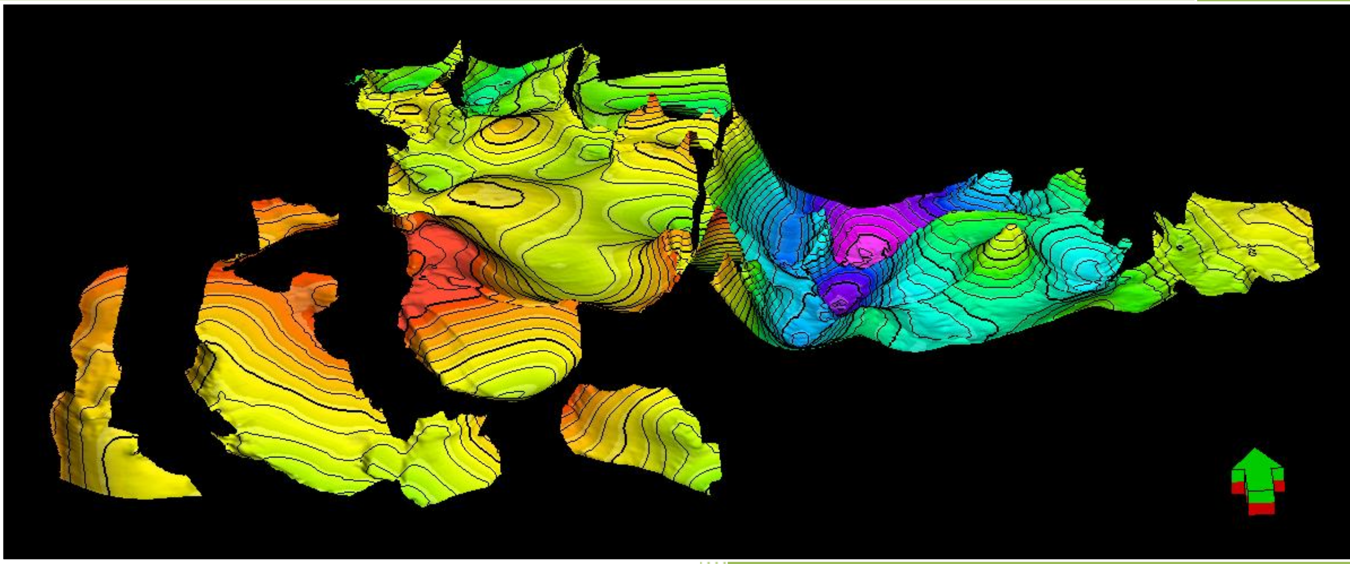
Volpriehausen Prospectivity Review



Mariska M. van Eijk

November 2014

Student No.: 1822446

Master Thesis (AM_450199)

Supervisors:
E. Rosendaal (EBN)
Prof. dr. J. de Jager (VU)
Prof. dr. J.J.G. Reijmer (VU)

EBN B.V., Daalsesingel 1, 3511 SV Utrecht, The Netherlands, Telephone: +31 (0)30 2339001.

VU University Amsterdam, Faculty of Earth and Life Sciences, Sedimentology and Marine Geology Group, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands, Telephone +31 20 59 87 360.

Abstract

The Volpriehausen Sandstone constitutes the second largest play in the Netherlands with onshore and offshore gas fields. Many Volpriehausen exploration wells in the study area in the Step Graben and Central Graben are old and based on 2D seismic. Now, with large 3D seismic coverage available, the structures and the amplitude support, which is typically used in exploration of the Volpriehausen Formation, is remapped and checked in the study area, in the northern Dutch offshore. Gas fields in the Volpriehausen are not always clearly characterized by a structural conformable amplitude anomaly, as appears from an evaluation of Volpriehausen gas fields. Also, no standard seismic character can be determined for a gas-filled Volpriehausen reservoir, since amplitudes of the top high amplitude reflector differ between the evaluated fields. Even though all evaluated gas fields have bright spots, these are not fully reliable direct hydrocarbon indicators (DHI's) since the reflector strength can also be influenced by other factors than gas fill, including salt plugging, porosity, tuning, processing effects and lithology transitions. Seismic interpretation, a dry well analysis and a comparison with Volpriehausen gas fields resulted in a better understanding about the controls on hydrocarbon distribution in the Volpriehausen Formation in the northern Dutch offshore. The Volpriehausen reservoir is generally present in consistent thickness (although some thinning to the north occurs); locally the reservoir is absent due to salt diapirism. Reservoir quality depends on the porosity, permeability, diagenesis and clay-content. The reservoir potential generally decreases towards the north, due to a decreasing thickness (from 70 to 15 m) and increasing clay-content in this direction (from <5 to 32%), consistent with the depositional model of a fluvial system building out northwards. The porosity varies between 14-28%, but a trend is difficult to recognize, due to limited well availability and inconsistent porosity calculations across the wells. Salt plugging of the pores decreases the reservoir quality, but might also provide a side-seal for the rest of the reservoir, as seen in the M1-A field. Halokinesis is important for trap formation, forming turtle-back anticlines, 3-way dip-closures against salt walls and 4-way dip-closures above salt structures, and may also reactivate faults, creating charge windows in the underlying Zechstein salt, as seen near wells E09-02, F04-03 and G07-02. The overlying Volpriehausen Claystone Member acts as top-seal in the entire study area, except at unconformities (E09, F10), where the sealing formation is thin or absent due to erosion. At these unconformities the Lower Cretaceous Shale forms the top-seal, additionally to the Volpriehausen Claystone Member. Faults in the overlying Claystone Member provide possible migration paths for hydrocarbons out of the Volpriehausen Sandstone Member, which has possibly happened in the four-way dip-closures of F04-01 and F04-03. Although, another more likely explanation for these dry holes is the absence of hydrocarbon migration into the trap. Charge forms the largest risk for the Volpriehausen play in the study area. The F15-A field is the northernmost Volpriehausen gas field and much is unknown or uncertain about charge into the Volpriehausen north of F15. Migration is difficult, since Slochteren shales, Zechstein Claystones, Zechstein salt and the Main Claystone Member (a.k.a. Lower Bunter shales) need to be crossed. Faults and 'withdrawn' Zechstein may provide migration paths. Differences in maturity of the source rocks are expected to exist between the Step Graben and Dutch Central Graben, since the DCG experienced larger amounts of burial. Dry hole analysis has shown that out of 20 wells, 12 found Volpriehausen reservoir. Of those 12, 4 are analyzed to be a valid negative test, most likely due to lack of hydrocarbon migration. All of these are situated in the Step Graben, leaving the Central Graben void of any valid Volpriehausen tests. The other 8 are not drilled within a Volpriehausen closure or have updip closure (>25 m). Analysis of seismic and well data has resulted in a prospect inventory, of which the Hutton, Cuvier, Ziegler, Wegener, Lyell, Anning and Kingfisher leads are considered to be most promising. Charge is considered to be the main risk for these leads. Although, in the G07-02 well near the Hutton lead trace gas has been encountered and the presence of charge is therefore considered less of a risk for this lead. For the Kingfisher, Ziegler and Anning leads overmaturity of the source rocks forms an additional risk, since they are located in the Dutch Central Graben, which experienced a large amount of burial.

Content

1. Introduction

The northern Dutch offshore has long been underexplored. Recently, high quality 3D seismic became available in this area, and a regional prospectivity review based on this new seismic data is currently taking place in EBN. This study is part of that regional prospectivity review and focusses on the Volpriehausen Sandstone Member in the Dutch Central Graben and Step Graben. The Volpriehausen Sandstone constitutes the second largest play in the Netherlands with onshore and offshore gas fields. Many Volpriehausen exploration wells are quite old and based on 2D seismic. Now, with the large 3D coverage available, it is possible to remap and check the amplitude support, which is typically used in exploration of the Volpriehausen Formation. Moreover, for further exploration controls on hydrocarbon distribution in the Volpriehausen Sandstones should be investigated. This research focusses on the 3D regional seismic interpretation of the Volpriehausen Sandstone Member, including a dry well analysis and a comparison with Volpriehausen fields outside the study area, in order to gain more knowledge about the hydrocarbon distribution in the Volpriehausen Sandstone Member in the northern Dutch offshore, and to review the remaining prospectivity of the Volpriehausen Sandstone Member in the study area.

The study area comprises parts of the A, B, E, F and G blocks in the Dutch North Sea, and is mainly focused on the Step Graben and Dutch Central Graben. The outline of the study area partly coincides with the outline of the DEF survey with high quality 3D seismic which became recently available (Figure 1). The DEF survey covers approximately 8000 km^2, of which the study area covers approximately 5000 km^2.

This research has been carried out as part of the DEFAB prospectivity review at EBN B.V. in Utrecht, and as a master thesis at the VU University Amsterdam. This report includes a geological history and setting of the area, a chapter about the methods used for this research, a results chapter including an evaluation and comparison with Volpriehausen fields outside the study area and a dry well analysis. Subsequently, the learnings are integrated into a prospectivity review, followed by the discussion, conclusions and recommendations.

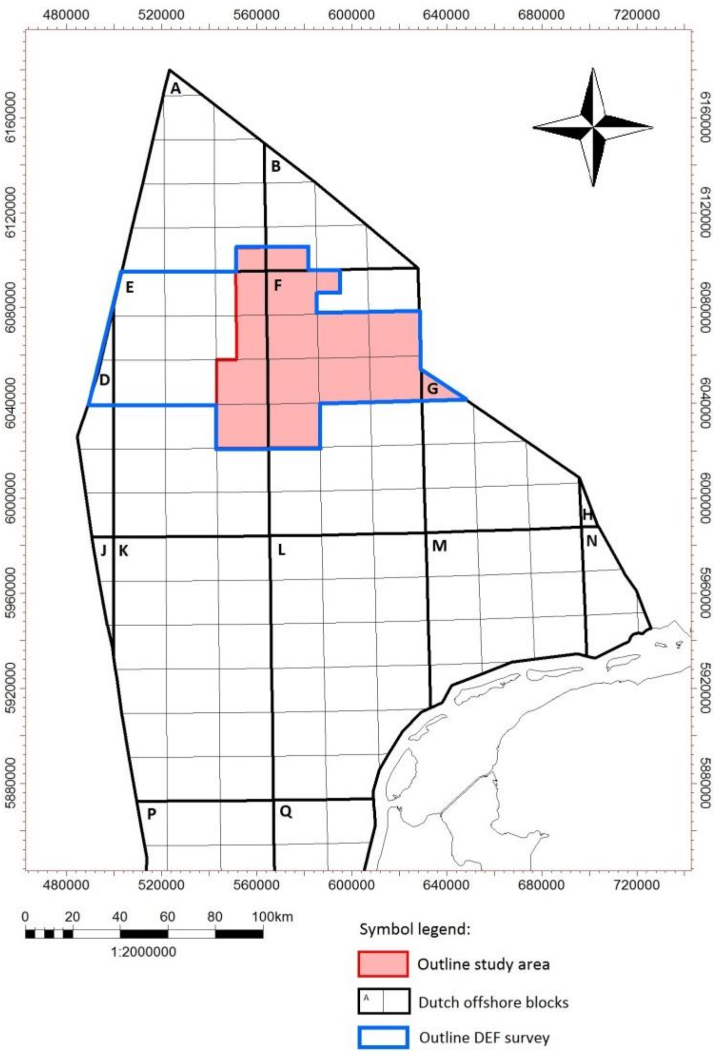


Figure 1 – Dutch offshore blocks with location of study area (red) and the DEF seismic survey (blue outline).

2. Geological History of the Dutch North Sea Area

The geological history of the Dutch North Sea is characterized by five main tectonic phases: 1) the Caledonian orogeny resulting in the suturing of supercontinent Laurussia, 2) the Hercynian or Variscan orogeny resulting in the formation of supercontinent Pangea, 3) Mesozoic rifting leading to the break-up of Pangea, 4) inversion due to the Alpine collision, and 5) recent developments in the Dutch North Sea area (Ziegler, 1990).

Basement faults have been reactivated repeatedly and even though the tectonic regime and stress direction changed through time, structures are mainly controlled by these basement faults. Faults are often parallel and the pre-existing structural features did seldom have orientations conform the regional stress of later episodes. Therefore, many faults have an oblique slip component (de Jager, 2007). Basement faulting has often caused the initiation of salt movement. Thick Permian Zechstein salt is present in most of the Dutch subsurface and caused extensive halokinesis, as well as extensional and transpressional faulting above the salt.

2.1 Caledonian orogeny

The Caledonian orogenic cycle started in the Late Cambrian and lasted until Early Devonian time. During this period the Iapetus Ocean and the Tornquist Sea closed at the Iapetus Suture Zone and the Trans-European Fault Zone, respectively. Collision of Laurentia, Baltica and Avalonia resulted in the formation of the Laurussian (or ‘Old Red’) mega-continent, with the Caledonian fold belt following the suture zone (Ziegler, 1990; de Jager, 2007). During the Caledonian orogeny the Lower Palaeozoic crystalline and metamorphic basement rocks that underlie the North Sea sedimentary basins were composed. The only direct evidence of Caledonian basement in the Dutch subsurface is altered biotite monzo-granite overlain by Devonian Old Red Sandstone, encountered in well A17-1 on the Elbow Spit High (Frost et al., 1981; Pharaoh et al., 1995; de Jager, 2007).

2.2 Variscan orogeny

The Variscan orogenic cycle lasted from Devonian to Early Permian time, while western Europe drifted towards the north into the northern hemisphere. The collision of Laurussia and Gondwana resulted in the formation of supercontinent Pangea. This led to the closure of the Rheic Ocean (proto-Tethys ocean) and the formation of the Rheno-Hercynian fold and thrust belt. North of this suture zone the Rheno-Hercynian Basin developed, due to post-orogenic collapse of the Caledonides (de Jager, 2007). This foreland basin extended from Ireland to Poland and was the precursor of the Southern Permian Basin (Ziegler, 1990). More about the Southern Permian basin will follow in chapter 3.1. During the Permian deposition took place in the Southern Permian Basin. The mountain belt south of the basin prevented humid air coming from the Tethys Ocean south of these mountains. This resulted in an arid climate in the Southern Permian Basin area (Geluk, 2005).

2.3 Break-up of Pangea and accompanying formation of rift basins

During the Mesozoic rifting took place, resulting in the break-up of supercontinent Pangea. Rifting started during the Triassic in the Arctic-North Atlantic and between Greenland and Scandinavia, and propagated southwards along two branches (de Jager, 2007). This is called the Kimmerian rifting phase. The eastern branch reached the southern North Sea area in the Middle Triassic. The Central Graben and the Viking Graben formed, which were active volcanic systems. Sedimentation took place under continuing thermal subsidence, leading to regular facies patterns (de Jager, 2007). The

Lower Buntsandstein sequence was deposited during gradual, regional subsidence of the entire Southern Permian Basin, including on previous Zechstein highs. At the end of deposition of the Lower Buntsandstein a bi-directional fault system of NNE-SSW and WNW-ESE trending faults was reactivated. Lateral movements were accommodated along the Tornquist Fault Zone and other faults with similar orientations (Geluk, 2005). Syn-sedimentary faulting caused differences in thickness of the Main Buntsandstein, compared to the regular thickness of the Lower Buntsandstein (Geluk, 2005).

This phase of extensional tectonics during the Early Triassic is also known as the Hardegsen Phase, or the first Kimmerian phase (Ziegler, 1990). The intensity of extensional tectonic movements increased during the Middle and Late Triassic. Extension triggered the wide-spread mobilisation of Zechstein salt, resulting in several unconformities in the Triassic: the Hardegsen Unconformity at the base of the Solling Formation, the Early Kimmerian I Unconformity at the base of the Red Keuper Claystone and the Early Kimmerian II Unconformity at the base of the Sleen Formation (Geluk, 2005). Rifting continued along the western branch, resulting in the opening of the Central Atlantic Ocean. In the Late Triassic Pangea split up into the two mega-continents Gondwana and Laurasia, of which the latter includes most of the present-day North America, Asia, Europe and Greenland.

Gradual uplift occurred during the Mid-Kimmerian phase (Middle Jurassic) in the central North Sea area. Here, the Iapetus suture intersected with the Tornquist-Teisseyre fault system. Sea level fell and sedimentation became restricted to the rift basins. Due to this uplift, extensive erosion took place. Sea levels rose when the North Sea area moved from the arid climate zone to sub-tropical latitudes of the Northern Hemisphere. During the Late Kimmerian phase, which lasted from Late Jurassic to Early Cretaceous, the Central Graben subsided further and the surrounding platform areas were uplifted again (Remmelts, 1996). Pangea continued to break up during the Cretaceous, when the main rift extension was in an E-W direction. Extensional stresses were mainly concentrated in the area between Greenland, the British Isles and Norway, and tectonic activity rapidly decreased towards the Dutch North Sea area (Ziegler, 1990; de Jager, 2007). While sea floor extension and thermal subsidence continued, sea level was high and the Chalk Group was deposited.

2.4 Inversion

In the Late Cretaceous the African, Indian and Cimmerian plates from the south and the Eurasian plate from the north collided. The Tethys system of oceanic basins started to close and the Alpine orogenic system developed. The Alpine orogeny took place from the Late Mesozoic into the Cenozoic. Increasing stresses resulting from this collision induced inversion of Mesozoic extensional basins and impeded crustal separation between Greenland and Norway (Ziegler, 1990; de Jager, 2007). Uplift due to inversion led to depositional thinning, local truncation of older sediments, and erosion of Upper Cretaceous chalk and Lower Tertiary clastics. Uplift in the inverted basins was a continuous process, but with acceleration pulses during the Campanian, Palaeocene and Late Eocene-Early Oligocene. The deformation intensity varies in the different basins. The amount of deformation is also influenced by the presence of salt. In basins with thick Zechstein salt deposits, such as the Dutch Central Graben, post-salt deposits were extensively uplifted and faults below and above the salt were entirely detached. Uplift in the Netherlands during the inversion amounted 1-2 km (de Jager, 2007). The amount of inversion was less in the Dutch Central Graben than in other basins in the north. While the centre of the Central Graben was uplifted by inversion, platforms flanking the graben continued to subside. During the last strong inversion pulse (Late Eocene-Early

Oligocene) NW-SE dextral strike-slip movements took place, accompanied by accelerated salt movements (Remmelts, 1996; de Jager, 2007).

2.5 Recent developments in the Dutch North Sea area

Rifting in the Lower Rhine Graben propagated northwards into the Netherlands during the Tertiary. Up to 2000 m of Tertiary sediments were deposited in the down-faulted Roer Valley Graben. The area is still tectonically active today, as indicated by recent earthquakes along the main bounding faults (Dost & Haak, 2007). Subsidence takes place in the entire North Sea area since the Neogene, whereas in the south-eastern part of the Netherlands uplift occurs in conjunction with uplift of the Rhenish Massif (De Jager, 2007; Wong et al., 2007). The Eridanos Delta developed during the Tertiary due to a gradual uplift of the Fenno-Scandian Shield, resulting in an increased clastic influx into the southern North Sea area. Quaternary deposits in the northern Dutch offshore reached up to 1 km in thickness and are thinning towards the south (De Jager, 2007).

3. Structures in the study area

3.1 Southern Permian Basin

The Southern Permian Basin is the largest sedimentary basin in Europe, underlying northern Poland, northern Germany, Denmark, The Netherlands and a large part of the North Sea. The basin is located in the former east-west trending Variscan foreland basin, which evolved into an intra-cratonic basin during the Late Palaeozoic, and overlies Early to Middle Permian rifts and volcanic centres (Ziegler, 1990; Geluk, 2005). The plate tectonic setting is within a wide transform zone linking the Arctic-North Atlantic and West Tethys rift systems (Ziegler, 1990). The Southern Permian Basin is bounded by the Rhenish and Bohemian Massifs in the south, the outline of the former Variscan thrust belt in the west, the Precambrian European Craton in the east, and the Ringkøbing-Fyn High and the Mid North Sea High in the north (Guterch et al., 2010). North of the Ringkøbing-Fyn High and the Mid North Sea High lies the east-west trending Northern Permian Basin (Ziegler, 1990), which underwent a similar evolution as the Southern Permian Basin. At the beginning of the Late Permian both basins were flooded with a sudden influx of seawater from the Arctic seas (Pharaoh et al., 2010). Several pulses of tectonic extension dissected the former Southern Permian Basin into smaller elements. This resulted in three basins, each with a marked difference in geological history: the Anglo-Dutch basin, North German Basin and Polish Trough. The northern Dutch offshore is part of the North German Basin. Thermal relaxation of the lithosphere and extensional tectonics drove the subsidence of the three basins, which increased in Middle to Late Triassic times (Geluk, 2005). Accommodation space shifted during the Olenekian from the Roer Valley Graben into the Dutch Central Graben (Geluk & Röhling, 1999).

3.2 Dutch Central Graben

The Dutch Central Graben (Figure 2) opened by several extension pulses in the Middle Permian, accompanied by extrusion volcanism (Lower Rotliegend Group). It is part of the Mesozoic North Sea rift system (Geluk, 2005). In the north the Dutch Central Graben is bounded by a series of large faults with decreasing vertical throws towards the south. In the west the graben is flanked by the Step Graben, with a stepwise increasing depth from the western flank towards the central zone of the Dutch Central Graben. In the east, this depth increase is more abrupt. In the southwest the Dutch Central Graben is bordered by the Cleaver Bank High and in the east by the Schill Grund High. The Terschelling Basin forms the south-eastern extension of the Central Graben. The southern boundaries are poorly defined. Faults in the Dutch Central Graben are approximately N-S trending in the north, and towards the south they interfere with NNE-SSW and NW-SE oriented faults. NW-SE trending structures dominate the structural grain in the south (Remmelts, 1996). During the Triassic major salt walls developed along the boundary faults, caused by movements along these faults. During the Olenekian WNW-ESE extension took place during the Hardegsen phase, resulting in subsidence. Lateral movements were accommodated along the Tornquist Fault Zone and other NW-SE faults (Ziegler, 1990; Geluk, 2005). Fault controlled subsidence continued during Early to Middle Jurassic times, resulting in higher formation thicknesses within the Dutch Central Graben. In the Late Jurassic and Early Cretaceous main rifting occurred and thick fluvial-shallow marine sequences were deposited. The surrounding platforms and highs were uplifted and eroded. During the Early Tertiary subduction took place, however, in the Dutch Central Graben subduction was less, compared to surrounding basins, resulting in thinner Tertiary deposits (De Jager, 2007). Overall, a great amount of burial has taken place in the DCG, risking overmaturity of the source rocks.

3.3 Step Graben

The Step Graben (Figure 2) is a N-S oriented graben located between the Elbow Spit High in the west and the Dutch Central Graben in the east. The transition between the Elbow Spit High and the Step Graben is characterised by normal faults and thick salt layers and salt domes along these faults. The northern part of the Step Graben is a complex terrace structure with lows and troughs (Wride et al., 1995). Triassic sediments are overlain by thin or no Lower Jurassic due to erosion when the graben was uplifted during the Mid-Kimmerian event. (Remmelts, 1996; Kombrink et al., 2012). Later, the basin subsided, resulting in deposition of thin Upper Jurassic sediments. Subsidence was less compared to the Central Graben, where thicker Jurassic sequences were deposited. Cretaceous sediments were largely preserved with a thickness of approximately 1 km. About 2 km of Cenozoic sediments are overlying the Cretaceous (Remmelts, 1996; De Jager, 2007).

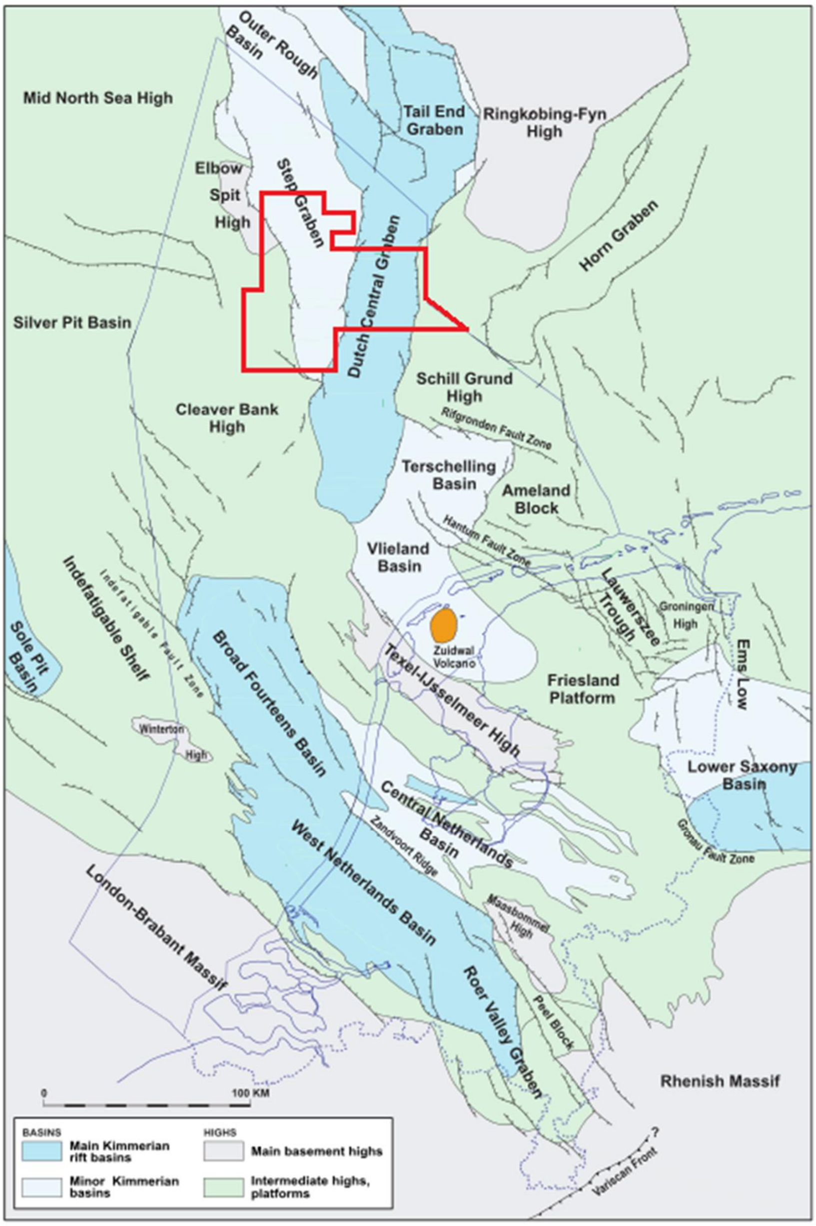


Figure 2 - Map of the Netherlands showing Mid and Late Kimmerian basins, highs and platforms. Study area is indicated by the red polygon. After: Geology of the Netherlands, by Th.E. Wong, D.A.J. Batjes & J. de Jager. Royal Netherlands Academy of Arts and Sciences, 2007: 5–26.

4. Halokinesis

The structural development of the southern North Sea area is strongly influenced by thick halite deposits in the Late Permian, known as Zechstein salt. Salt movement is almost exclusively related to basement faulting. These faults triggered the movement of salt, controlled the relative location of the salt structures, and controlled the rate of the movement. Halokinesis has had a great impact on the deformation, distribution and thickness of the Mesozoic sedimentary cover (Remmelts, 1996; De Jager, 2007). Initially, salt movement will be mainly lateral, leading to the formation of salt-pillows. This will leave the overlying sedimentary cover intact. Such salt pillows have mainly formed on the stable platform areas, where salt flow was minor. Along the edges of platforms salt movement was stronger, leading to the development of some diapiric structures. Strong salt movement occurred in basinal areas, including the Central Graben and the Step Graben, resulting in salt walls and salt domes (Remmelts, 1996). The thick Zechstein salt package has caused faulting above the salt to be decoupled from basement faulting. Most salt walls and domes follow the main sub-salt fault trends. Hence, the salt movements apparently were triggered by basement faulting (De Jager, 2007).

Halokinesis is an important phenomenon for the oil and gas industry in this area, since salt movement can result in different types of hydrocarbon traps. Moreover, salt can be a very good seal, and create migration routes and secondary permeability. Zechstein salt often forms a barrier between the Carboniferous source rocks and Mesozoic reservoirs. However, migration routes have been created locally, where salt has been withdrawn and formed a salt window. The three main types of traps related to salt structures above the Zechstein are 1) dip closure of reservoir rocks against a salt diapir, 2) four-way dip closure in a turtle back anticline, and 3) four-way dip closure above salt structures. Salt can also have negative effects in the form of salt plugging (chapter 7.7 Salt plugging), reservoir compartmentalization, leakage along reactivated faults, and poor seismic imaging of the structures (Remmelts, 1996).

4.1 Halokinesis in the Central Graben

The Central Graben is bounded by faults with offsets of several hundreds of metres at the Base Zechstein, leading to differential loading of salt on either side of these faults. This generates an excellent situation for salt movement. A large amount of salt has moved from its original position into salt walls bordering the Central Graben. NNE-SSW diapiric salt walls have developed in the Central Graben and Step Graben, conform the structural grain of the basement. Some solitary circular salt domes developed in the Central Graben (e.g. F9 block) as a result of two interfering fault trends. At these points, the dominant N-S structural trend of the Central Graben interferes with NW-SE fault trends. A local maximum salt flow can occur at such an intersection point of faults, creating a solitary salt dome (Remmelts, 1996). A salt wall above the boundary fault separating the Step Graben from the Central Graben shows a rim syncline at the side of the Central Graben. Salt flow towards this structure is indicated by the large local thickness of Upper Jurassic sediments. According to Remmelts (1996) the diapiric stage of this structure was in the Cretaceous.

4.2 Halokinesis in the Step Graben

The Step Graben is situated in a transitional position between the rift shoulder and the Central Graben (Remmelts, 1996). Long salt walls have formed due to strong salt movements along the faulted steps. The salt is getting thinner towards the A-quadrant. Two N-S salt walls in the east of the Step Graben (B10, 13, 16, F1) are nice examples of this phenomenon, and are clearly linked to large fault displacements in the basement. Another N-S fault transects the Step Graben, west of the boundary fault, with a recent vertical throw of 150-200m, accompanied by a salt wall. Here, tilting of the overburden has been caused by salt flow and tectonics. Depletion of salt on the western side of the fault block resulted in subsidence of the overlying sediments, preventing erosion of these sediments in the Early Cretaceous. In contrast, on the eastern side of the fault block the salt accumulated, leading to steepening of the overburden, which was subsequently eroded.

5. Stratigraphy

A schematic overview of the stratigraphic column in the study area is shown in Figure 3. The basement consists of continental to paralic Carboniferous deposits and Permian Upper Rotliegend anhydritic shales. Overlying this basement are the Zechstein evaporites deposited in the Late Permian, when a large transgression from the Barents Sea rapidly flooded both the Northern and Southern Permian Basins and brought full-marine conditions to these basins (Ziegler, 1990; Geluk, 2005). Due to periodic glaciations in Gondwana, which controlled the marine invasions from the Barents Sea, the Zechstein deposits are characterised by a strong cyclic character of transgressional carbonates and claystones, followed by evaporites (Ziegler, 1990; Geluk, 2005). At this time, the Permian Basin had a paleo-latitude of around 20°N. When the Zechstein Sea retreated from the Southern Permian Basin, the basin first evolved into an extensive sabkha with isolated saline ponds, and evolved later into an extensive inland playa environment. During this episode the sediments of the Lower Germanic Trias Group were deposited, which can be divided into the Lower Buntsandstein Formation and the Main Buntsandstein Subgroup. The latter consists of the Volpriehausen, Detfurth and Hardegsen formations.

5.1 Lower Buntsandstein Formation (Late Permian-Induan)

In the Early Triassic sedimentation became continental and a cyclic alternation of fine-grained (brackish to saline) lacustrine sandstones and clay-siltstones was deposited in a playa lake. This succession is known as the Lower Buntsandstein Formation. Its thicknesses varies between 20 and 40 m. Due to the uniform subsidence in the area the formation can be correlated over large distances up to several hundred kilometres. Climatic Milanković cycles controlled the sedimentation of the Lower Buntsandstein Formation. The formation has two members, which are the Main Claystone Member and the Rogenstein Member. The Main Claystone Member is the equivalent of the German Upper Bröckelschiefer and Calvörde Formation. The Rogenstein member contains of claystone with regular intercalations of up to 1 m thick oolite beds. Towards the south the oolite beds are laterally replaced by sandstones. Post-depositional erosion reduced the thickness of the formation, especially on the swells (Geluk, 2005).

5.2 Main Buntsandstein Subgroup (Olenekian)

The deposition of the Main Buntsandstein Subgroup marks a change in subsidence patterns in response to rift tectonics. Rifting shifted from southern and western Netherlands northwards into the Central North Sea Graben (Geluk, 2005). The extension happened in four main pulses: pre-Volpriehausen, pre-Detfurth, pre-Solling and intra-Solling. The strongest pulse occurred prior to deposition of the Solling Formation (Geluk & Röhling, 1997, 1999). Characteristic for the Subgroup are the unconformities at the bases of the Volpriehausen, Detfurth and Solling Formations, induced by these extension pulses. The formations of the subgroup are tectono-stratigraphic units, each consisting of a large-scale fining-upward cycle with sandstones at the base, followed by clay-siltstones. The sandstones of the Main Buntsandstein Subgroup in the southern Dutch offshore are fluvial deposits and become eolian towards the north. Within these sand sequences a hierarchical system occurs, which is assigned to Milanković climatic cycles (Geluk & Röhling, 1997). The clay-siltstones are playa-lake deposits. Redeposition of fluvial sands in central parts of the basin occurred during dry periods, and playa lake expansion towards the basin margins occurred during periods of low clastic influx. Repetition of these processes caused the cyclic alteration in the Main Buntsandstein Subgroup.

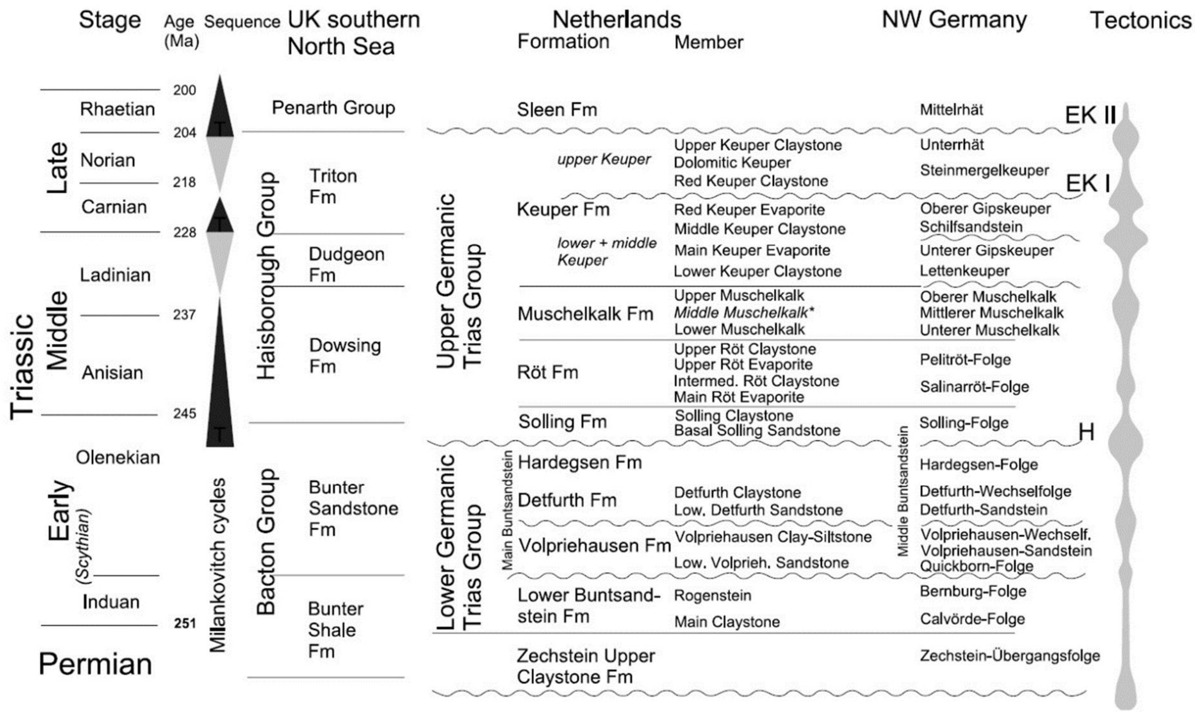


Figure 3 – Stratigraphic subdivision of the Triassic in the Netherlands and adjacent countries. Transgressive sequences in black, regressive sequences in grey. EK I: Early Kimmerian I Unconformity at the base Norian; EK II: Early Kimmerian II Unconformity at base Rhaetian; H: Hardegsen Unconformity; * Middle Muschelkalk is an informal unit and comprises the Muschelkalk Evaporite and Middle Muschelkalk Marl. After: Van Adrichem Boogaert & Kouwe (1994), Johnson et al.. (1994), Geluk & Röhling (1999) and Kozur (1999). Sequences after Gianolla & Jacquin (1998). Ages after ISC (2003); note that only the age of the Permian-Triassic boundary is officially approved.

5.3 The Volpriehausen Formation

5.3.1 The Lower Volpriehausen Sandstone Member (RBMVL)

Depositional environment

Deposition of the Volpriehausen Formation took place in a large intra-cratonic basin in a fluvio-lacustrine environment (Ziegler, 1990; Geluk, 2005), as shown in Figure 4. At the time of deposition the base level had lowered due to rifting and fluvial systems from the Variscan hinterland were able to build out towards the north, over the Southern Permian Basin, splitting up into several thinner sandstone units (Geluk, 2005; De Jager, 2007). The Variscan Mountains were the main source for the clastics until Middle Triassic times; later the Fennoscandian Shield became the main sediment source. Climate controlled the sediment dispersal, indicated by the cyclic and contemporaneous way of outbuilding. Humid periods with higher rainfall in the hinterland caused higher fluvial activity, resulting in sandy fluvial systems building out far into the playa. The Volpriehausen sandstones were deposited during such a period of high fluvial activity. Periods of high fluvial activity alternated with dry periods. During these dry periods eolian processes redistributed the sands (Fontaine et al., 1993, Geluk, 2005). The fluvial sandstones were predominantly deposited in the southern Dutch offshore, opposed to the eolian sandstones that occur in the northern Dutch offshore (Fontaine et al., 1993; Dronkert & Remmelts, 1996; Geluk, 2005).

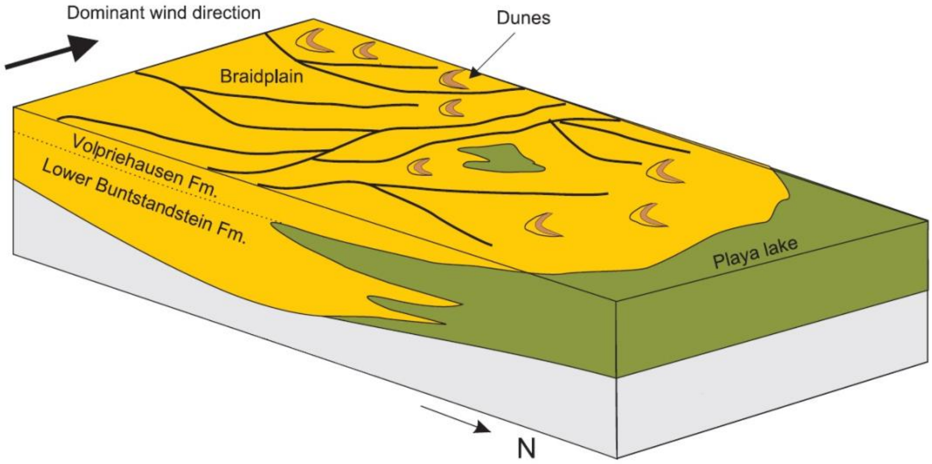


Figure 4 – Depositional model for the lower Buntsandstein and Volpriehausen formations in the Dutch offshore. Yellow = predominantly sandstones, green = predominantly siltstones. During deposition of the Volpriehausen Formation fluvial systems built out to the north, resulting in thinning sandstones an increasing clay-content towards the north. Modified after: Wong et al. (eds) 2007.

The thickness of the Volpriehausen Sandstone varies. According to Geluk & Röhling (1997, 1999) and Geluk (2005) these thickness variations have different causes, including syn-depositional thickening of the Lower Volpriehausen Sandstone, a facies transition of the lower part of the Volpriehausen clay-siltstones into sandstones, syn-sedimentary faulting, enhanced subsidence in the grabens, as well as uplift and erosion elsewhere. Extensional tectonics during deposition resulted in rapid subsidence of the Dutch Central Graben and uplift of NNE-SSW oriented swells in the Dutch offshore. Deposition of the Volpriehausen Formation in this area has resulted in a higher formation thickness in the lows and a reduced thickness on the swells. The Central North Sea Graben has two depocentres, where more than 60 m of sandstones were deposited, which are thinning towards the north. West of the Netherlands Swell its thickness can reach up to 100 m, but towards this swell the formation thins and becomes less than 5 m thick. Erosion removed much of the initial cover of the main Buntsandstein, especially on the swells (Geluk, 2005).

Stratigraphy

The Volpriehausen Formation (Olenekian age) has an estimated duration of 2.3 My (Geluk & Röhling, 1999). However, above and below the Volpriehausen Formation a hiatus is present of approximately 0.5 My, due to erosion of several 10's of metres (Geluk & Röhling, 1997). The Volpriehausen Formation consists of two members: the Volpriehausen Sandstone Member at the base, and the Volpriehausen Clay-Siltstone Member on top. The succession shows an overall coarsening-upward trend in the gamma-ray (Geluk, 2005; Röhling, 1991). The lower boundary of the Volpriehausen Sandstone member is placed at the appearance of thick sandstone beds. In general, the sediments consist of clean to slightly silty sands and contain few fossils (Vittori et al., 1990; Geluk, 2005). Vittori et al. (1990) and Moreau (1990) have recognised four lithological units based on core data of F15-5 and F15-7, indicated on Figure 5. The main pattern of these sequences is an evolution from playa to dunes. Cementation in the sandstone is variable, predominantly anhydrite and dolomite and locally fully halite. Cementation often takes place in the upper part of the sandstone, which indicates a gradual abandonment of fan sediments (Dronkert et al., 1989).

Characteristics

The Lower Volpriehausen Sandstone Member consists of arkosic sand, with a quartz content of slightly less than 50%, cemented by high percentages of calcite, dolomite, and locally halite (Fontaine et al., 1993; Dronkert & Remmelts, 1996; Geluk, 2005). The minimum porosity of the rocks lies between 5-25%. The open porosity ranges between 0-20%. Permeability ranges between 0-500mD, in the most sandy intervals it ranges between 5-50 mD (Dronkert et al., 1989). Cementation can be a problem, especially in the Dutch Central Graben salt plugging of the pores occurs (Fontaine et al. 1993, Dronkert & Remmelts, 1996; Geluk, 2005). This will be discussed in more detail in chapter 7.7.

5.3.2 The Volpriehausen Clay-Siltstone Member

The Volpriehausen Clay-Siltstone Member consists of a succession of lacustrine siltstones and marls, with minor sandstones and a number of thin carbonate oolite beds. The sandstones are cemented by dolomite, calcite and ankerite, and are more fine-grained than sands of the Lower Volpriehausen Sandstone Member. The Clay-Siltstone Member was deposited in the entire basin with little variation in thickness. However, before the overlying Detfurth Formation was deposited, uplift and erosion took place, leading to significant thickness variations of the Volpriehausen Formation (Geluk, 2005).

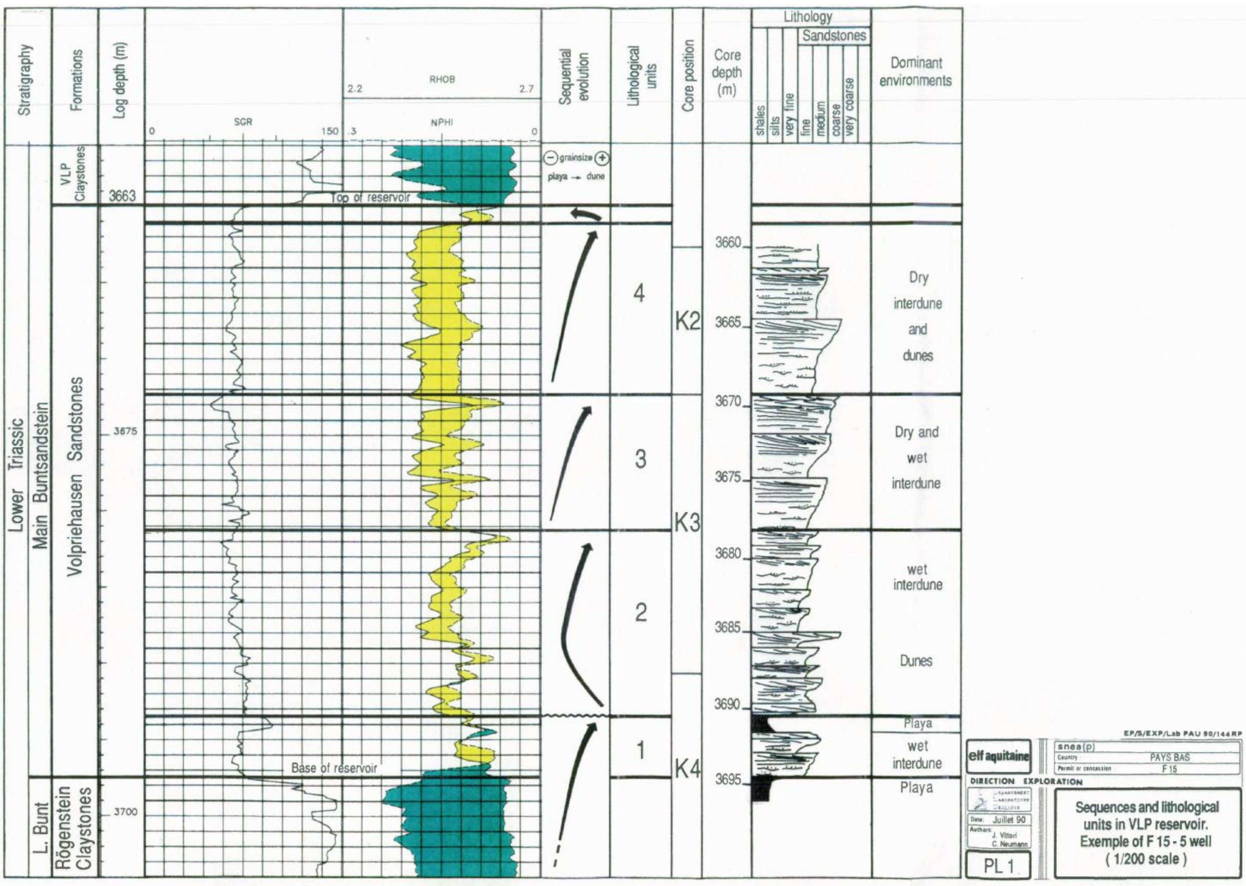


Figure 5 - Lithological units units within the Volpriehausen Sandstone Member based on core data from F15-5 and F15-7 wells. From: Vittori et al., 1990.

5.4 The Detfurth Formation

Before deposition of the Detfurth Formation erosion took place, the Detfurth Unconformity was created, cutting into the Volpriehausen Formation. The Detfurth Formation consists of a basal fluvial sandstone, called the Detfurth Sandstone Member. The overlying Detfurth Claystone Member consists of a succession of claystones with thin layers of siltstone. The Claystone Member was deposited in a more humid climate, when lacustrine deposition expanded over the area. In the Dutch Central Graben 60-100 m of Detfurth Sandstone was deposited. The Claystone Member follows the thickness trend of the Sandstone Member. The Detfurth Formation only occurs in Early Triassic lows, due to uplift and erosion before the Solling Formation was deposited (Geluk, 2005).

5.5 The Hardegsen Formation

This formation is composed of siltstones with thin sandstone beds. The present-day thickness varies and was strongly influenced by the pre-Solling erosion event, which explains the isolated occurrences of the formation in the Dutch offshore. Syn-rift subsidence in the Dutch Central Graben during deposition resulted in thickening of individual sequences. Here, up to 200 m was deposited (F09-03). Unlike the other formations of the Main Buntsandstein Subgroup the Hardegsen Formation is not an independent sequence, but rather forms the upper part of the Detfurth-Hardegsen sequence (Geluk, 2005).

5.6 The Upper Germanic Trias Group

The Upper Germanic Trias Group consists of the Solling, Röt, Muschelkalk and Keuper Formations, deposited on the Base Solling Unconformity. After the pre-Solling erosion event the sediments of the Solling Formation were deposited during the latest Olenekian. They comprise a basal sandstone, which is overlain by a succession of siltstones and claystones. In the Middle Triassic sea level rose and the Röt Formation was deposited, followed by the Muschelkalk and Keuper Formations. The latter contains fine-grained coastal plain to marine clastic sediments and covers the complete Late Triassic (Van Adrichem Boogaert & Kouwe, 1993-1997; Geluk, 2005).

6. Methods

6.1 Dataset

The dataset used for this research comprises seismic data and well data. The seismic data are part of a high quality TWT 3D seismic volume, acquired in 2011 by Fugro. It is called the DEF survey and covers parts of the D, E, and F licence blocks. The DEF survey covers approximately 8000 km^2. The study area (5000 km^2) is fully covered by the 3D DEF survey (for outline DEF survey see Figure 1 in Introduction). The seismic data uses the European convention, where a blue reflector is a peak (increase in acoustic impedance), shows a positive amplitude and represents a 'soft kick', whereas a red reflector is a trough (decrease in acoustic impedance), has a negative amplitude and represents a 'hard kick'.

The well data used for this study is public data from the NL Olie- en Gasportaal (NLOG). The types of data used include gamma ray logs, sonic logs, neutron density logs, gas logs, well tops and well reports. A total of 30 wells are present in the study area, of which 12 drilled the Volpriehausen. Eight wells were drilled to pre-Triassic strata, but the Volpriehausen Sandstone Member was absent. The remaining 10 wells were not drilled deep enough to encounter the Volpriehausen and are therefore not relevant for this study. Figure 6 shows a map with the wells relevant for this study, located in the study area.

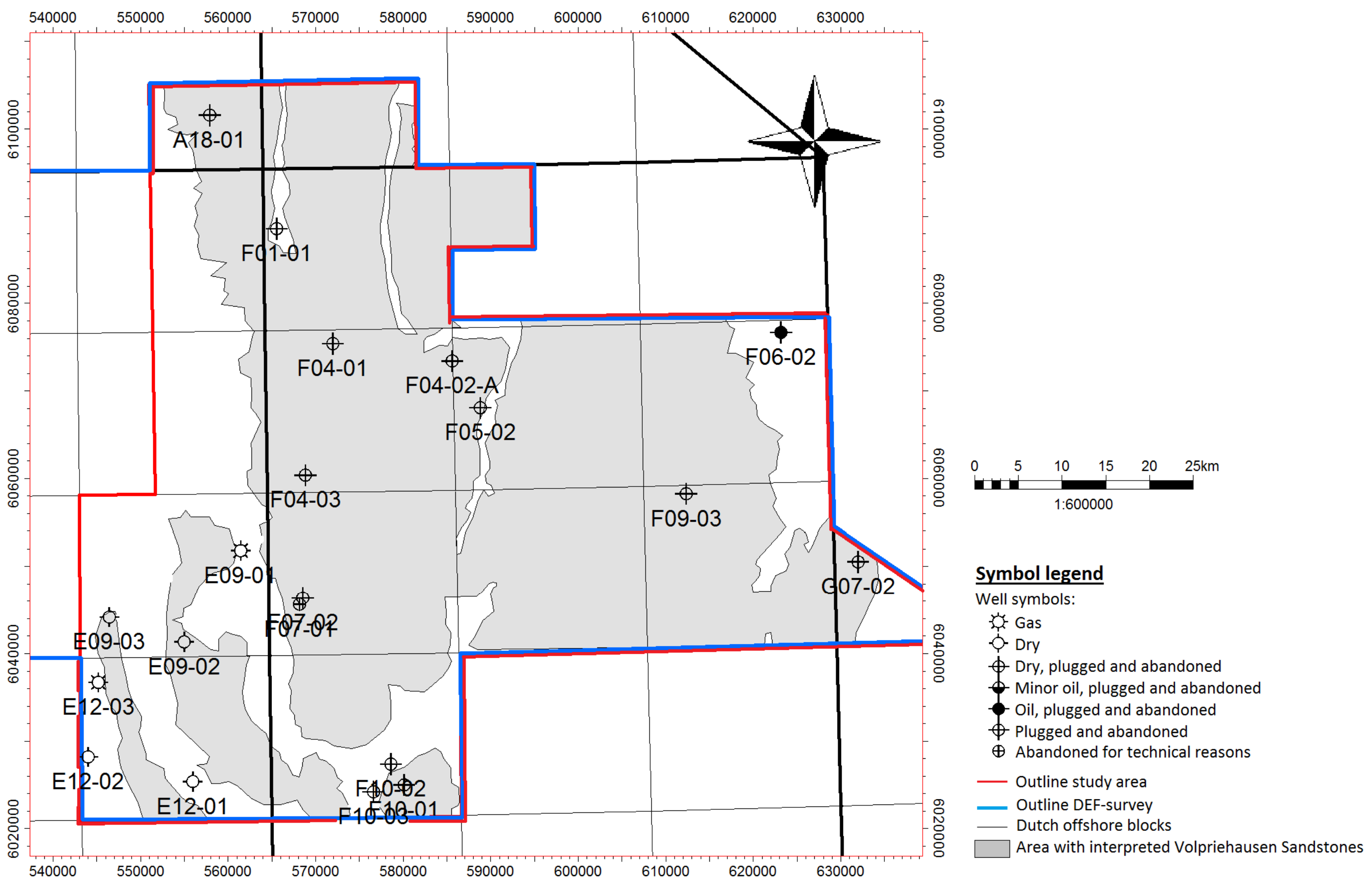


Figure 6 - Wells in the study area, relevant for this study. In 12 wells (in grey area) the Volpriehausen Sandstone is present, in 8 wells (outside grey area) the Volpriehausen Sandstones are absent.

6.2 Seismic interpretation

For this study an existing regional interpretation of the Top Volpriehausen Sandstone Member done by EBN was extended, and corrections were made where necessary. The seismic appearance of the Lower Triassic is very characteristic due to the high continuity of the reflectors. The base of the Lower Germanic Trias Group is marked by a high amplitude reflector, followed by a zone of low amplitude and transparent seismic appearance representing the Lower Buntsandstein. The first high amplitude reflector above this zone marks the Volpriehausen Sandstone Member, and results from two superimposed reflections of the top and base of the Sandstone Member. The thickness of the Volpriehausen Sandstone Member roughly coincides with the tuning thickness for common seismic wavelets, resulting in a blue soft kick reflector (www.dinoloket.nl).

In order to tie the wells to the seismic synthetics were created of wells in the study area that drilled the Volpriehausen Sandstone Member and had enough data available (checkshot, GR, RHOB, sonic (DT)) at Volpriehausen level. This was the case for five wells in the Step Graben: A18-01, F04-02-A, F05-02, F07-01 and F10-01. Checkshots were used to correctly place the logs in depth and time. Then sonic calibration was used to calibrate the wells to the seismic and to obtain a time-depth relationship, but in most cases an already existing time-depth relationship from the DEFAB-team in EBN was used. Subsequently, a wavelet was extracted and synthetic seismograms were created. No time shift or other adjustments were needed.

The wells that had a time-depth relation available (well tops) and/or a synthetic seismogram were used as reference or starting points for seismic interpretation. No well ties were available in the Central Graben. The interpretation here was only based on seismic character. A visual quality check on the interpretation was carried out by comparing seismic character across the entire study area, after which the interpretation was partly adjusted in the Central Graben area. The Lower Buntsandstein has a relatively constant thickness, as can be seen on seismic (Appendix A1). Therefore, this method of QC (Quality Check) was considered acceptable.

Based on the seismic interpretation a surface map has been created (in TWT) with time contour lines.

A time-depth conversion of the overburden has been performed based on a seismic velocity model built by TNO, called VELMOD-2 (Van Dalfsen et al., 2007), and data from the DEFAB-team in EBN. The resulting velocity model was a layer cake model, based on sonic logs and depth markers of lithostratigraphic layer boundaries in approximately 70 wells in the DEFAB area. The seismic velocity was modelled per lithostratigraphic layer, with a grid of 500 by 500 m, covering the study area. Table 1 shows the different layers and the values that were used for each layer. As velocity function the function $V=V_0+K*Z$ was used, where V is the velocity and K is a constant value. The VELMOD-2 model was created for the Netherlands, onshore and offshore. It should be noted that the model has its limitations. On some lithostratigraphic levels, including the Lower Germanic Trias Group level, very few data points represent the entire DEFAB area. Therefore it was chosen to use simplified V0 maps with constant values or simple trends, which would not strongly deform the structures on Volpriehausen level. These constant values were based on averages in the study area derived from the DEFAB-study in EBN, or, if no data were available from the DEFAB-study, derived from VELMOD-2. The K values have been determined based on linear regressions using the $V_{int} - Z_{mid}$ method (Robein, 2003; Van Dalfsen et al., 2007). Well tops were used to calculate the difference, also called residual, between the well tops and the time-depth converted surfaces. Table 2 shows the residuals for the surface representing the Top Volpriehausen Sandstone Member after correction. A complete table with residuals and corrections for all surfaces used in the layer-cake model can be found in the Appendix (A8). Wells or well tops with abnormalities were excluded from the model. Due to time constraints it was not possible to create a more accurate velocity model, however, the velocity model used is considered acceptable for the purpose of this study.

The velocity model was used to create a depth map of the Top Volpriehausen Sandstone Member. Also, a thickness map was created, based on well tops (converted to isochore points). It should be taken into account that the thickness map shows the measured thickness (MD) and not the true lithological thickness. In places with steep dipping layers, this may cause a distorted picture.

Based on the seismic interpretation of the Top Volpriehausen Sandstone Member amplitude maps were created. Amplitudes were extracted exactly at the horizon interpretation, and maximum amplitude was extracted from a window of 10 ms above and below the interpreted horizon. Depth contours are plotted on the amplitude maps, which is helpful when searching for structural conformable amplitude anomalies (see prospectivity review; chapter 8).

6.3 Evaluation and comparison with Volpriehausen fields

Volpriehausen fields outside the study area (F15-A, L2-FA, L5-FA, M1-A, G16-B and G14-G17) were evaluated by well reports, post mortem reports (if available), seismic and well logs from NLOG and the EBN database. From these evaluations a general picture was derived on what aspects contribute to a successful Volpriehausen play, but also which attribute analyses are assumed to be helpful. These fields were then compared with the dry Volpriehausen wells in the study area.

6.4 Attribute analysis

A seismic attribute analysis has been performed on the interpreted Top Volpriehausen Sandstone Member. The maximum amplitude has been extracted from a window of 10 ms above and below the interpretation. The most prominent features on this map are discussed. Also, amplitudes which are structural conformable have been identified, based on the maximum amplitude extraction in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone Member and depth contours plotted on this map. Furthermore, an amplitude extraction has been done on the interpretation and in a window of 20 ms above the interpretation, in order to locate good quality reservoirs (based on the field evaluation, as discussed in 6.3).

6.5 Dry well analysis

A dry well analysis was performed on the 12 wells in the study area that encountered the Volpriehausen Sandstone Member. For this analysis well reports, post mortem reports and logs from NLOG and the EBN database, as well as seismic data were studied. An extensive table showing the results of this analysis can be found in the Appendix (A5), as well as depth maps, well logs (where available) and seismic sections of each well. The dry well analysis data were summarized in color-coded maps representing the different aspects of a successful play: structure, reservoir, charge and seal. The updip potential was estimated based on depth maps and seismics. When the well was drilled within closing contours from the crest, and the difference in height was more than 25 m, the well was considered to have updip potential.

6.6 Prospectivity Review

Gained knowledge from the workflow described above was integrated into a prospectivity review. Maximum amplitude maps (window 20 ms above and below the interpretation) with depth contours were used to indicate undrilled closures and updip potentials of dry wells in the study area. Characteristics of these leads, including amplitude, thickness, height, area and main risks were studied and shown in a table (Table 5). The amplitude maps and seismic sections of the leads are included in the Appendix (A6).

Table 1 - The layer-cake velocity model, with the data used per layer. K values were derived from the VELMOD-2 model (Van Dalfsen et al., 2007) and V_0 has been derived from the DEFAB-study in EBN or the VELMOD-2 model from TNO.

Layers	V_0		V_0 from	K
Base North Sea Supergroup	Constant	1750	DEFAB	-0.321
Base Chalk Group	Constant	2020	DEFAB	-0.864
Base Rijnland Group	Constant	2000	DEFAB	-0.508
Base Schieland Group	Constant	2300	DEFAB	-0.7
Base Altena Group	Constant	1560	Average in Northern Dutch offshore, from VELMOD-2	-0.601
Base Upper Germanic Trias Group	Surface	2400-2800	VELMOD-2	-0.367
Lower Volpriehausen Sandstone Member	Constant	2675	VELMOD-2	-0.367
Base Lower Germanic Trias Group	Constant	2675	VELMOD-2	-0.367

Table 2 – The residuals after correction at the Top Volpriehausen Sandstone Member, in meters and percentages. The column with Z correction shows how much the Z was corrected in meters and percentages. The amounts of correction were considered acceptable.

Well	Z (m)	Residual at Top Volpriehausen Sandstone Mb		Z correction	
		Residual (m)	Residual (%)	Z correction (m)	Z correction (%)
A18-01	-3696.47	0.0001	0.00	-194.4	5.3
B17-02	-3596.91	-96.3675	2.68	11.51	0.3
E09-02	-2443.21	0	0	-47.34	1.9
F04-01	-2761.1	0.0001	0.00	-8.93	0.3
F04-02-A	-3136.52	0.0001	0.00	-11.31	0.4
F04-03	-2954.11	-3.2976	0.11	-81.79	2.8
F05-02	-2724.98	0.0002	0.00	-12.61	0.5
F10-01	-2835.3	0	0	-59.52	2.1
G07-02	-3511.5	-0.0001	0.00	-13.35	0.4

7. Results

7.1 Seismic interpretation

The top of the Volpriehausen Sandstone Member was interpreted on high quality 3D seismic data of the DEF survey. Throughout the entire study area a peak was picked as Top Volpriehausen Sandstone. This reflector generally has a high amplitude, except near salt domes or walls (Figure 7). Its seismic character is distinguishing: high amplitudes representing the Top Zechstein, with a zone of seismic transparency and a relatively constant thickness above, representing the Main Claystone Member, also known as the Lower Bunter Shales. The Volpriehausen Sandstones succeed these claystones. This distinctive seismic character is visible in Figure 7. Seismic sections out of the study area showing the regional seismic interpretation are included the Appendix A1. These sections show the generally high continuity of the reflector representing the Top Volpriehausen Sandstone Member, except near and under salt, where simplified interpretations have been made where necessary, due to poor seismic signal. In the deepest parts of the Dutch Central Graben and in steep dipping reflectors (F5) the amplitude and continuity are less. However, it also occurs that in structural lows the amplitudes are high (for example at the border of E6-F4, in block F7, F10 and at the border of F9-G7). The seismic signal in the Step Graben and the Dutch Central Graben is largely similar, except that the Volpriehausen is deeper in most parts of the Dutch Central Graben and therefore the seismic frequency is lower in these parts, resulting in wider reflectors.

A 2D time (TWT) surface has been created, based on the regional seismic interpretation of the Top Volpriehausen Sandstone Member (Figure 8). White areas indicate absence of the Volpriehausen, due to penetration of salt walls and erosion, or truncation at unconformities.

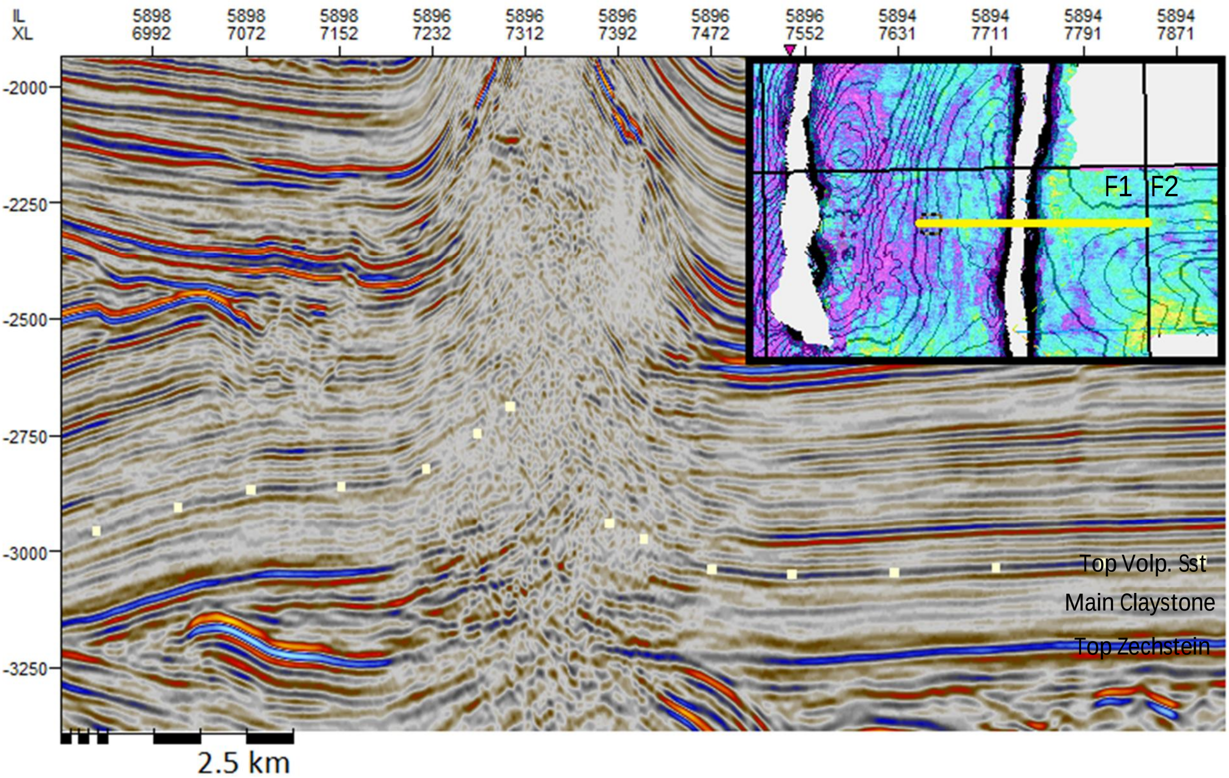


Figure 7 - Seismic section in the north of the study area showing the typical seismic character of the Volpriehausen and its underlying lithologies, as well as the decreased seismic signal near salt domes. The yellow dots indicate the interpreted Top Volpriehausen Sandstone Member. In the upper right corner an overview map (maximum amplitude in window of 10 ms above and below the interpretation) shows the location of the seismic section with a yellow line.

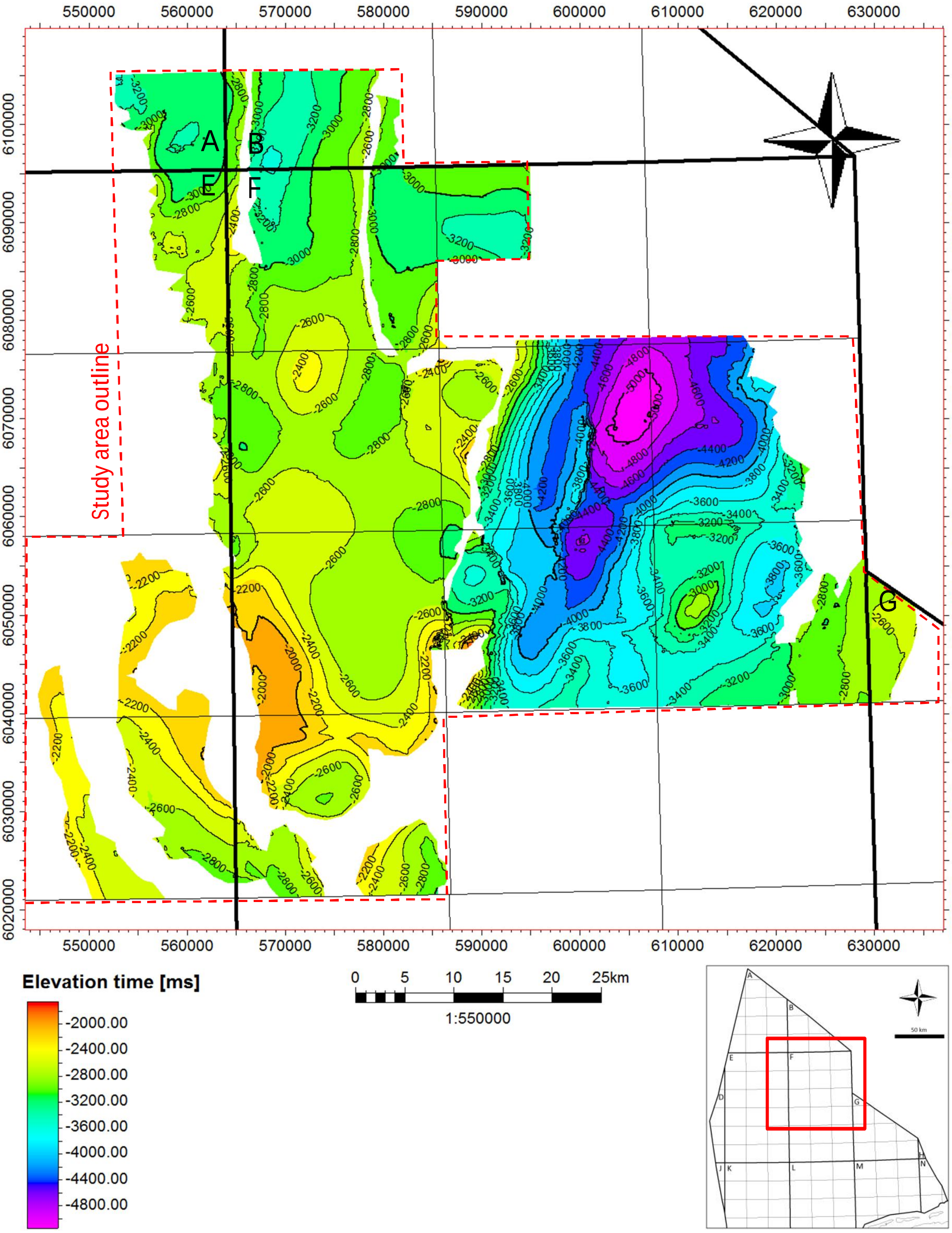


Figure 8 - Top Volpriehausen Sandstone Member time map (ms) resulting from regional seismic interpretation. Time contour interval: 200 ms. The red dotted line indicates the outline of the study area. The overview map in the lower right corner shows the location of the study area.

7.1.1 Thickness Volpriehausen Sandstone Member

At well locations in the study area the thickness of the Volpriehausen Sandstone Member is known from well data. These thicknesses were used to create a thickness map (Figure 9) at which the thicknesses at well locations are also indicated. The thickness decreases in northern and also in eastern direction. The thickness varies from 15 m in the north of the study area to 30 m in the east and 75 m in the south. In the west a thickness of 36 m was measured in well F04-03, but since thicknesses over 50 m were measured north, east and south from this point, this is considered as an exception on the decreasing trend towards the north. In the Dutch Central Graben few data points are present, as wells are not deep enough to encounter the top and base of the Volpriehausen Sandstone Member. In well F09-03 the base of the Volpriehausen Sandstone Member was not encountered, therefore no exact thickness is indicated at this location on the thickness map. A minimum thickness of 55 m applies for this well, based on this information. However, when studying the character of the logs of this well and other wells in the study area, it seems that the base has been encountered and that the thickness of the Volpriehausen Sandstone is 51 m (Appendix A4 and A5; well log F09-03). This thickness is added to the map with an asterisk.

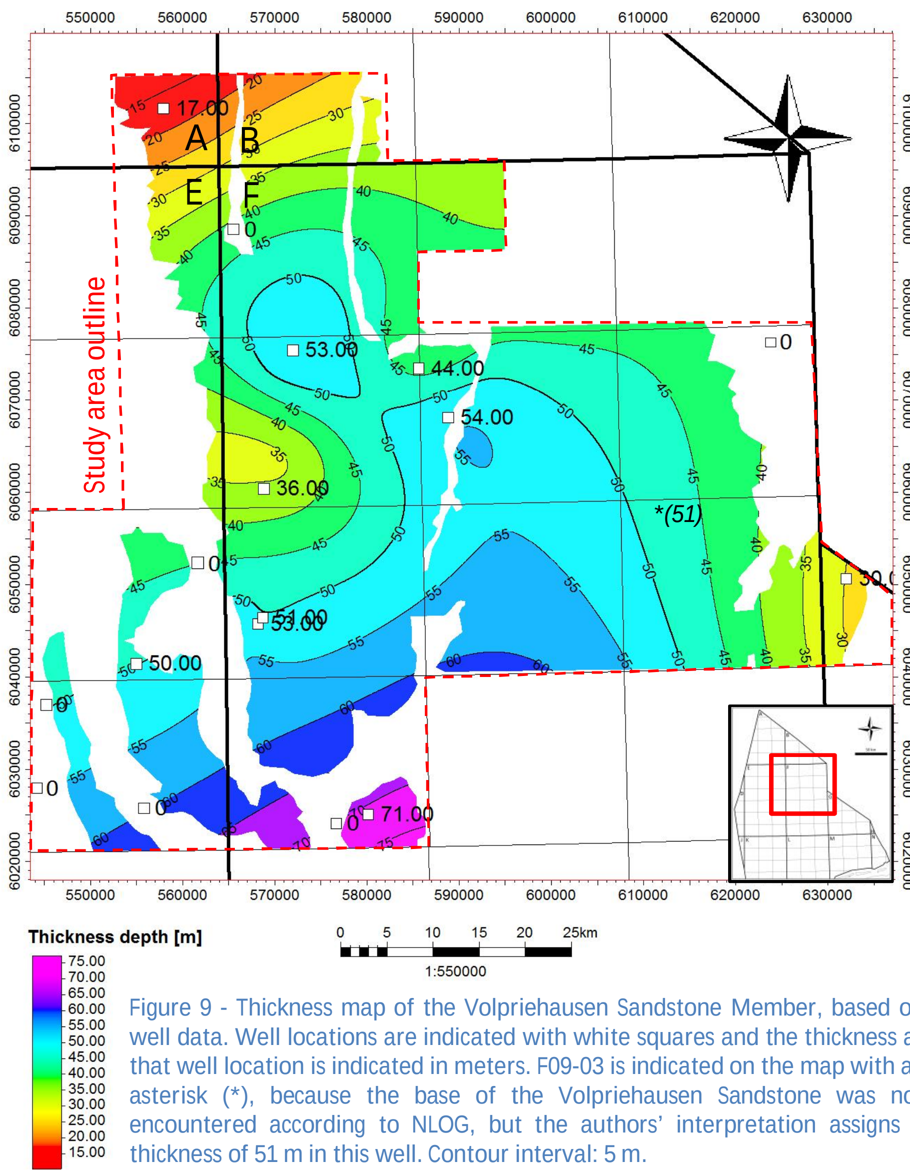


Figure 9 - Thickness map of the Volpriehausen Sandstone Member, based on well data. Well locations are indicated with white squares and the thickness at that well location is indicated in meters. F09-03 is indicated on the map with an asterisk (*), because the base of the Volpriehausen Sandstone was not encountered according to NLOG, but the authors' interpretation assigns a thickness of 51 m in this well. Contour interval: 5 m.

7.1.2 Time-depth conversion

The TWT surface of the Top Volpriehausen Sandstone Member was then converted to depth using a layer-cake model, as described in the Methods chapter. The resulting depth map is shown in Figure 10. It clearly shows the outlines of the Step Graben and the deeper Dutch Central Graben and N-S trending faults. The depth map shows noticeable differences with the time map (Figure 8) in areas bordering salt walls (B16, E3, E6, E9, F1, F8, F10, G7) and near salt domes in the Dutch Central Graben (F5, F6, F9). It should be noted that at locations where salt is overhanging the Top Volpriehausen time imaging is unreliable. In case of steep dip, seismic imaging of true reflectors is difficult. Locally, the depth map may show incorrect depths of the Top Volpriehausen where salt overhang occurs. In reality the Top Volpriehausen may be less shallow than indicated on the depth map in these locations with salt overhang. The structures may be present, however, in reality these structures may be more subtle.

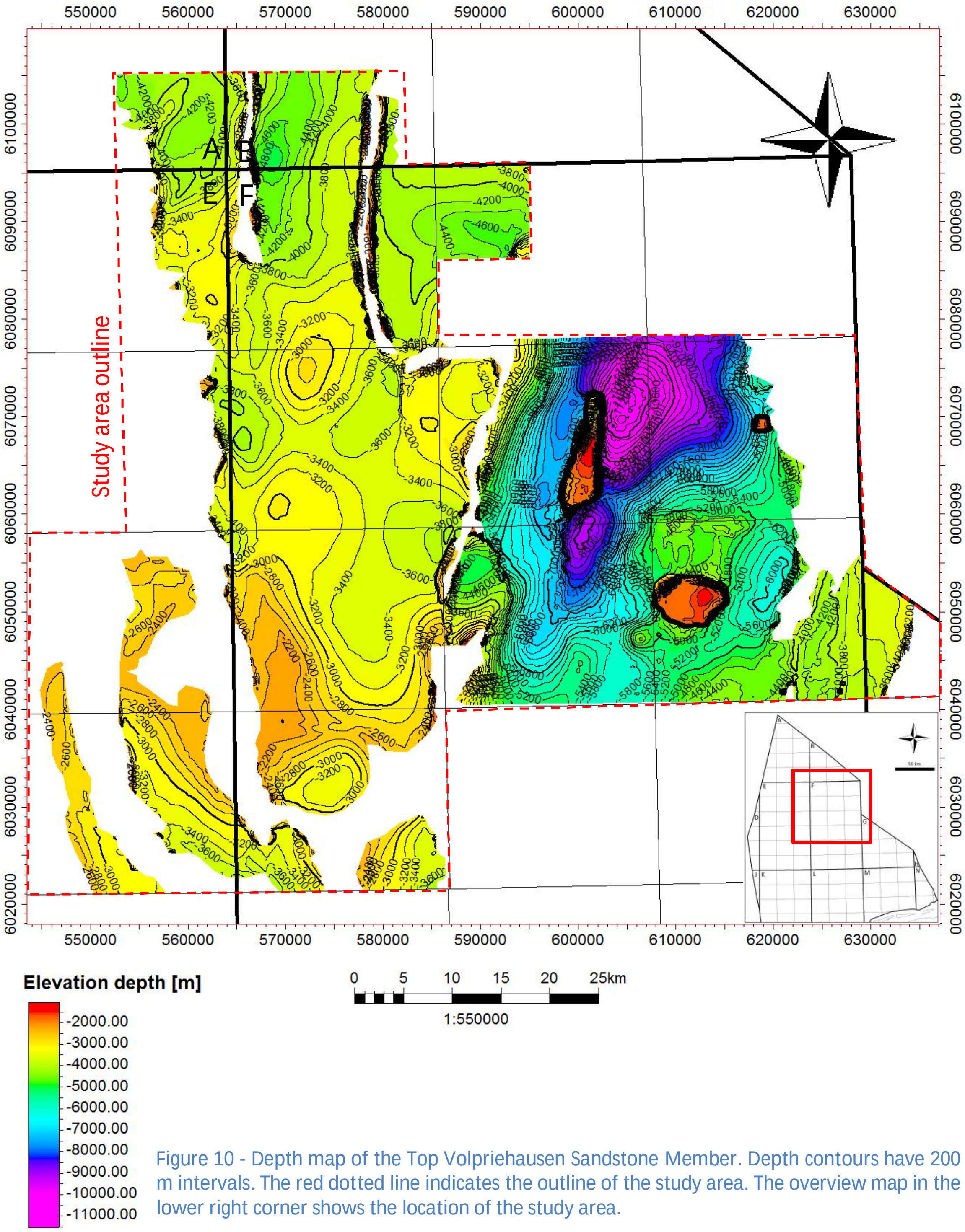
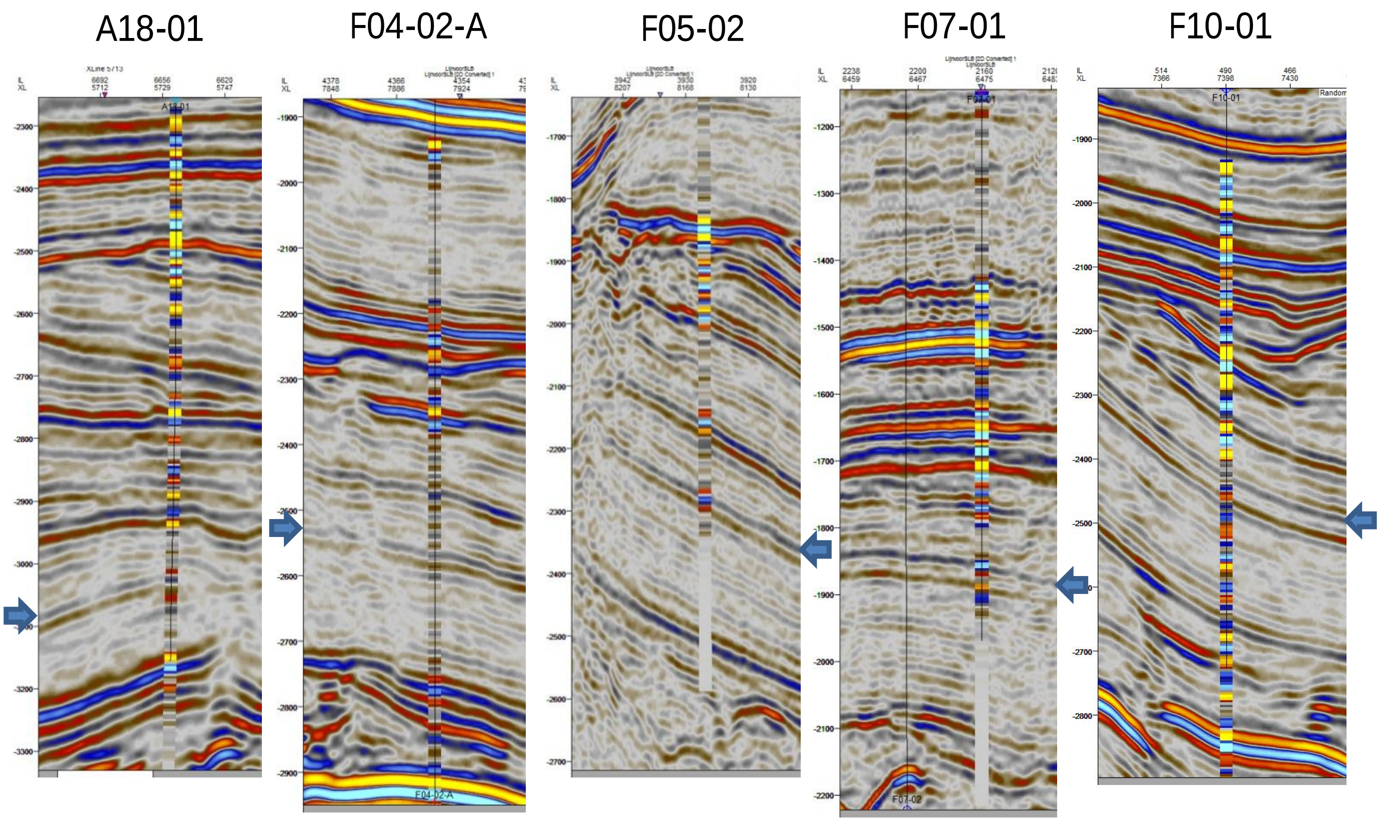


Figure 10 - Depth map of the Top Volpriehausen Sandstone Member. Depth contours have 200 m intervals. The red dotted line indicates the outline of the study area. The overview map in the lower right corner shows the location of the study area.

7.2 Well correlation

In order to tie the seismic to wells, synthetics were created (in Petrel version 2012.5) of wells in the study area that drilled the Volpriehausen Sandstone Member and with enough data available at the Volpriehausen level. This was the case for five wells in the study area (Figure 11). The same synthetics, but with seismic flattened on the Top Zechstein are included in Appendix A3. The synthetic seismograms fit the seismic relatively well, indicating that the time-depth relation used is acceptable and no time shift or other adjustments were needed. The well locations were used as starting or reference points for the seismic interpretation.



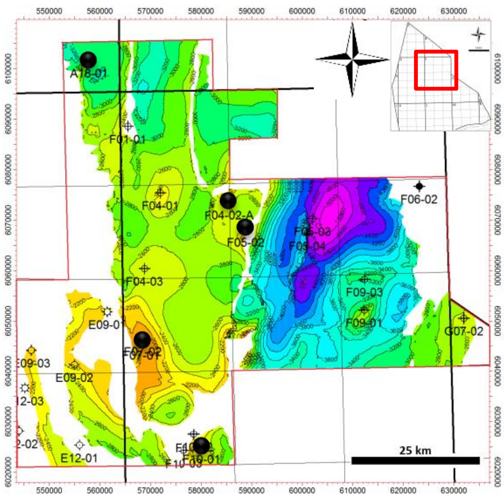


Figure 11 - Synthetics for five wells in the study area. Blue arrows indicate the Top Volpriehausen Sandstone Member. Blue reflector indicates peak, red indicates trough. The locations of these seismic well ties are indicated on the (time) map on the right with black dots.

No seismic well ties at Volpriehausen level were available in the studied sector of the Dutch Central Graben, therefore another method was used to check the seismic interpretation in this part of the study area. A quality check was done based on seismic character. The seismic character was compared throughout the entire study area (Figure 12), leading to some adjustments of the interpretation in the Dutch Central Graben area. In Appendix A2 the interpretation before and after quality control is shown. In the Step Graben the seismic character does not vary much, except for the continuity of the reflectors (Figure 12.2). The character varies more in the Dutch Central Graben, possibly due to the higher depth of the Volpriehausen in this area and corresponding decrease in seismic quality. The frequency of the reflectors is lower in the deeper areas (Figure 12.5 and Figure 12.10). In Figure 12.6 and Figure 12.11 high amplitude reflectors are present in the Main Claystones, which typically have a transparent seismic character. This might indicate a local variation in lithology within the Main Claystone Member in this area.

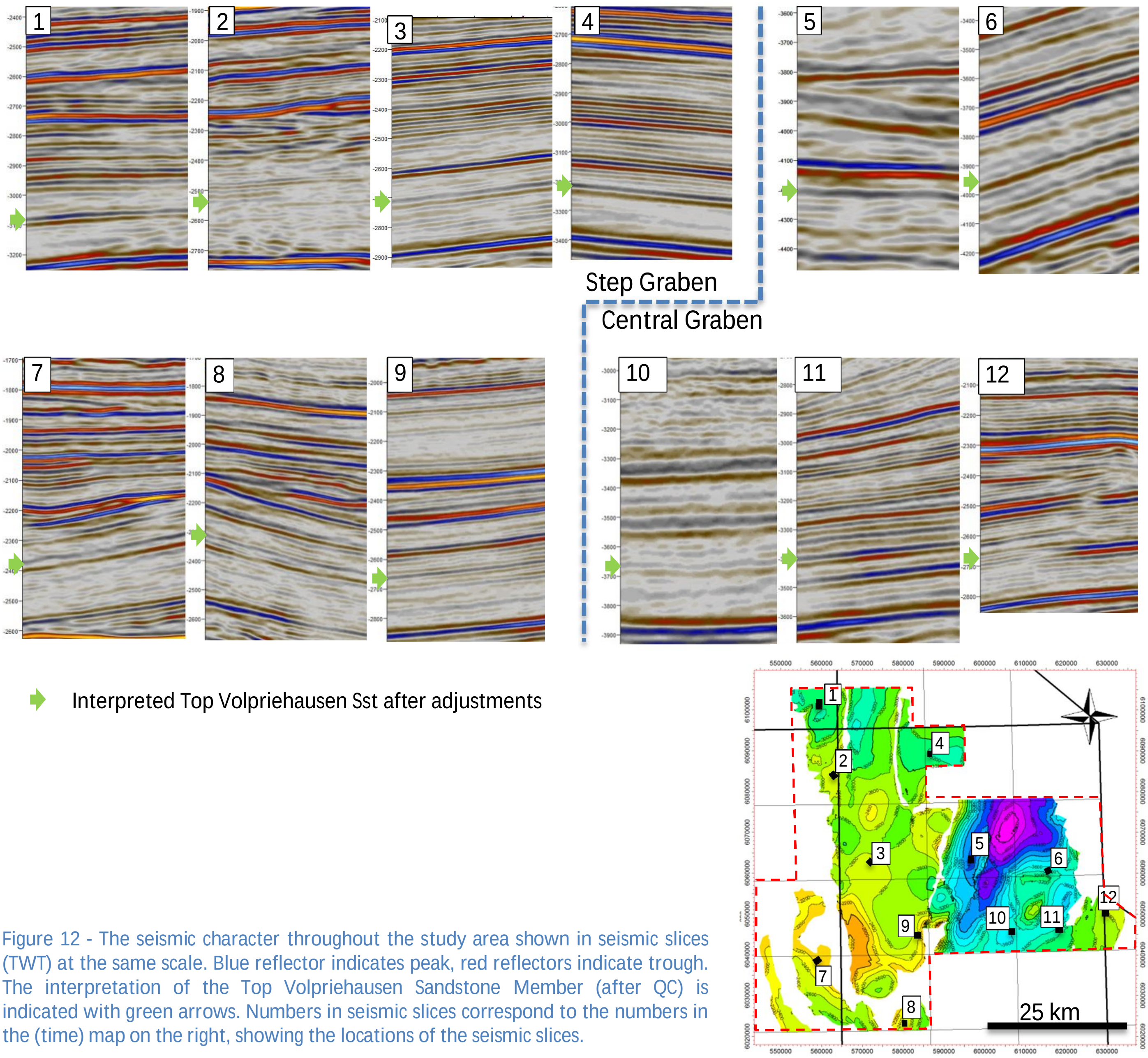


Figure 12 - The seismic character throughout the study area shown in seismic slices (TWT) at the same scale. Blue reflector indicates peak, red reflectors indicate trough. The interpretation of the Top Volpriehausen Sandstone Member (after QC) is indicated with green arrows. Numbers in seismic slices correspond to the numbers in the (time) map on the right, showing the locations of the seismic slices.

7.2.1 Well log description

Available well logs of the wells which drilled the Volpriehausen Sandstone Member in the study area are included in Appendix A4. The scale of all the well logs is set to 1:1000, the same for all wells. No well logs were available (at Volpriehausen level) for the wells E09-03, F04-03 and G07-02. A description of the remaining nine well logs is given below. For locations of the wells, see Figure 6.

A18-01

A18-01 is the most northern well in the study area, and following the thickness trend as described in chapter 7.1.1. It shows a Sandstone Member of only 17 m. The GR log shows a relatively high clay content in the lower half of the sandstone member. The sonic log is higher (70-75 us/ft) at over- and underlying claystone members, indicating that the clays are water-rich (pers. com. Jan Lutgert (EBN)). The sonic log is lower (65 us/ft) in the top of the sandstone reservoir. The density log shows small differences in density between the sandstones and claystones in this part of the section. Based on these logs the top 5 m of the sandstone reservoir has the best quality.

E09-02

The GR log of well E09-02 has a blocky appearance and is divided into three parts, separated by thin claystone banks. The top sandstone unit is 30 m thick, the middle 15 m and the lowest unit 3 m. The three sandstone parts have a GR of 50 gAPI, and an overall high DT (80-90 us/ft), which is similar to the DT at claystone levels above, in and below the Volpriehausen Sandstone Member. This high DT can indicate a good porosity, but also high water contents. The density log shows values of approximately 2.3 g/cm^3 for the sandstones, and approximately 2.6 g/cm^3 for the claystones embedded in the sandstone member.

F04-01

Well F04-01 shows an overall higher GR compared to other wells in the study area, especially at the claystone sections above and below the Volpriehausen Sandstone Member. The claystones have a GR of approximately 60 gAPI, the sandstones have a GR varying between 25-50 gAPI. Within the sandstone member four sandstone units are distinguishable, separated by clay units. The sandstone units have a DT between 75-80 us/ft and are recognizable on the density log with a value of approximately 2.3 g/cm^3 opposed to 2.6 g/cm^3 for the embedded claystones. The top sandstone unit and the third from the top seem to have the best reservoir qualities, based on these logs. The porosity is fair to good, as indicated in the geological report (www.nlog.nl).

F04-02-A

The GR log of the F04-02-A well indicates four main sand units within the Volpriehausen Sandstone member, separated by claystone units. The DT log at the sandstone units is higher (75-80 us/ft) opposed to the lower values at clay levels in the Volpriehausen Sandstone Member (70-75 us/ft). The claystones above and below the Volpriehausen Sandstone Member have higher values (up to 80 us/ft). This might indicate that the sandstones have good porosities, and that the claystone above and below the Volpriehausen Sandstone Member may have high water content. The density log show an overall increase with depth, but the sandstone units within the Volpriehausen Sandstone Member are clearly distinguishable with a density difference of 0.3 g/cm^3 between the claystones and sandstones. All four sandstone units seem to have good reservoir properties, based on these well logs. The porosity in the sandstone member ranges from 14-23.5% (well report – www.nlog.nl).

F05-02

The Volpriehausen Sandstone Member shows four sand units, with thicknesses varying between 5-13 m, separated by claystones up to 8 m thick. The GR log of well F05-02 has relatively high values compared to the other GR logs in the study area. Sandstones of the Volpriehausen Sandstone Member have values varying between 60-85 gAPI, the claystones within, above and below the Sandstone Member have values between 100-120 gAPI. The DT log show highest values (up to 90 us/ft) in the top sand unit of the Volpriehausen Sandstone Member, which can indicate a good porosity in this 13 m thick unit. The density log shows clear distinctions between clay and sand units within the Sandstone Member. The lowest densities (2.3 g/cm^3) are measured in the top sand unit, which adds to the assumption that this unit has the best reservoir properties, based on these well logs. A porosity of 16% has been measured in this well (geological report – www.nlog.nl).

F07-01

The Volpriehausen Sandstone Member is situated shallow in this area, compared to the rest of the study area, which is reflected in the DT log. It has high values, indicating high water content because less compaction has taken place at this shallow depth. From the logs three sand units can be distinguished, separated by claystone beds. The top and middle sand units have a blocky GR appearance (approximately 40 gAPI), a low density (2.25 g/cm^3, and a high DT (up to 100 us/ft), which can either indicate a high porosity or high water content due to lack of compaction. These units may have good reservoir properties. The reservoir quality of the lower sand unit is less, because the density in this unit is similar to clays values.

F07-02

The F07-02 well is located close (800 m) to the F07-01 well, and the properties are similar. The density log of F07-02 is missing, but is expected to be comparable to the density log of F07-01. The Volpriehausen Sandstone Member in F07-02 can be divided into three sand units as well, with GR values of about 40 gAPI. The DT shows high values, which could indicate good porosities, however, in this case it is expected that the DT shows high values due to lack of compaction and thus a high water content. A high porosity of 28% has been measured in this well (well report – www.nlog.nl). Similar as in F07-01, the top and middle sand units have the best reservoir properties based on these logs, and the reservoir quality of the lower sand unit is less, due to limited thickness (3 m), relatively low DT and high density.

F09-03

In contrast to the F07-01 and F07-02 wells, the F09-03 well drilled Volpriehausen Sandstone at large depth (4820 m compared to 2000 m). Only a minimum thickness of 55 m (MD) can be given for the Volpriehausen Sandstone Member in the F09-03 well, since the members' base has not been encountered according to well tops on www.nlog.nl. However, it cannot be precluded that its base is present at a depth of 4871 m (MD), but that it is not interpreted as such, due to a lack of additional and deeper data. If the base of the Volpriehausen Sandstone Member is present at 4871 m, the member has a thickness of 51 m. At least three sandstone units are distinguishable, separated by claystone beds, based on the well logs. The top sandstone unit has a thickness of approximately 30 m, the second sand unit of 14 m, and the third unit of at least 2 m. The GR has an irregular appearance, with values varying between 48-70 gAPI at sand levels and high values at clay levels (95-120 gAPI). The DT log has low values, due to the large depth with corresponding compaction, resulting in clays with low water content. The density log has overall high values, also due to the large depth, but the differences between sands and clay are clear. The overlying Claystone Member has a density of approximately 2.8 g/cm^3, in contrast to the Sandstone Member that shows a density of approximately 2.65 g/cm^3. Based on these logs the top and middle sandstone unit within the Sandstone Member have the best reservoir properties. The third Sandstone unit is thin (if the members' base is indeed at 4871 m), or clay-rich with associated high density (if the members' base has not been drilled).

F10-01

Well F10-01 has a thick Volpriehausen Sandstone Member (71 m). The GR has an odd appearance and its correctness is questionable. No clear difference between sands and clays can be distinguished based on this log. On the density log, however, it is possible to distinguish at least two sand units. The top of the Sandstone Member is marked by a clear transition in density (drop of 2.6 to 2.3 g/cm^3), near the base a claystone level is distinguishable, and at the base the lower sand unit can be identified as a 4 m thick sandstone. The DT log has a part missing in the Volpriehausen Claystone Member, which is solved by connecting the two parts with a straight line. The DT is decreasing towards the base of the Sandstone Member, implying a decrease in porosity towards the base. The best reservoir quality is expected to be in the top ¾ of the Sandstone Member. In the well report (www.nlog.nl) a good porosity is indicated for the Sandstone Member in this well.

7.3 Porosity

Information about porosity of the Volpriehausen Sandstone Member was retrieved from well reports and logs from the NLOG and EBN database. Porosity information was not available for every well in the study area. The available porosity information is indicated in Figure 13, in boxes at well locations. The porosity varies between 14 and 28%, or fair to good, and even very good porosities were measured in E09-03, F07-02 and F04-02-A. Due to the limited amount of data a trend is difficult to recognize. It should be taken into account that these porosities probably have been calculated for different intervals, or are averages. Significant improvement would be a consistent porosity calculation by a petrophysicist for all wells with similar intervals.

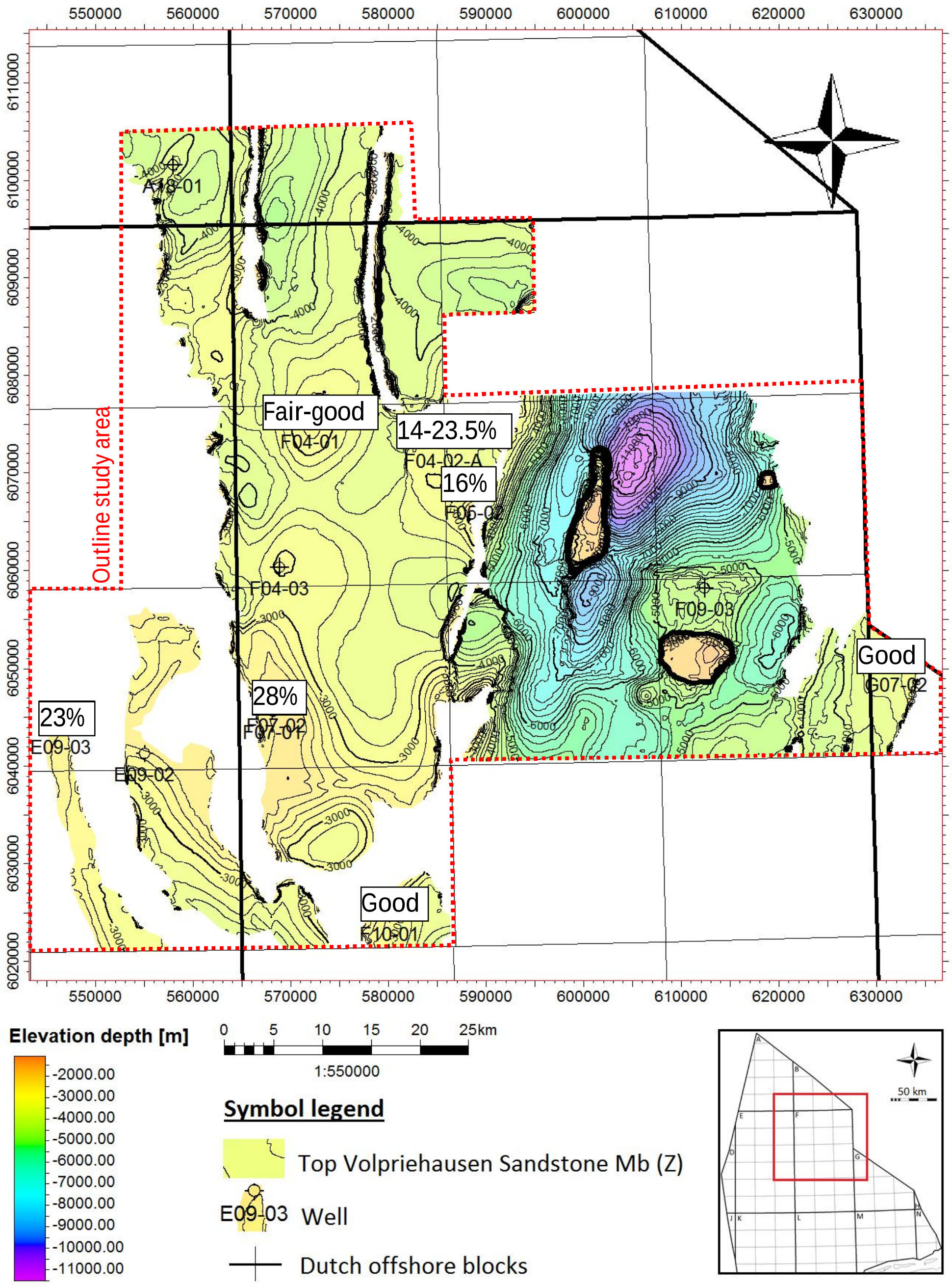


Figure 13 - Porosity variations in the study area, indicated in text boxes on a depth map of the Top Volpriehausen Sandstone Member. Due to limited available porosity information the porosity is not indicated at every well location. If known, the porosity is indicated in %, if only an indication of the porosity is known, this indication is shown.

7.4 Attribute analysis

A seismic attribute analysis has been performed on the interpreted Top Volpriehausen Sandstone Member. First, amplitude anomalies are explained within the study area. Second, structural conformable amplitudes are discussed in more detail. And third, a typical amplitude extraction method being used by an operator in the Netherlands, in order to locate good quality reservoirs, has been performed in this study. Figure 14 shows the maximum amplitude in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone. The most prominent features in this map are explained below, with corresponding numbers.

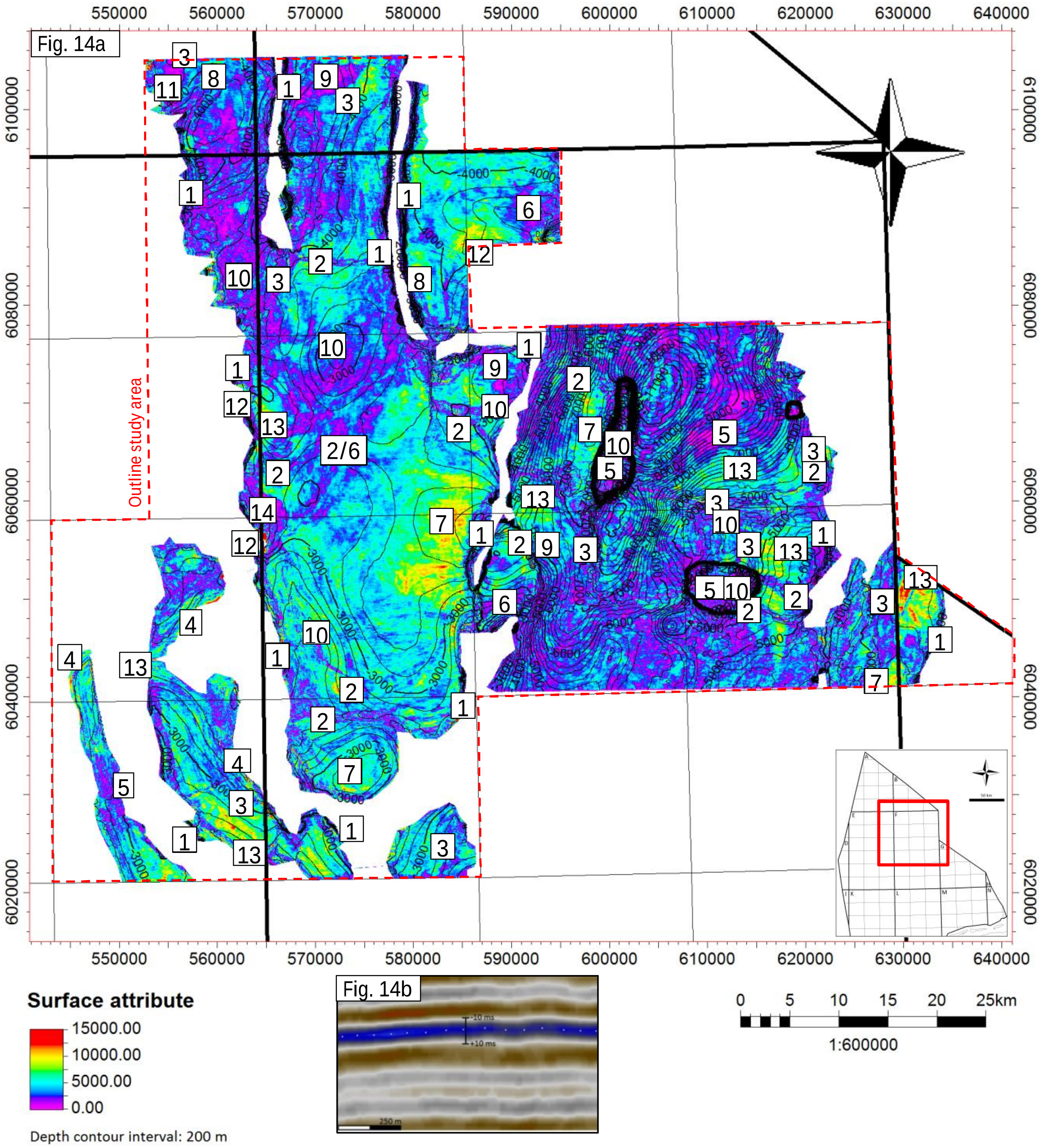


Figure 14 – A: Map of study area showing the maximum amplitude in a window of -10 and +10 ms above and below the interpreted Top Volpriehausen Sandstone Member. This window is indicated in a seismic section (Figure 14b). The numbers in Figure 14a correspond with the numbers in the text.

1) In purple areas (Figure 14) amplitudes are low and/or the seismic signal is poor. At several places along salt walls the amplitude is low. Due to the nearby presence of salt in these locations the continuity of the seismic reflectors has decreased (Figure 17), resulting in zones with low amplitudes near the actual salt walls.
2) Fault zones can be identified in map view, based on amplitudes. They are characterized by a (narrow) zone with low amplitudes.
3) Faults can also be recognized in map view by a sharp transition between high and low amplitudes.
4) High amplitudes at or near unconformity.
5) Zone with poor seismic quality.
6) Zone with seismic transparency.
7) Structural low with high amplitudes.
8) Structural high with high amplitudes.
9) Structural low with low amplitudes.
10) Structural high with low amplitudes.
11) High amplitudes above thick salt, amplitude decreases if salt thickness decreases (Figure 17).
12) Thin Volpriehausen coincides with reflector of Top Zechstein, resulting in a high amplitude (possibly mis-pick).
13) High amplitude dipping reflectors.
14) Possible mis-pick, due to a fault causing offset or due to a 'polarity flip', possibly caused by salt plugging, resulting in a local hard kick (Figure 15).

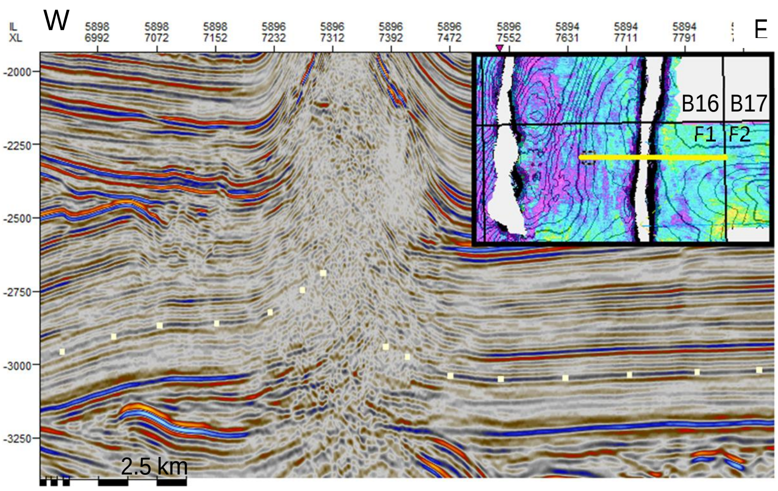


Figure 17 - This seismic section shows an example of reduced seismic signal near a salt wall (No. 1 in Figure 14), in the NE part of the F1 block in the Dutch offshore. The yellow dots indicate the interpreted Top Volpriehausen Sandstone Member.

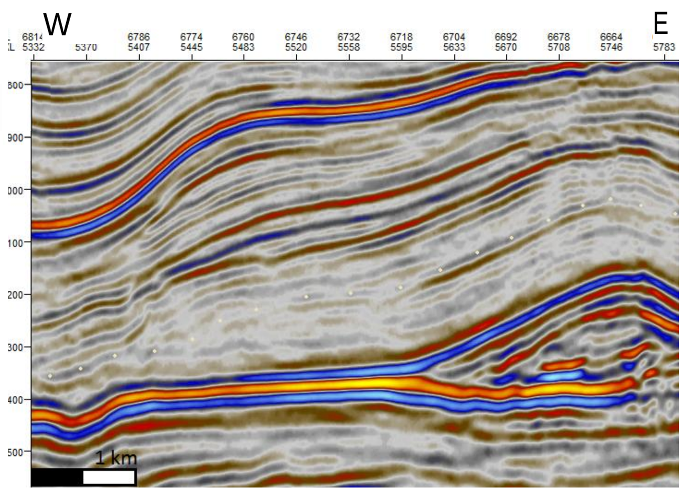


Figure 17 - Higher amplitudes of the Volpriehausen Sandstone above thick salt, decreasing amplitudes above thinner salt. In northern part of the study area (A18), near well A18-01.

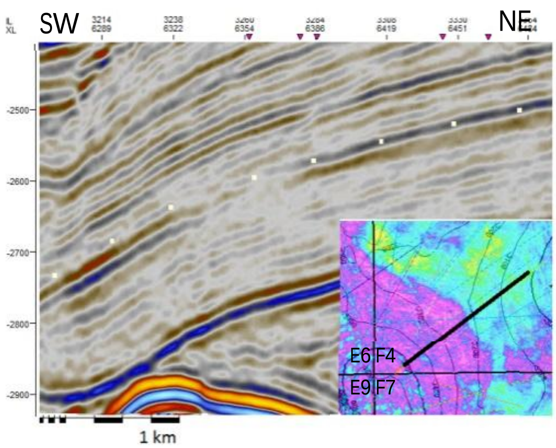


Figure 15 - Seismic section through the southwestern corner of the F4-block, showing a possible mis-pick. Possibly due to a fault with offset or a polarity flip caused by salt plugging, resulting in a local hard kick (red reflector). This has caused the amplitude anomaly indicated as No. 14 in Figure 14. The interpreted Top Volpriehausen Sandstone Member is indicated with yellow dots.

7.4.1 Structural conformable amplitudes

A maximum amplitude extraction has been done in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone Member. Depth contours are plotted on this amplitude map, in order to locate structural conformable amplitude anomalies. In the study area a few cases of 4-way dip closures with high amplitudes on the crest were detected. Some cases of structural lows are present in the study area with high amplitudes conform depth contours. This might indicate good reservoir properties, however, structural lows are no valid traps, so these cases are not further discussed. Remaining structural (high) conformable amplitudes are visible as dipping reflectors near salt walls, faults or at unconformities, and are indicated with numbers on maps of the study area (Figure 18, Figure 19, Figure 20) and described below.

1. In the southeastern corner of the F1 block a structural high conformable amplitude anomaly is visible from the -3950 m depth contour upwards. A seismic line through this anomaly (Figure 21) shows that the amplitude increases towards the salt wall, which is the anomaly visible in Figure 18. Close to the salt wall the amplitude decreases due to salt above, influencing the seismic signal. A change in polarity can be observed in the same place, possibly due to salt plugging. From -3830 m depth and shallower this structure has a 4-way dip closure, which will be discussed in chapter 8 as the Cuvier lead.
2. In the F5 block next to the salt wall another structural conformable amplitude anomaly is visible in Figure 18. Here, the amplitude increases in steep dipping reflectors towards the salt (Figure 22). The updip potential of well F05-02 will be discussed in chapter 8 as the Wegener lead.
3. In Figure 19, in the E9 block, high amplitudes are conformable a structural high. The highest amplitudes are from -2450 m upwards, towards the unconformity in the north and west. Medium to high amplitudes occur in a larger range, from -2600 upwards up to the unconformity in the west. Line 3 (Figure 23) shows these high amplitudes, the highest are at the unconformity. E09-03 was drilled in this structure (at -2340 MD), but no gas was encountered in the Volpriehausen Sandstones.
4. Line 4 (Figure 19 and Figure 24) also shows an increase in amplitude towards an unconformity in the east. A narrow rim of closing contours against the unconformity forms the Lyell lead (chapter 8).
5. Line 5 (Figure 20 and Figure 25) shows increased amplitudes east of a fault, near a salt wall in the east. This 3-way dip-closure against the salt wall forms a lead (Ziegler), as will be discussed in chapter 8.
6. In the top corner of the Dutch part of the G7 block high amplitudes are visible (Figure 20), bounded by a fault in the west and a salt wall in the east. Figure 26 shows a seismic line through this area of high amplitudes. No seismic (and therefore no amplitude map or depth contours) are available from the northern half of the G7 block, because this is German territory. Therefore, this northern boundary remains inconclusive whether the contours are closing, or whether the high amplitudes continue northwards. These structural conformable amplitudes form the Hutton 1 and 2 leads in chapter 8.

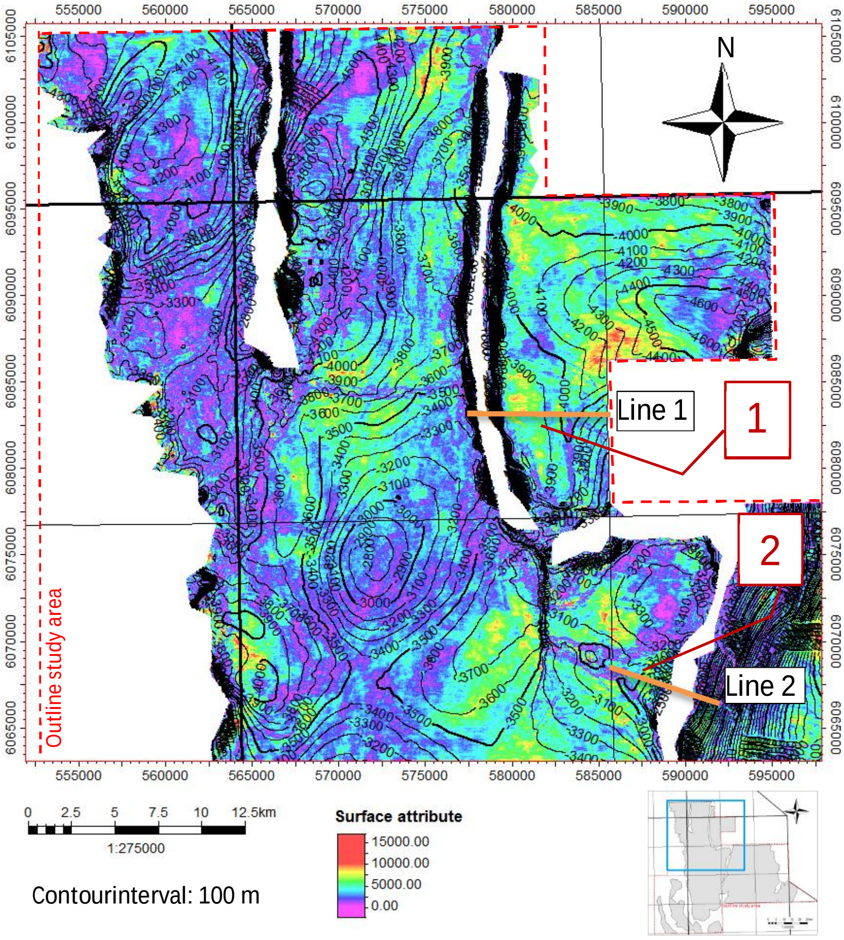


Figure 18 - Map showing the maximum amplitude in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone Member in the northern part of the study area, as indicated by the blue box in the overview map.

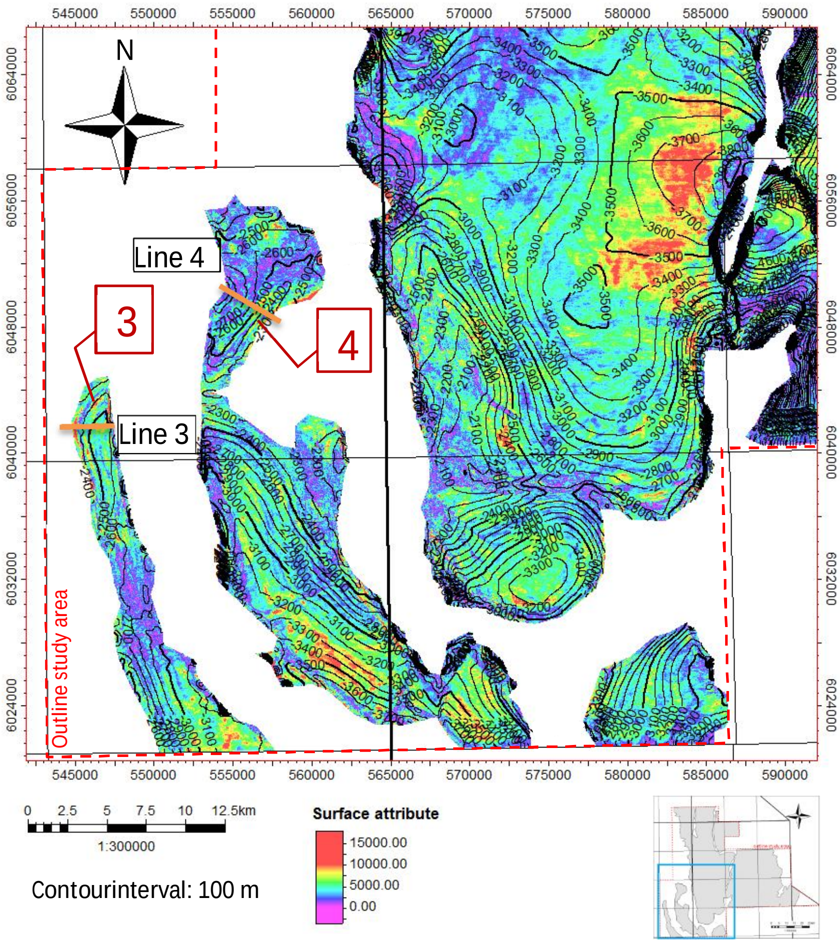


Figure 19 - Map showing the maximum amplitude in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone Member in the southwestern corner of the study area, as indicated by the blue box in the overview map.

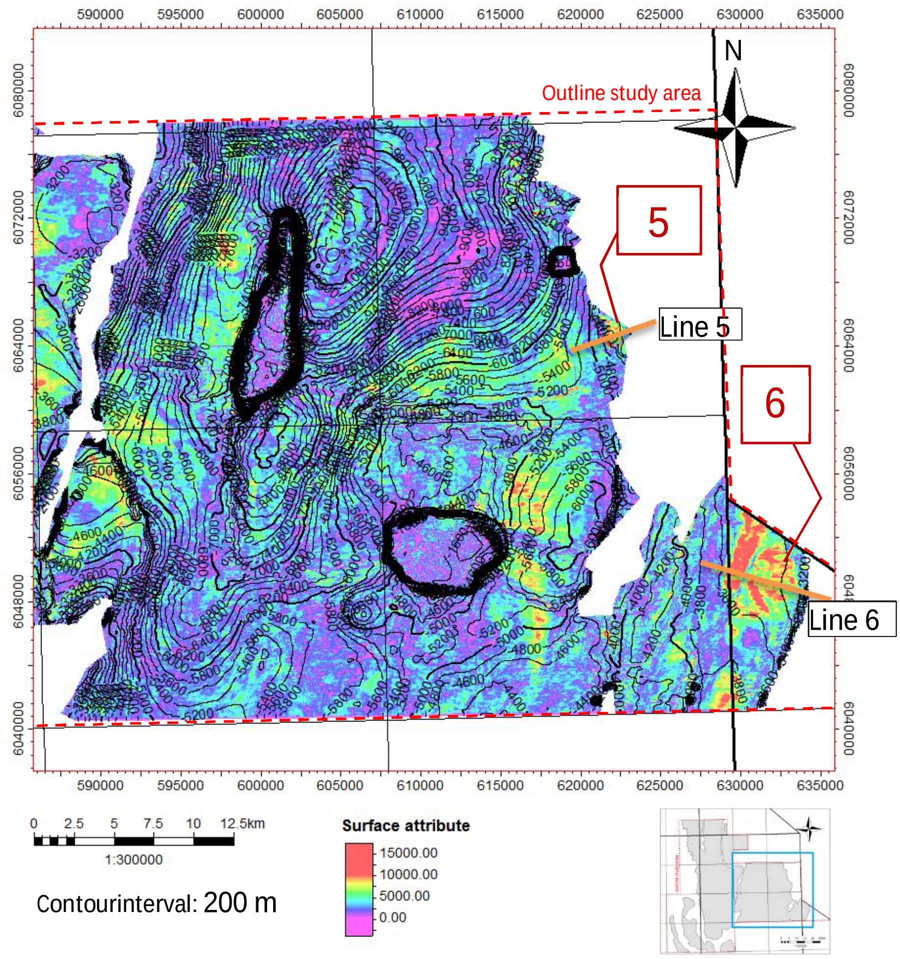


Figure 20 - Map showing the maximum amplitude in a window of 10 ms above and below the interpreted Top Volpriehausen Sandstone Member in the eastern part of the study area, as indicated by the blue box in the overview map.

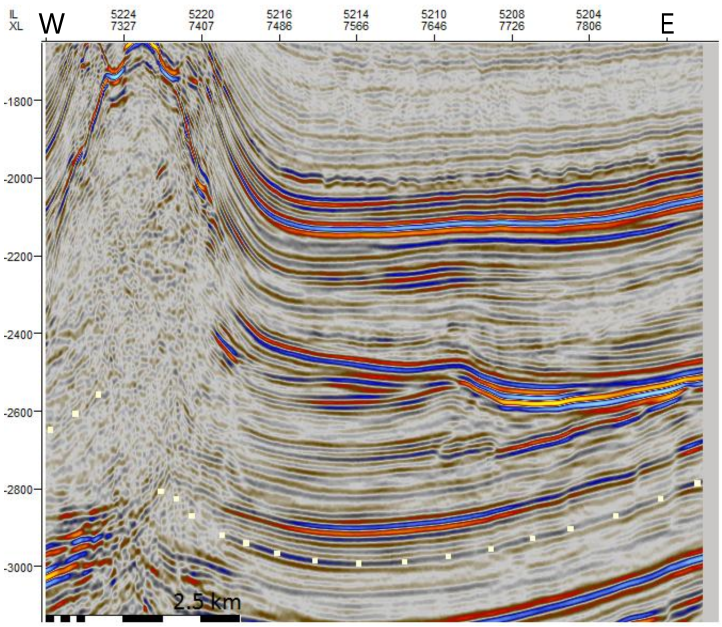


Figure 21 - Line 1 (For location see Figure 18).

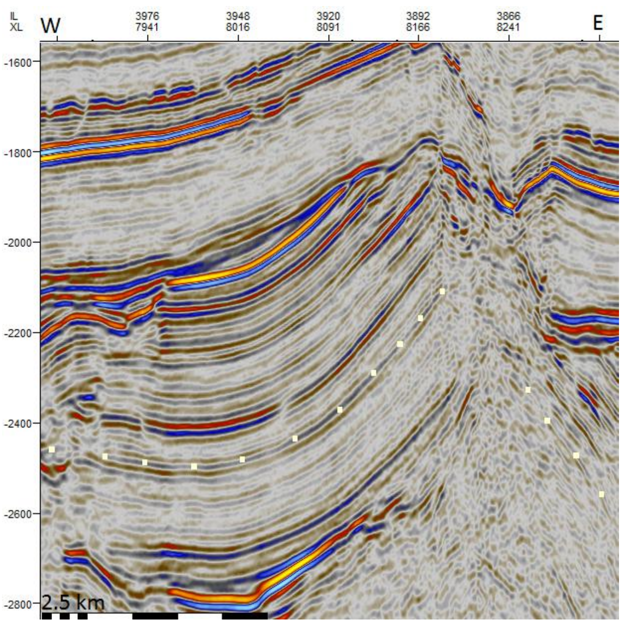


Figure 22 - Line 2 (For location see Figure 18).

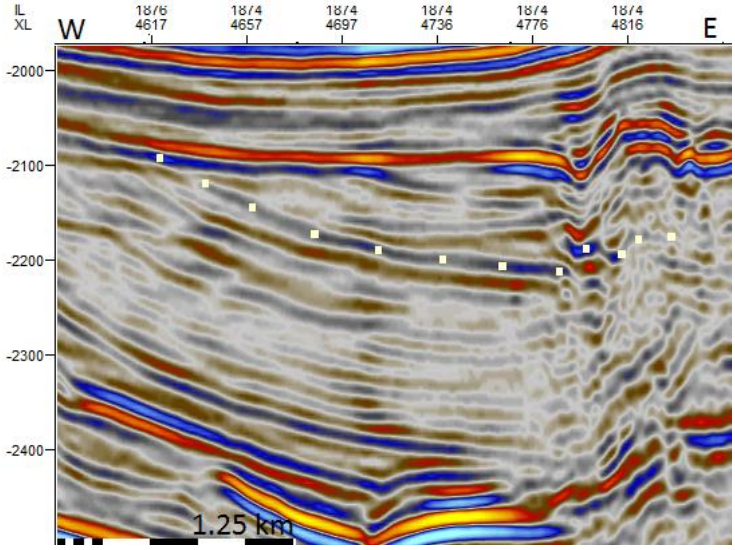


Figure 23 - Line 3 (For location see Figure 18).

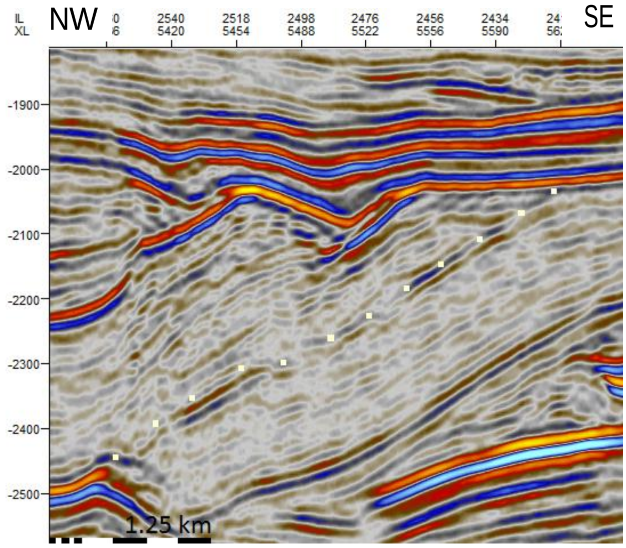


Figure 24 - Line 4 (For location see Figure 19).

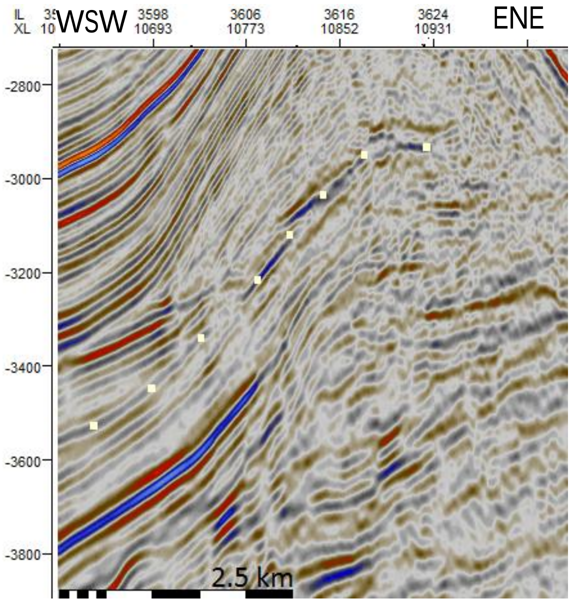


Figure 25 - Line 5 (for location see Figure 20).

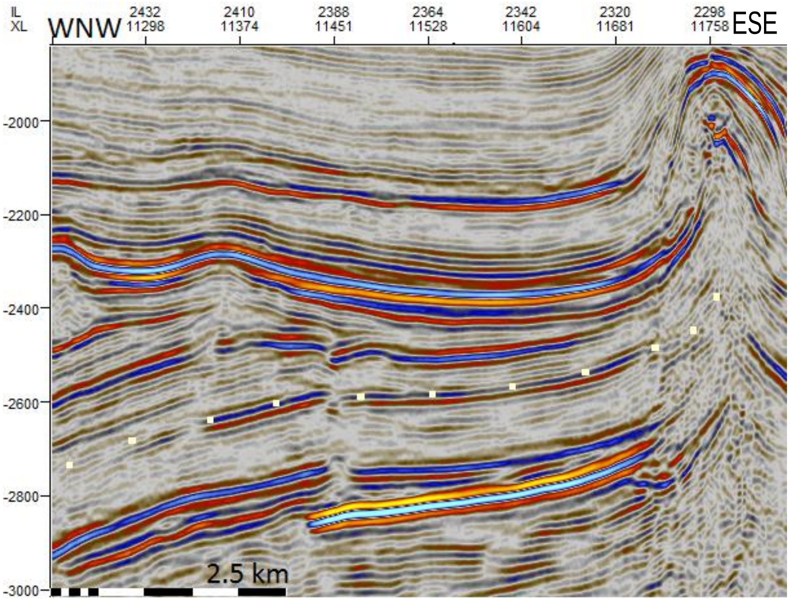


Figure 26 - Line 6 (for location see Figure 20).

7.4.2 Good quality reservoirs

A typical amplitude extraction that is being used by an operator in the Netherlands is that a good quality Volpriehausen reservoir (porous and water/gas bearing) has a peak, followed by a clear trough. A gas-bearing reservoir has higher amplitudes compared to a water-bearing reservoir (Figure 58, chapter 7.7). This same extraction has been performed in this study. The amplitude has been extracted on the interpreted Top Volpriehausen Sandstone Member level (Figure 27) and in a window of 20 ms below that horizon (Figure 28), in order to locate the good quality reservoirs following this operators' method. The areas with strong amplitudes in both maps are highlighted with yellow circles in Figure 27 and are possibly good and/or gas-bearing reservoirs.

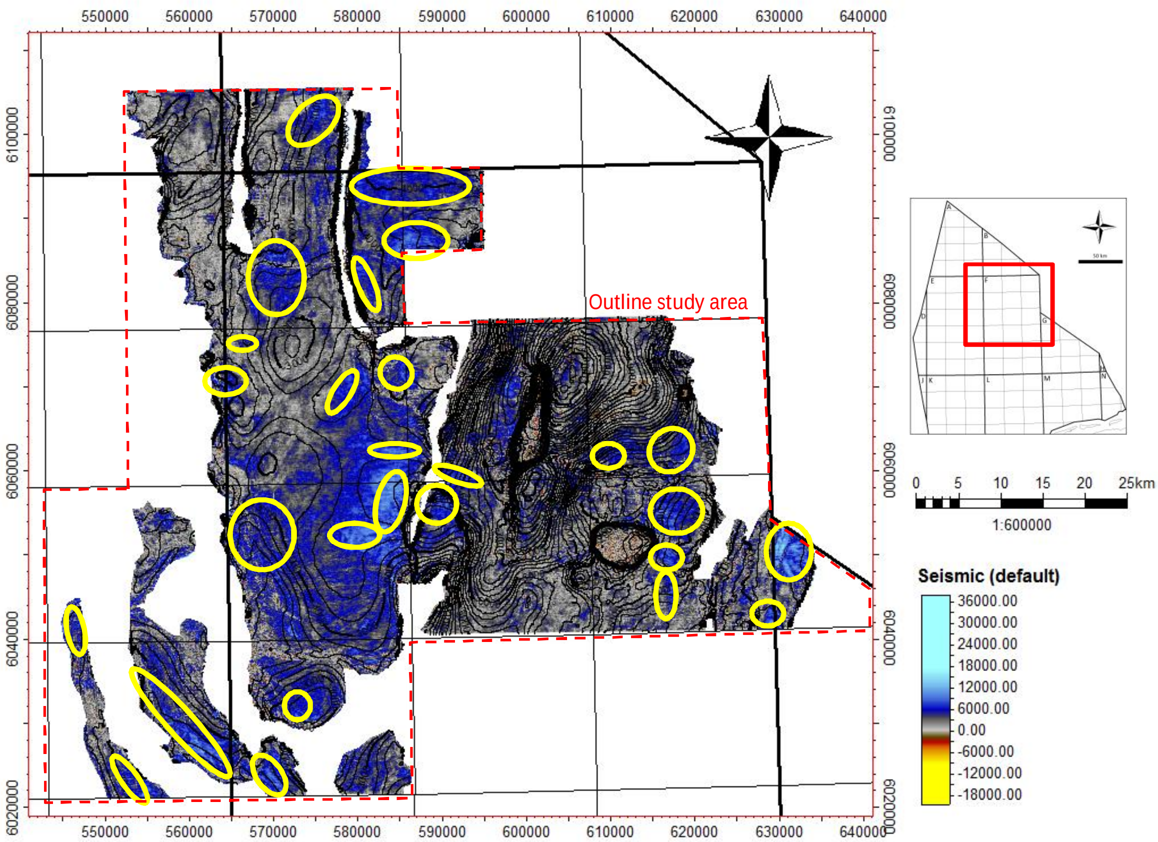


Figure 27 - Amplitude extracted from interpreted Top Volpriehausen Sandstone Member. Blue amplitude indicates peak. Yellow circles indicate areas where a peak is followed by a clear trough (Figure 28), and thus a possibly good reservoir.

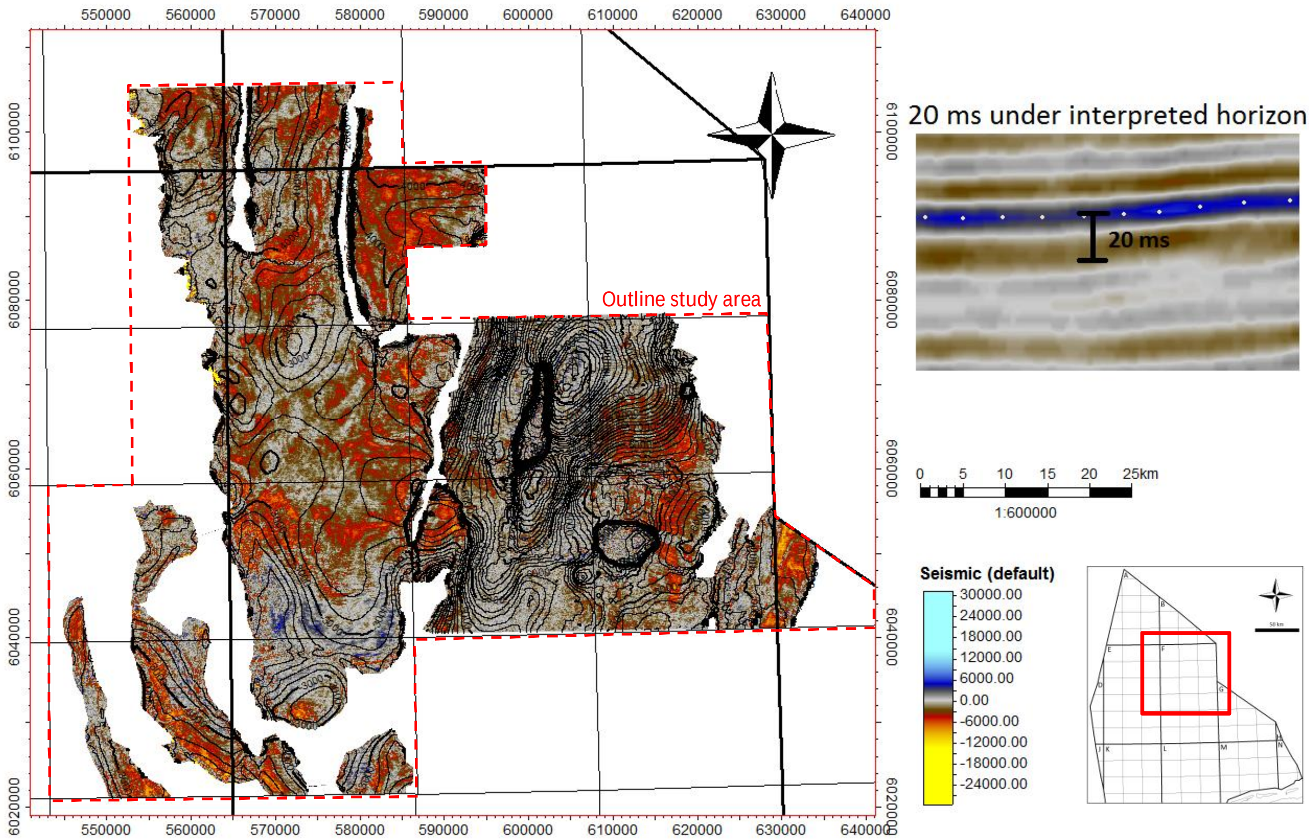


Figure 28 - Amplitude extraction from a window of 20 ms below the interpreted Top Volpriehausen Sandstone Member. Red amplitude indicates trough, blue indicates peak, according to European convention.

7.5 Evaluation and comparison of Volpriehausen fields outside study area

No producing or produced Volpriehausen gas-fields are present in the study area, therefore an evaluation has been done of producing Volpriehausen fields south of the study area, in order to obtain a better understanding of gas-filled structures in the Volpriehausen Sandstone Member. The F15-A, L2-FA, L5-FA, M1-A, G16-B and G14-G17 fields are evaluated. Their location is indicated in Figure 29. All six fields are currently producing. If available, amplitude maps and well logs were added. Information was retrieved from www.nlog.nl and TCM presentations from the EBN database.

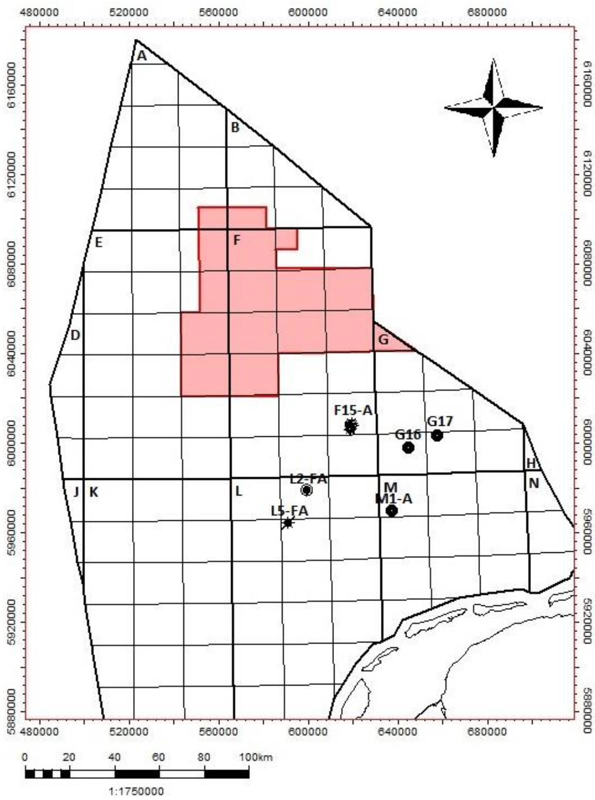


Figure 29 – Map of the Dutch offshore showing the locations of the discussed Volpriehausen fields outside the study area (indicated in red).

7.5.1 F15-A field

The F15-A field is the northernmost producing field from the Volpriehausen in the Netherlands and is located at the eastern margin of the Dutch Central Graben, at a depth varying between 3300-3800 m depth. The field is trapped in a turtle-back anticline of halokinetic origin (Figure 31). On GR and RHOB logs (Figure 30) the Sandstone Member is clearly distinguishable as blocky sands with low clay content. The DT log shows a decrease in porosity towards the base of the member. The reservoir is approximately 37 m thick, consists of coarse sandstones and has claystones above and below. Based on sedimentology, the reservoir can be divided into 5 units, with decreasing porosity with depth (Fontaine et al., 1993; Vittori et al., 1990). The upper unit forms an exception, with poor porosity due to high clay content. A schematic overview of this subdivision is shown in Table 3. However, this subdivision is not clearly distinguishable on the well logs (Figure 30). The porosity is affected by salt deposits, especially in unit 2, where anhydrite cementation decreased the porosity. It is generally accepted that Westphalian coals are the source rock for this field. Hydrocarbons must have migrated along faults in areas with very thin or no Permian Zechstein salt (salt withdrawal), such as can be seen to occur directly below the field. The reservoir is sealed by juxtaposed Middle-Late Triassic mudstones and evaporites across boundary faults. The amplitude of the Top Volpriehausen Sandstone in this field is characterized by a strong trough (red reflector on Figure 31), followed by a clear peak (blue reflector).

Table 3 – Subdivision of the Volpriehausen Sandstone Member in the F15-A field. (From: Fontaine et al., 1993)

Subdivision of the reservoir	Porosity	Permeability
Unit 5	Poor due to high clay content	Low due to high clay content
Unit 4	14-18%	0.8-80 mD
Unit 3	13-18%	1-30 mD
Unit 2 (anhydrite cementation)	12-16%	0.7-20 mD
Unit 1	8-13%	0.3-0.7 mD

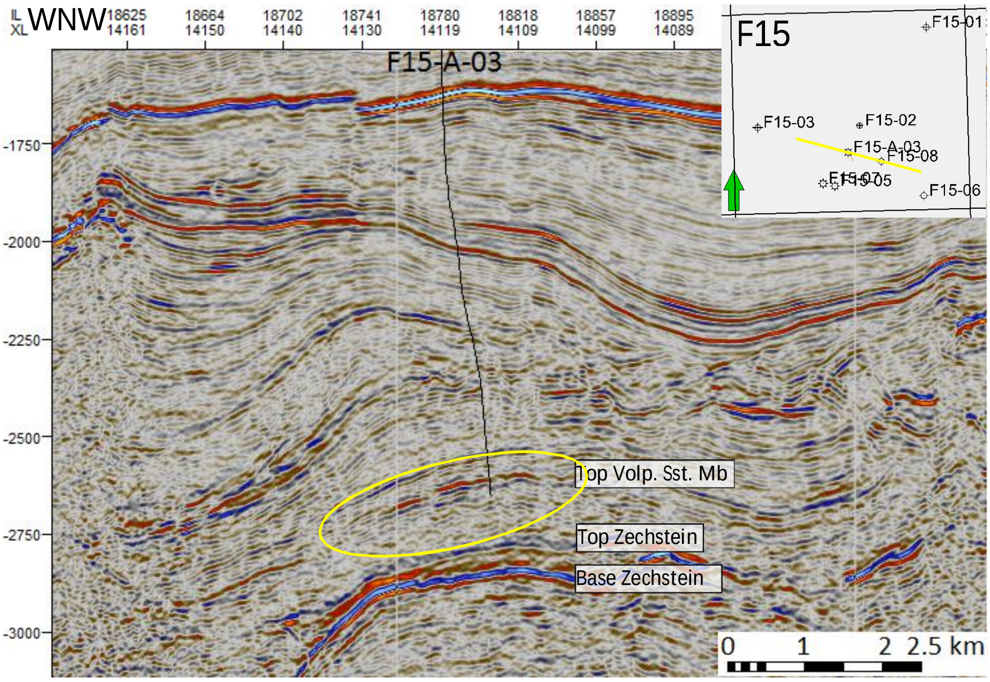


Figure 31 - Seismic section showing the turtle-back anticline structure of the F15-A field. The Top Volpriehausen Sandstone Member is characterized by a strong red reflector, which is a trough, with a peak (blue reflector) below.

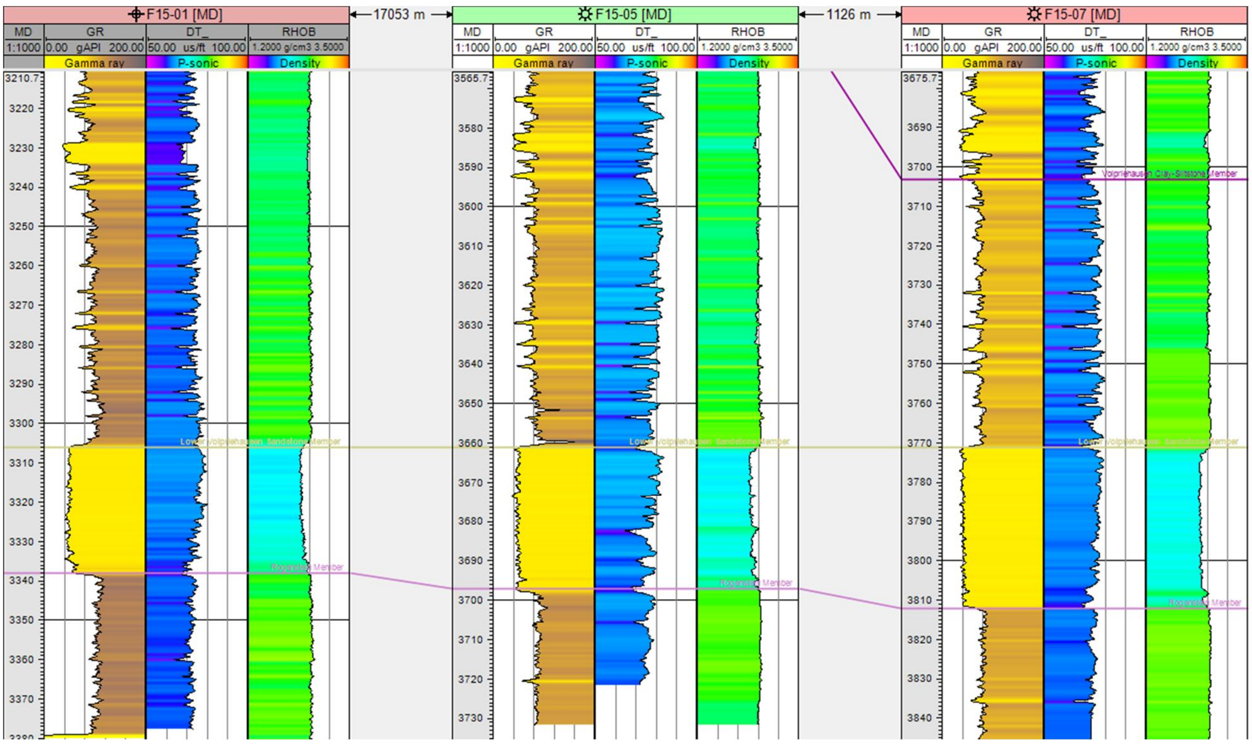


Figure 30 - Well logs of exploration wells near the F15-A field showing the top and base of the Volpriehausen Sandstone Member. The GR logs show massive sands with low clay-content. The RHOB log also shows a clear distinction between the over- and underlying claystone members, and the Sandstone member. The DT log shows an overall decrease in porosity within the Sandstone Member, towards the base.

7.5.2 L2-FA field

The L2-FA field is located in the southern Central Graben and has the Volpriehausen Sandstone Member as reservoir. Gas is currently being produced from this field. The 47 m thick reservoir consists of course sandstones and is gas bearing over its entire thickness. Clay- and siltstones with sand beds are overlying and underlying the sandstone reservoir (Figure 32). The Sandstone Member is clearly visible on the three logs. The GR shows clear sands with low clay-content, the DT log shows a high porosity, and the RHOB indicates a low density, opposed to the high density of the overlying Claystone Member. The field has a three-way dip closure and is trapped against a salt dome (Figure 33). On the other side of the saddle the L2-FB field is located. The gas field has likely been charged from a Carboniferous source and faults in the Top Zechstein are assumed to have provided a migration path. The overlying claystones act as top seal, and salt is sealing from the side. The reservoir has an average porosity of 12%, a permeability varying between 1-14 mD, and a water saturation of 60%. Anhydrite cementation is present on and flanking the L2-FA structure, due to the movement of groundwater under a compactional drive mechanism towards the margins of pressure cells. Lateral changes in anhydrite cement distribution is thought to be controlled by the distribution of hydrofractured fluid pathways (Brown et al., 2001). The reflector showing the Top Volpriehausen Sandstone Member is a peak with a clear trough below, and a less high peak below that (Figure 33). Figure 34 shows an amplitude map of the Top Volpriehausen Sandstone Member (confidential), with clear structural conformable amplitudes, red indicating low amplitudes, and blue and purple high amplitudes.

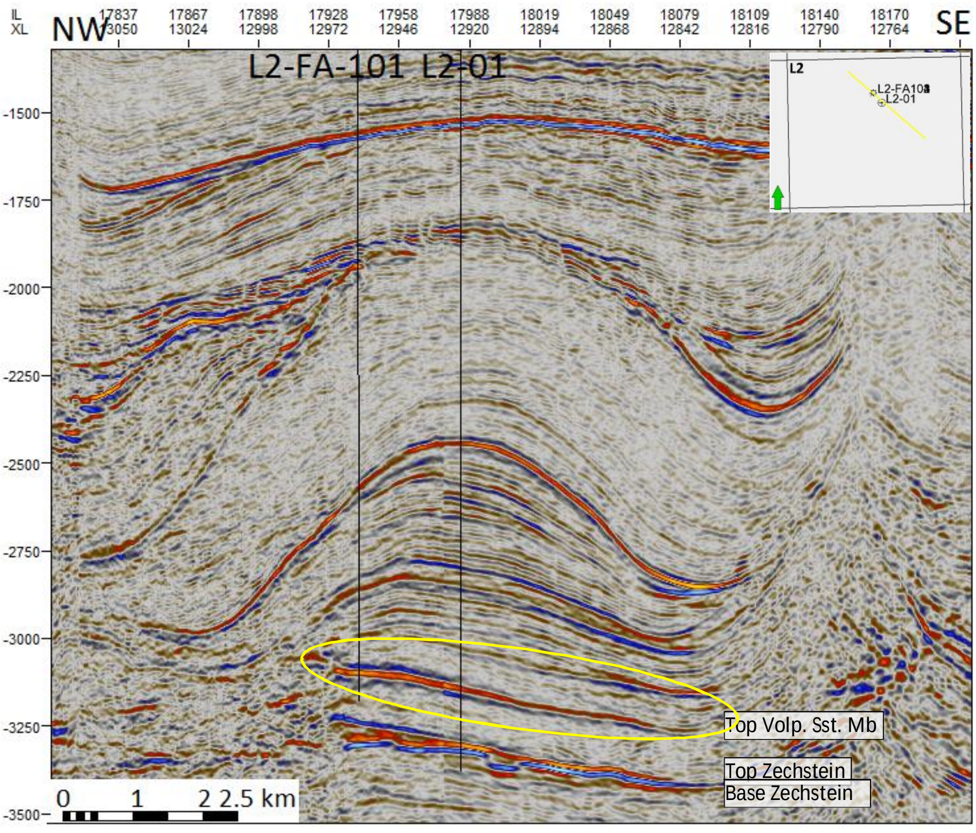


Figure 33 - Seismic section through the L2-FA field, showing the locations of the L2-FA-101 and L2-01 wells. The Top Volpriehausen is a peak with a strong trough below and a less high peak below that.

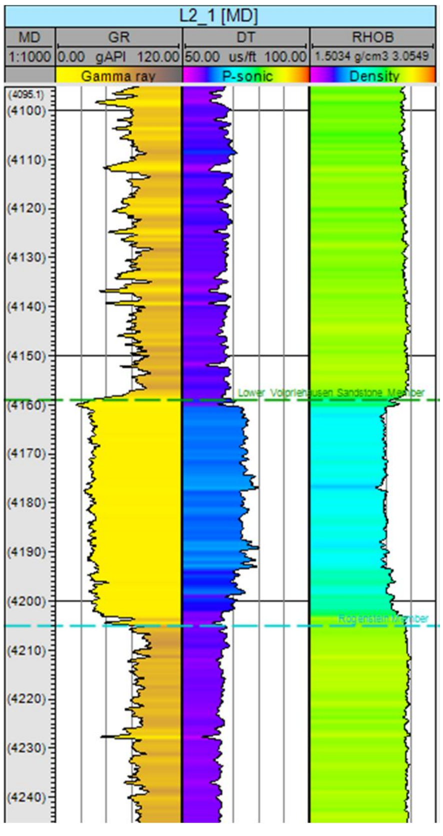


Figure 32 - Well log of the L2-01 exploration well, showing the top and base of the Volpriehausen Sandstone Member.

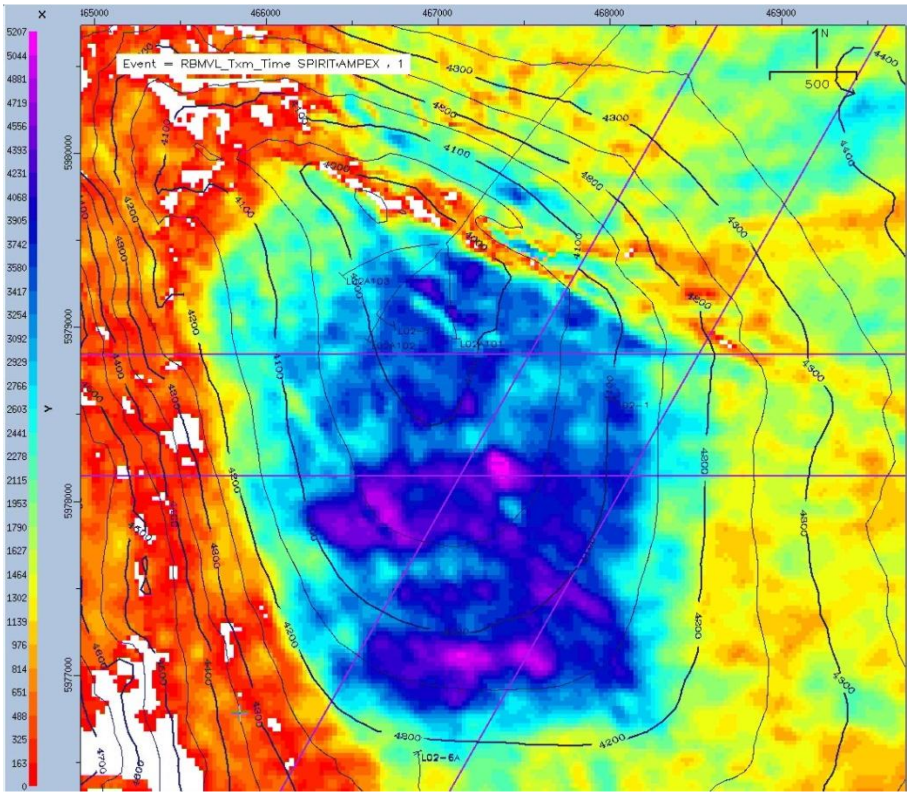


Figure 34 - Amplitude map of the Top Volpriehausen Sandstone Member in the L2-FA field (AMPI 2003 PSDM tRBMVL). Contours are depth contours with a 100 m interval. From: EBN database, confidential.

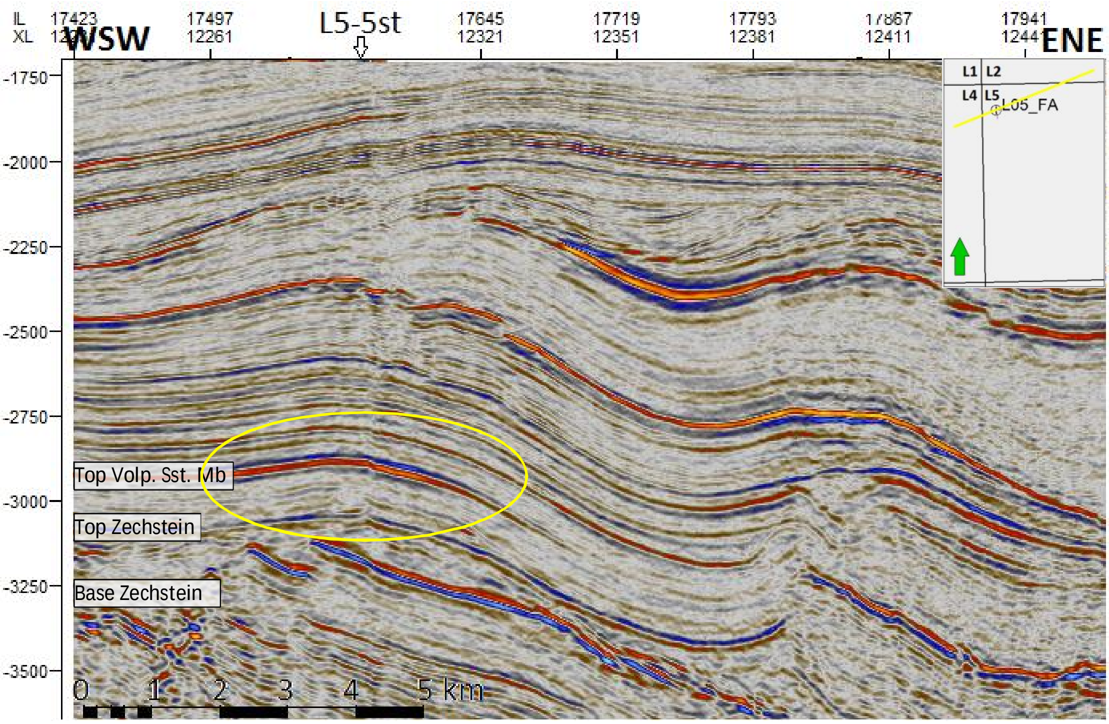


Figure 35 - Seismic section through the L5-FA field in the northwestern corner of the L5 block, showing the location of the L5-5st well (Figure 36). The Top Volpriehausen Sandstone Member can be recognized by a high blue (peak) reflector, with a high red (trough) reflector below. The faulted Zechstein below has provided a migration path for the gas.

7.5.3 L5-FA field

The currently producing L5-FA field is located 18 km southwest of L2-FA, in the southern Central Graben (Figure 29). An approximately 50 m thick reservoir of Volpriehausen sandstones has a simple, elongate, slightly faulted turtle-back structure (Figure 35), with a vertical relief of approximately 150 m. The overlying clay-siltstone sequence acts a seal, as can be seen from the density contrast between the sand and clays in the RHOB log (Figure 36). The GR log shows clear sands with low clay-content in the Volpriehausen Sandstone Member, except for one (1 m thick) clay bed near the base of the Sandstone Member. The porosity decreases towards the top and base of the member, as indicated by the DT log, similar to the trend in density within the Sandstone Member. Carboniferous shales and coals are assumed to have been the source rock for this field, and charge seems possible along faults through thin Zechstein salt. The sediments are tight, and the porosity ranges from 0-9%. Halite and dolomite are the dominant pore filling sediments, anhydrite is of less importance. Halite cement in L5-5A precipitated from saline groundwater (Brown et al., 2001). Permeability ranges from 0.01-33.6 mD. Figure 35 shows a high peak as Top Volpriehausen Sandstone, with a high trough below, and a less high peak below that.

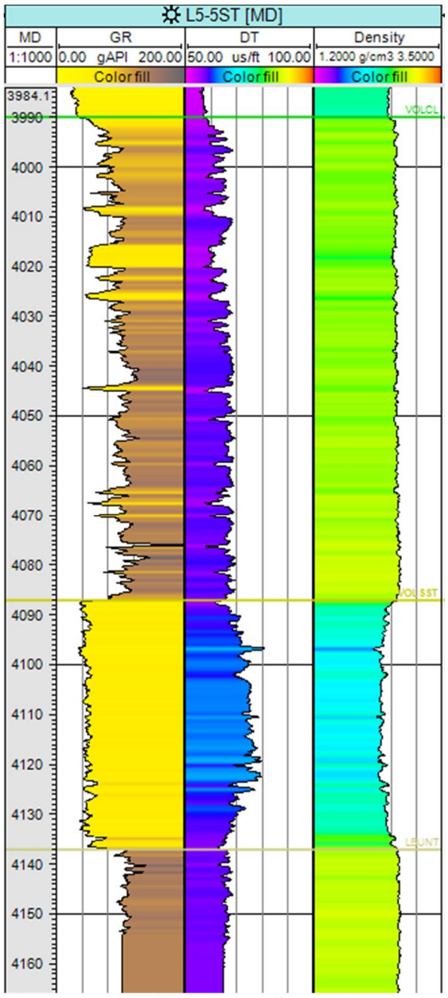


Figure 36 - Well log of well L5-5 (st) in the L5-FA field, showing a 50 m thick Volpriehausen Sandstone reservoir, with clay-siltstones above and below.

7.5.4 M1-A field

The M1-A field is currently producing and is located in the Terschelling Basin. The Volpriehausen Sandstone Member serves as reservoir and the gas is trapped in a stratigraphic trap at the flank of a salt dome. The reservoir is 30 m thick. A gas column of at least 32 m is present with the spill point at -3950 m. The GR log shows a blocky appearance of the Sandstone Member (Figure 39), with claystones above and below. The clay-content within the sandstone member is low. The DT shows a high peak halfway, indicating a level of high porosity, but this extremely high peak could possibly be a measurement error. The density log shows a clear distinction between the claystones and sandstones. On the seismic section (Figure 37) and on an amplitude extraction (Figure 38) the associated amplitude anomalies are visible. On seismic the Volpriehausen Sandstone member is recognisable by a high trough, with a less high peak below. The amplitude map displays not entirely structural conformable amplitudes. Hydrocarbons likely have migrated from Carboniferous source rocks along faults through thin Zechstein salt windows. Upper Germanic Triassic evaporites act as seal in the north and south, in the east and west the salt plugged Volpriehausen sandstones are sealing. The gas bearing part of the reservoir has an average porosity of 7%, a N/G of 94%, and a water saturation of 34% (from post mortem M1-4). M1-2 and M1-3 both have low permeability. The porosity and permeability have been reduced due to cementation by halite (in M1-2) and illite (in M1-3).

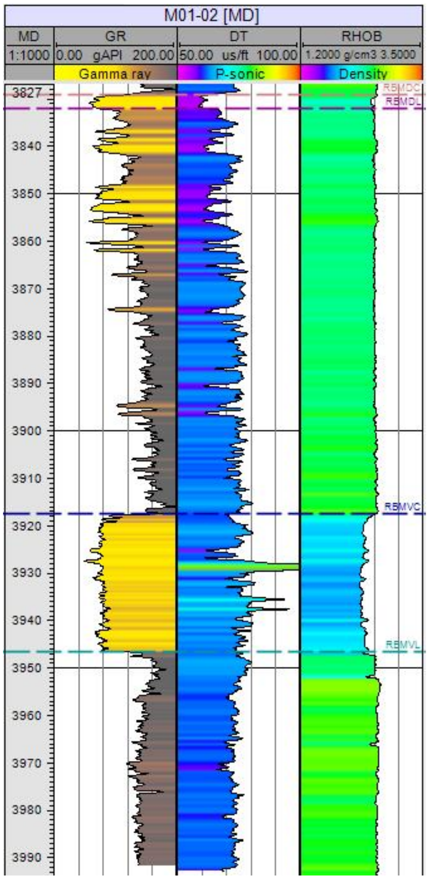


Figure 39 - Well log of well M01-02 in the M1-A field, showing a 30 m thick Volpriehausen Sandstone reservoir. Clay and siltstones are present below and above the Sandstone Member. Questionable if the peak in DT at 3928 m is correct or a measurement error.

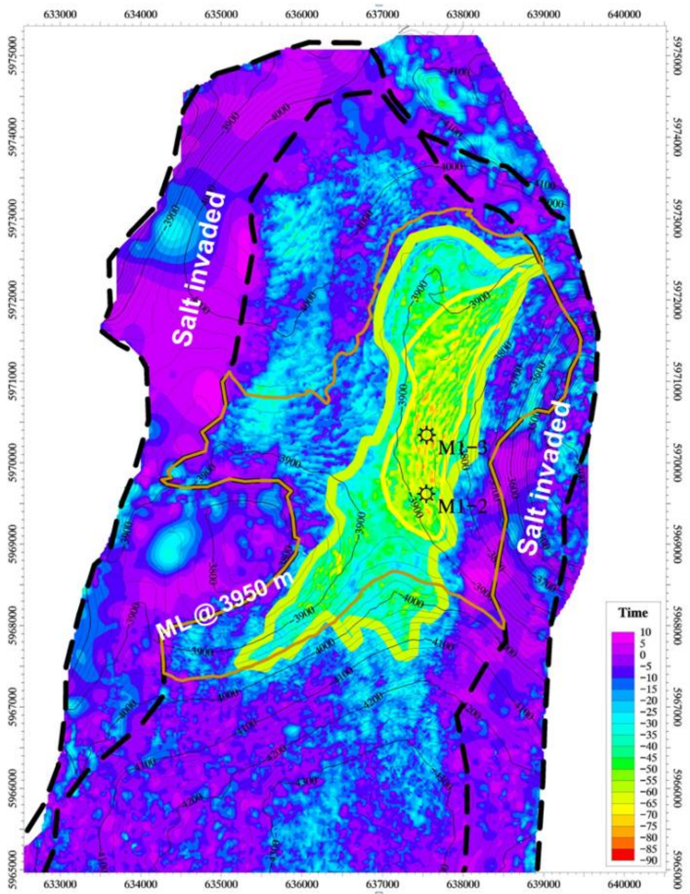


Figure 38 – Maximum peak amplitude map of the Top Volpriehausen Sandstone Member, in the M1-A field. High negative amplitudes are present at the M1-2 and M1-3 well locations. The orange line indicates the ML spill-point at -3950 m.

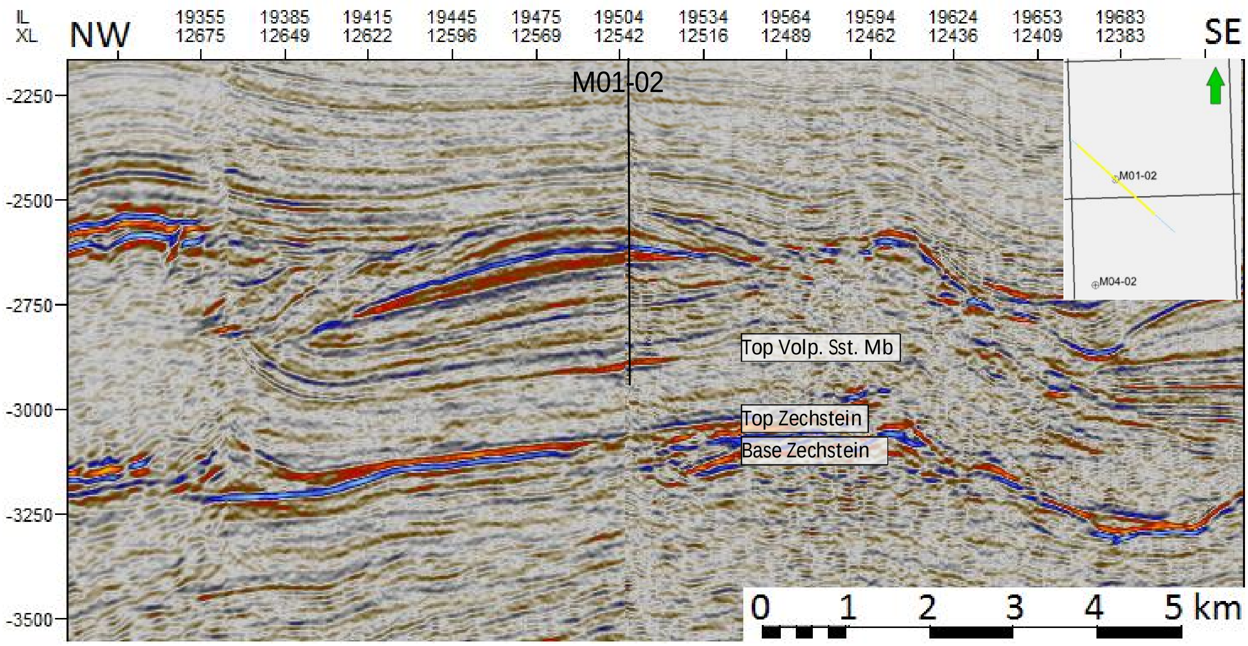


Figure 37 - Seismic section through the M1-A field in the south of the M1 block. A high red reflector (trough) indicates the Volpriehausen Sandstone reservoir.

7.5.5 G16-B

The G16-B field is located in a dipping structure towards the southeast, bounded by a salt wall (Figure 40). Volpriehausen sandstones form a good quality reservoir, with an estimated porosity of 13-15% and a water saturation of 30-35%. The reservoir is approximately 30 m thick and consists of coarse sandstones, with clay- and siltstones above and below. Since no logs were available of wells in the G16-B field, well G16-04 was used as analogue. The depth and thickness in the text and Table 4 are values of the field. The GR on Figure 41 has a blocky appearance, indicating clean sandstone reservoir. The DT log differs compared to DT logs of the other fields, as it has low values (60-70 us/ft) at sandstone levels, and high values (90 us/ft) at claystone levels. The density log shows no differences between the overlying Claystone Member and the Volpriehausen Sandstone Member. There is no reference to salt plugging found in the available data. Gas is currently being produced from this field. The overlying Volpriehausen claystones are top sealing, and the salt wall acts as side seal. Gas likely has migrated from Carboniferous source rocks, along faults and updip into the trap. Figure 42 shows an amplitude map of the base Volpriehausen Sandstone Member (from GDF Suez, 2012). It is difficult to judge the structural conformity due to faults and compartments. The seismic section shows a high trough with high peak below, and a less trough below that.

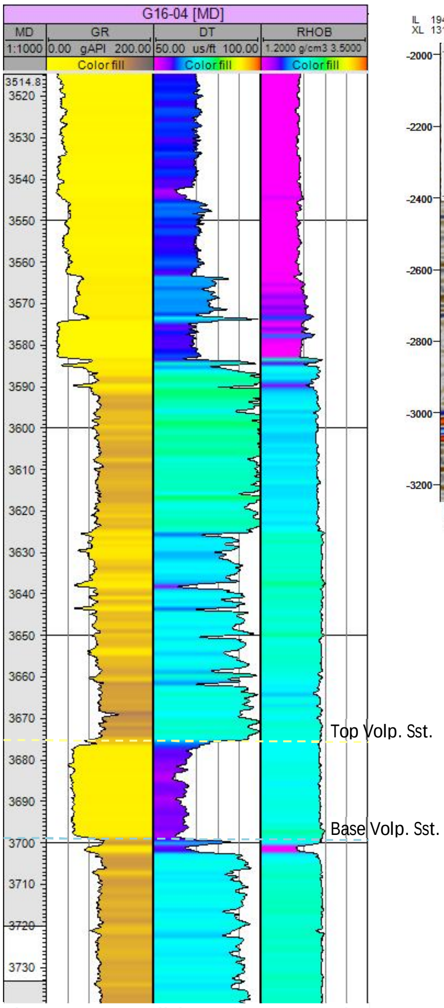


Figure 41 - Well log of G16-04. The Volpriehausen Sandstone member is located at a depth of -3675 to -3699 m. The sandstone member is clearly distinguishable on the DT log, but not on the RHOB.

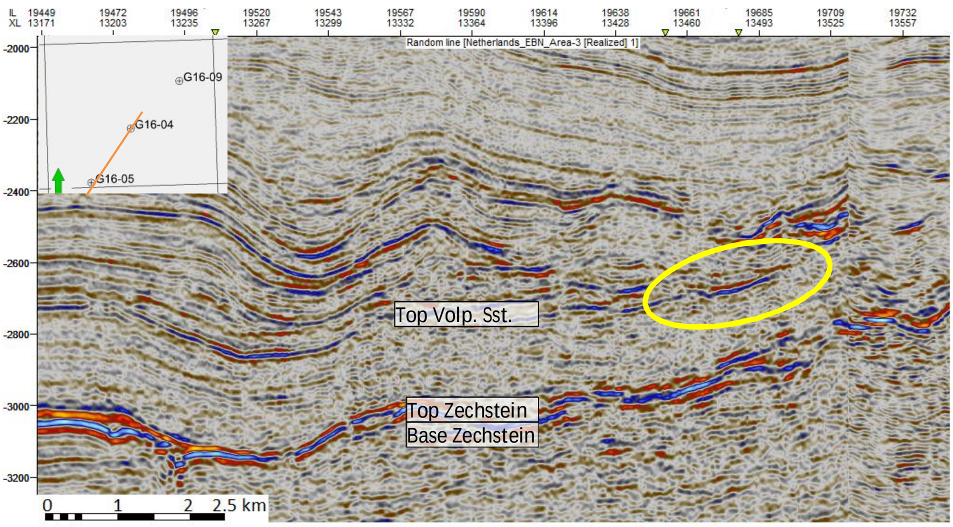


Figure 40 - Seismic section through G16-B. The field is indicated with the yellow circle, the location of the seismic section is indicated in the map view of the G16 block in the upper left corner.

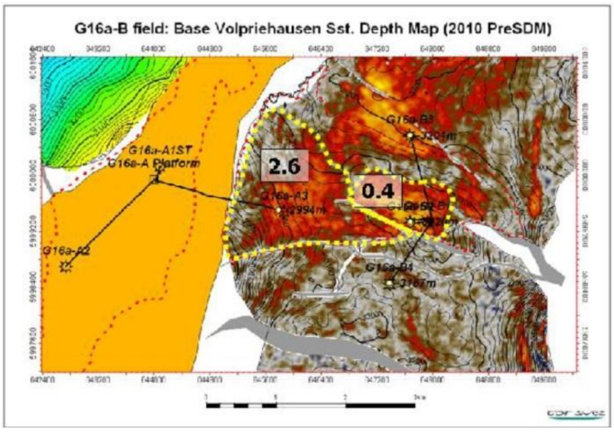


Figure 42 - Amplitude map of the Base Volpriehausen Sandstone Member showing the G16-B field. The 2.6 and 0.4 indicate Volumetric IGIP in BCM. Contours are base Volpriehausen Sandstone depths. From: GDF Suez, 2012.

7.5.6 G14-G17

The currently producing G14-G17 field is located in a NNE-SSW trending syncline, flanked in the east by salt walls. The structure is of Triassic origin, formed by halokinesis, and is truncated by the Base Cretaceous Unconformity. The field is located in the G14 and G17 licence blocks, but this sub-chapter focusses on the G17 part of the field. The Volpriehausen Sandstones form a 25 m thick reservoir (Figure 43), are clearly distinguishable from the over- and underlying claystones, have a blocky appearance on the GR and have high gas shows. The measured porosity is 16.2%, N/G is 92.8%, average water saturation is 17.2%, and the average permeability is 5 mD, in the gas bearing part it is 27 mD (Clyde, 2001). Claystones are not distinguishable from sandstones in the DT log, but they are in the density log. Carboniferous shales and coals are assumed to be the source rock, and the Rifgrunden fault zone (RFZ) likely provided a conduit for gas charge, subsequent to trap formation. Salt plugging is not mentioned in well reports. On seismic the Top Volpriehausen Sandstone Member is a high peak with high trough below (Figure 44).

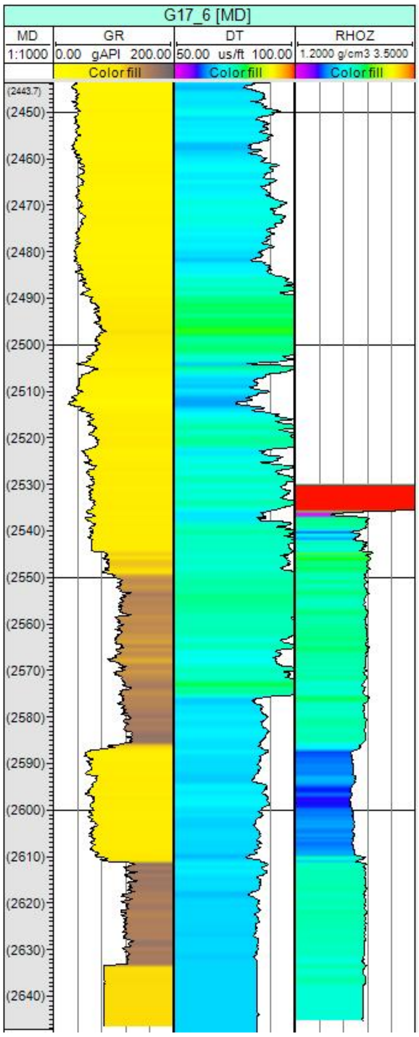


Figure 43 - Well log for the G17 gas field. The Volpriehausen Sandstone Member consists of 25 m of sandstones, with claystones above and below. The Volpriehausen Sst Mb is clearly distinguishable in the density log, but not in the DT.

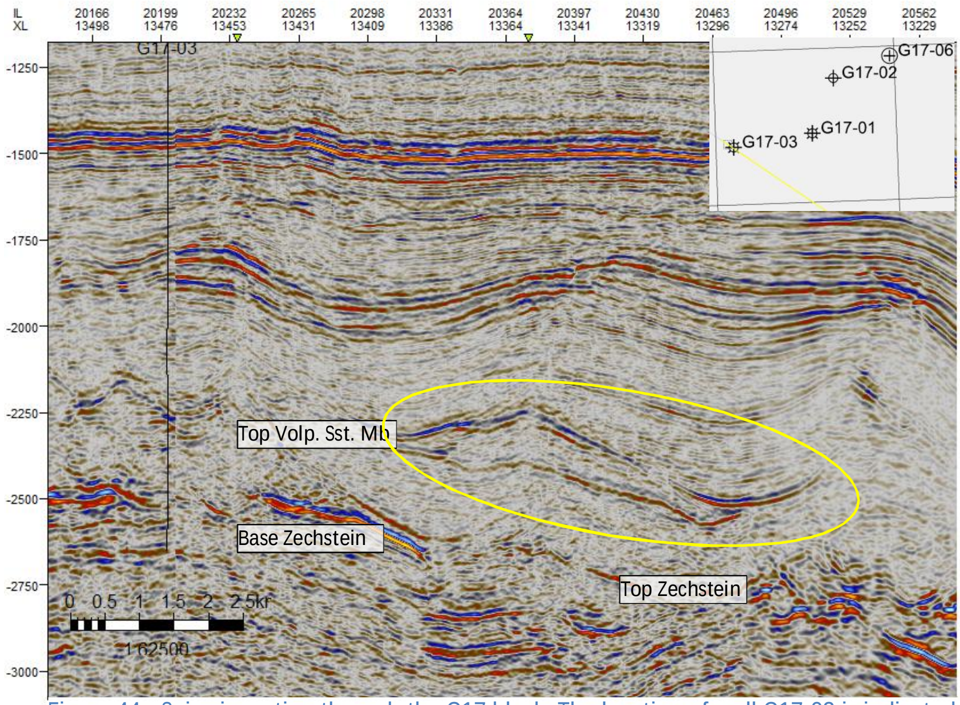


Figure 44 - Seismic section through the G17 block. The location of well G17-02 is indicated. The Top Volpriehausen Sandstone Member is characterized by a trough, with a high peak and less high trough below.

7.5.7 Comparison of the fields

Proven fields in the Volpriehausen sandstones are mainly trapped in turtle-back anticlines or other types of traps related to salt movement of the underlying Zechstein salt. Traps also occur at unconformities. The depth of the Top Volpriehausen Sandstone Member varies between -2926 (G17) and -4224 m (L5-FA). Thickness varies between 25-50 m, and heights of the gas column is 300 m in the L2-FA, G16-B, and G14-G17 fields, 256 m in the F15-A field, and 140 m in the L5-FA field. In M1-A only a minimum column height is known of 32 m. The overlying clay- and siltstones can act as top seal if not faulted, and salt can act as side seal. This can be in the form of a salt wall or as salt plugged reservoir rocks. In all evaluated fields the Carboniferous shales and coals are assumed to be the (mature) source rock. Hydrocarbons can migrate through windows of thin or faulted Zechstein salt, or where salt has been withdrawn. On GR logs Volpriehausen fields are generally recognized by its monotonous and blocky appearance, caused by a constant and almost pure sand content and uniform lithofacies development. DT logs are increased at the sandstone level, indicating good porosities. Density logs typically show slightly increasing densities towards the top and base of the Sandstone Member. From the discussed fields it can be deduced that a gas-filled Volpriehausen reservoir is typically characterized by high amplitude reflectors on seismic. However, it varies and a trough or peak might form the top high reflector (Table 4). According to an operator in the Netherlands, the reservoir quality may be deduced from the amplitudes of the Volpriehausen reservoir. A water or gas bearing reservoir would have a peak as Top Volpriehausen sandstone, followed by a clear trough, a salt-plugged reservoir would have a trough as Top Volpriehausen sandstone, followed by a clear peak, and if a salt-plugged Volpriehausen reservoir is incorrectly picked the top is a clear peak, followed by low energy events. From the discussed fields it can also be concluded that the presence of anhydrite does not rule out the sandstones for being a good reservoir. A partly salt plugged reservoir can still be a good reservoir in the non-salt-plugged part, i.e. salt plugging can be very local. In fact, the salt plugged part can act as a side seal, as seen in M1-A. Table 4 gives an overview of the characteristics of the discussed fields.

7.5.8 Comparison of fields to study area

The Volpriehausen fields are trapped in turtle-back structures, dip-closures against salt walls, or at unconformity traps. These traps are largely similar to potential trapping styles in the study area, which are also 4- and 3-way dip closures, against salt walls, and unconformity traps. The reservoir thickness in the Volpriehausen fields varies between 25 and 50 m, comparable to the Volpriehausen thickness in the study area, which varies between 15 and 75 m. Porosities of the fields outside the study area (7-18%) are lower compared to the porosities measured in the study area (14-28%). The N/G is slightly lower in the study area. Permeability in the study area is known from one well (E09-03) and is with an average of 3.12 mD significantly lower compared to the permeability measured in the fields (Table 4).

Generally, the Volpriehausen fields south of the study area are deeper than the drilled Volpriehausen Sandstones inside the study area. The G14-G17 gas field has the shallowest Volpriehausen reservoir, at -2926 m depth. The other fields have depths varying between -3535 (F15-A) and -4224 m (L5-FA). Wells A18-01 and G07-02 in the study area encountered Volpriehausen Sandstones at depths comparable to depths of the Volpriehausen gas fields south of the study area. The deepest Volpriehausen Sandstone Member drilled in the study area is in F09-03 (-4823 m). The other wells encountered the Volpriehausen Sandstones at shallower depths. The Volpriehausen Sandstones in the undrilled structures will be discussed in the prospectivity review (chapter 8). They

Table 4 - Characteristics of the Volpriehausen gas fields discussed in chapter 7.5.

Field	Structure	Depth of Top Volp. Sst. (m)	Thick-ness	Column	Reservoir quality	Salt plugging	Amplitude	Amplitudes structural conformable
F15-A	Turtle-back anticline	-3535	37 m	265 m	Good, except for the upper unit with high clay content. Por: 8-18% Perm: 0.3-80 mD	Reservoir is partly salt-plugged	Strong trough (red) with a clear peak below (blue)	Amplitude map not available and structural conformity not mentioned in well reports
L2-FA	3-way dip closure against salt wall	-4115	47 m	300 m	Por: 12% Perm: 1-14 mD Water sat: 60%	Anhydrite cementation recorded from wells on and flanking the L2-FA structure	Peak with strong trough below, and less high peak below that	Yes (amplitude map is confidential)
L5-FA	An elongate, slightly faulted turtle-back	-4224	50 m	140 m	Porosity: 0-9% Perm: 0.01-33.6%	Halite cementation due to saline groundwater. Anhydrite is less dominant	Strong peak with strong trough below	Amplitude map not available. Structural conformity is not mentioned in reports, except that the FWL has caused an amplitude switch-off on seismic.
M1-A	Stratigraphic trap at flank of salt dome	-3918	30 m	> 15 m	Average por: 7% N/G: 94% Water sat: 34% 15 m gas column	The reservoir is salt-plugged in the E and W of the field, acting as side-seal	Strong trough (red reflector) with less clear peak below	Amplitudes are not entirely conform
G16-B	Dipping structure bounded by salt wall	-3610	30 m	300 m	Porosity: 13-15% Water sat: 30-35%	No salt plugging	High trough with high peak below, and less trough below that	Not entirely conform
G14-G17	Flank of syncline overlain by unconformity, bounded by salt wall in east	-2926	25 m	300 m	Porosity: 16.2% Perm: 5-27 mD N/G: 92.8% Water sat: 17.2%	No salt plugging	Trough with high peak and less high trough below	Amplitude map not available, and structural conformity is not mentioned in well reports.

generally have depths comparable to the Volpriehausen gas fields south of the study area, with a few exceptions (Table 5).

The clay-content in the Volpriehausen Sandstone increases in northern direction when comparing the well logs of the study area and the fields (Figure 45, Figure 47). The dry wells in the study area have higher clay content within the Volpriehausen Sandstone Member, whereas the fields show clear sands with a blocky GR appearance. Also the DT log shows significant differences. The high DT log of the L2 well at Volpriehausen Sandstone level indicates a good porosity. The F04-02-A well has an irregular DT log, indicating a varying porosity due to the alternation of sands and clays within the Sandstone Member, or higher water contents within the claystones, due to lack of compaction. The higher clay-content within the Sandstone Member in the study area also shows in the density log, which has an increased number of high intervals compared to the density log of the L2 gas field (Figure 45).

Another difference between the fields and the study area is the thickness of the Zechstein salt. South of the study area salt windows exist where the salt has withdrawn, and faulting is assumed to be high enough to provide migration paths through the salt, as seen in the discussed fields. However, in the entire study area Zechstein is present below the Volpriehausen. But there are places in the study area where the Zechstein salt is thin or grounding. Faults in the Zechstein in the study area can be seen on seismic, but uncertain is whether these faults form a migration path for hydrocarbons.

The seismic character of the Volpriehausen Sandstone Member differs in the study area, compared to the Volpriehausen gas fields outside the study area (Figure 46). Generally, in the study area the Top Volpriehausen Sandstone Member is characterized by a peak, followed by a trough and a less high peak. Locally, polarity flips might occur, e.g. due to salt plugging as seen in Figure 21. In the Volpriehausen fields the seismic character differs per field; in F15-A and M1-A the top high amplitude reflector is a trough instead of a peak. The brightness in Figure 46b-e compared to Figure 46a results from the reservoir being gas-filled.

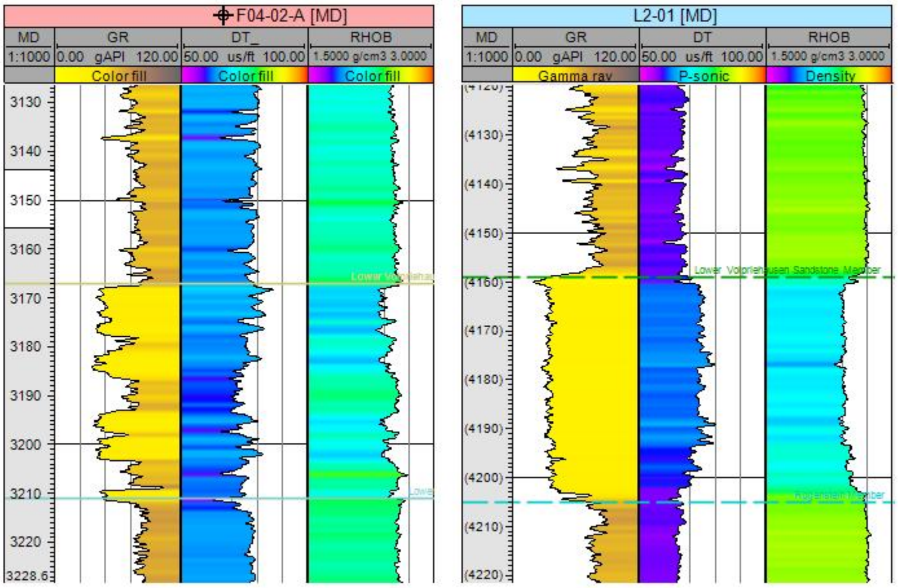


Figure 45 - Well logs of the Volpriehausen Sandstone Member of a dry well in the study area (F04-02-A) and a well of a gas field outside the study area (L2-01).

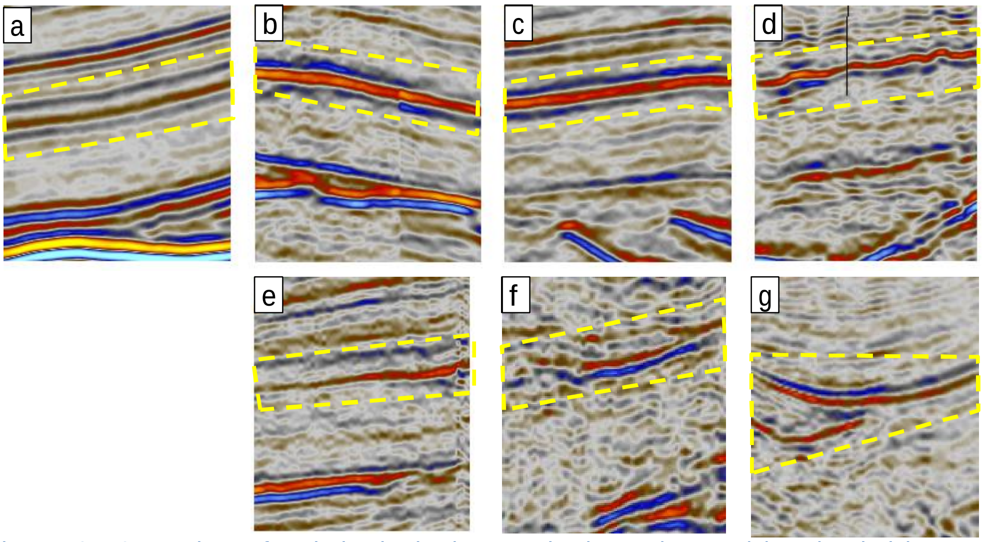


Figure 46 - Comparison of typical seismic character in the study area (A) and Volpriehausen Sandstone gas-fields outside the study area. B: L2-FA, C: L5-FA, D: F15-A, E: M1-A, F:G16-B, G: G17. Red reflectors are troughs, blue reflectors are peaks.

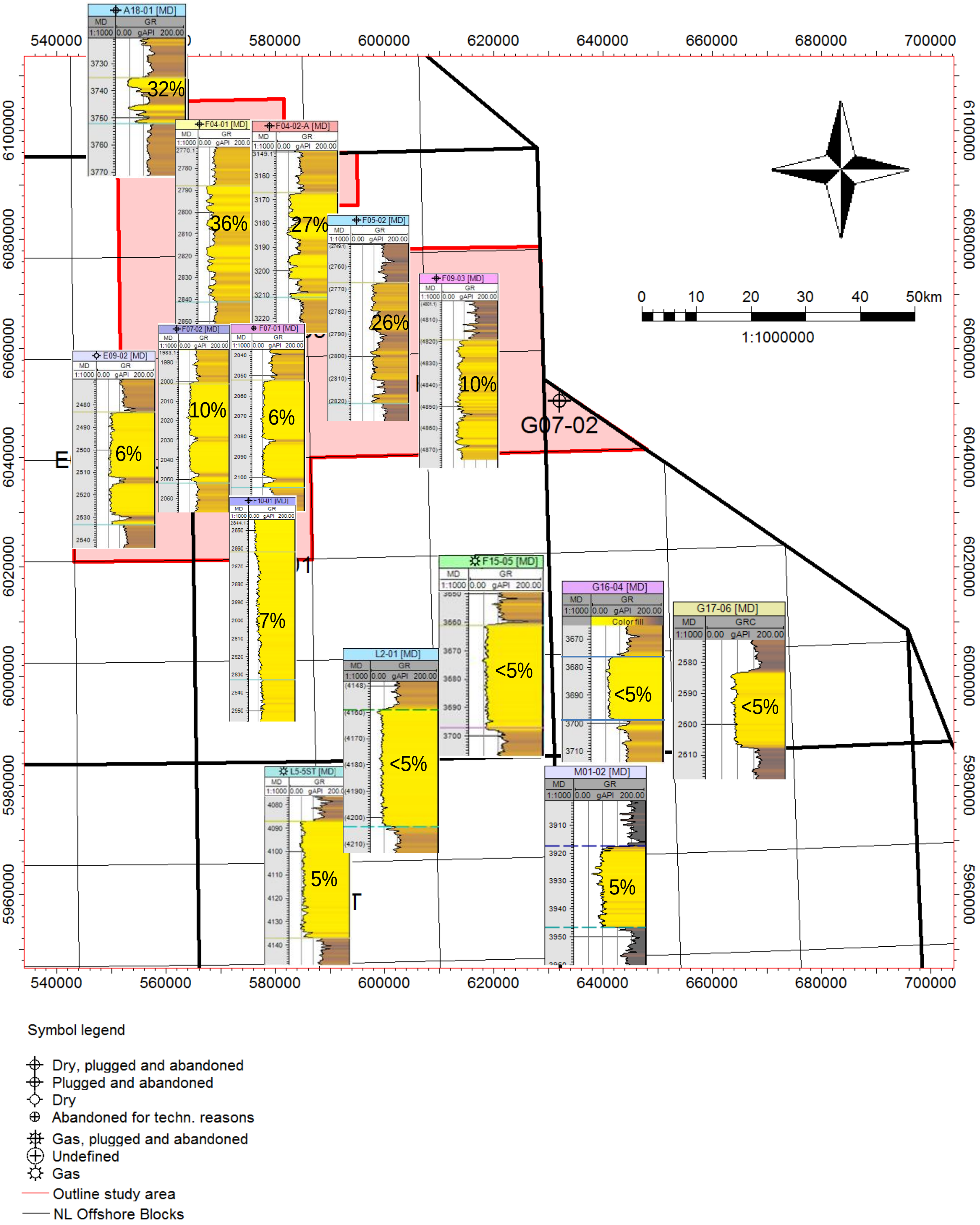


Figure 47 - Map of the study area and well locations south of the study area, showing GR logs of the Volpriehausen Sandstone Member at well locations, if available. The scale of the logs is 1:1000 (MD), and 0-200 gAPI on the x-axis. Also, an approximation of the clay-content (in percentages) within the Volpriehausen Sandstone Member is shown per log. This shows a trend of increasing clay-content towards the north.

7.6 Dry well analysis

A dry well analysis has been performed on twelve wells in the study area that encountered the Volpriehausen Sandstone Member. The locations of these wells are shown in Figure 48. This chapter covers the dry well analysis by describing the different aspects of a play, summarized in color-coded maps. A more extensive version of the dry well analysis can be found in the Appendix (A5), including a table with details per well, seismic sections, well logs and more detailed depth maps for the twelve wells discussed in this dry well analysis.

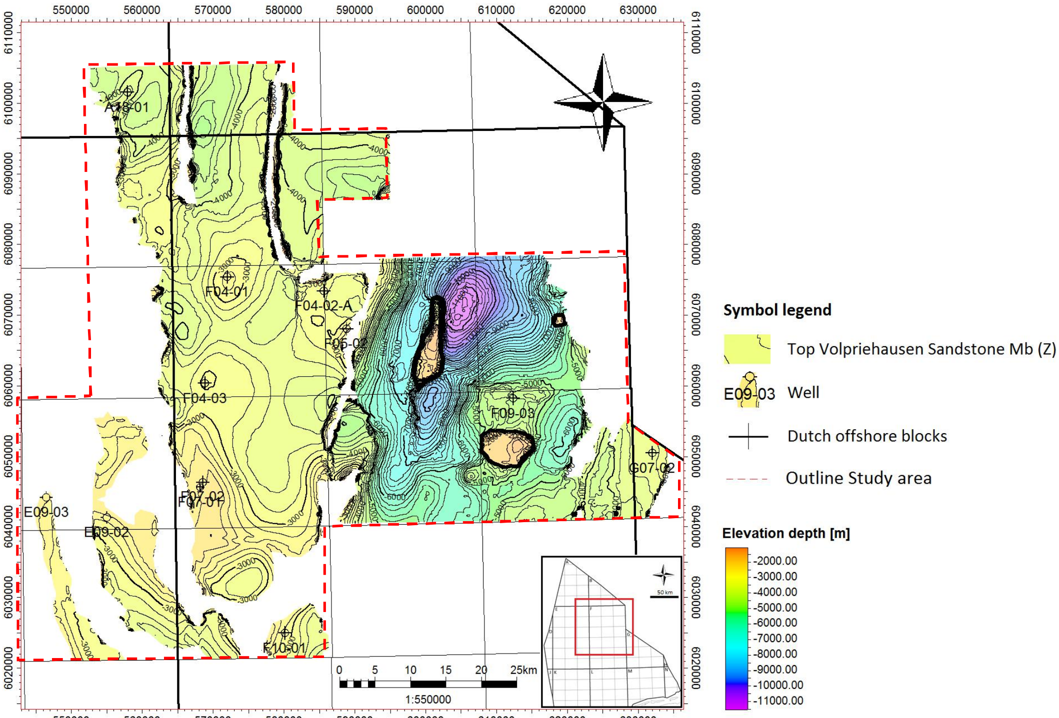


Figure 48 - Depth map of the Top Volpriehausen Sandstone Member, showing the locations of the 12 wells used for this dry well analysis.

The first aspect to a play is the structure; whether the trap forms a structural high and has closing contours or forms a valid trap in another way in the depth domain. The trap effectiveness for twelve wells in the study area is shown in Figure 49. Three wells in the south of the study area drilled an unconformity trap (E09-02, E09-03 and F10-01), two wells drilled a four-way dip-closure (F04-01 and F04-03), five wells drilled a three-way dip-closure against a salt wall (A18-01, F05-02, F07-01, F07-02 and G07-02), one well drilled a large plateau-like structure (F09-03) and one well lacked a valid structure at Volpriehausen level (F04-02-A). Wells without valid structure and without closing contours are indicated with red dots on Figure 49. Orange dots indicate that the well was drilled far (>50 m) down-dip from the crest of the structure.

Not all wells have been drilled on the structures' crest. An updip potential was estimated, from entry depth to the crest of the structure, when the well was drilled within closing contours of the structural high. A cut-off of 25 m was used; less was considered a too small value for updip potential. At well locations F04-01 and F04-03 the well drilled the Volpriehausen Sandstone Member at the crest of the structure, but due to a possibly breached top-seal there is a remaining potential at shallower stratigraphic levels, e.g. the Detfurth and Solling sandstones. In some cases (F10-01 and G07-02) the updip potential is unknown because the contours exceed the outline of the DEF seismic survey. The remaining and updip potential per well is indicated on Figure 49 in textboxes.

The second aspect is reservoir, which is generally present in the study area, except over salt domes where the Volpriehausen Sandstone has been eroded (Figure 50). The reservoir quality is indicated with plusses and minuses in this map. One plus indicates a neutral situation, in some cases due to a lack of more details about the reservoir quality. The reservoir thins towards the north, from 75 m to 17 m in A18-01. Anhydrite is expected to have influenced the reservoir quality in a negative way in F09-03 and E09-02, which is the reason for the minuses at these locations. F04-01 and F04-02-A have relatively high clay-contents, opposed to F07-01 and F07-02, which have a much lower clay-content (Figure 47, Figure 50). It should be noted that no completely tight (fully salt-plugged) reservoirs were encountered in the study area, and that reservoirs of lower quality (marked by a minus in Figure 50) cannot be excluded from being possibly partly gas filled.

Figure 51 shows the charge, which includes the presence of source rocks, timing and presence of migration paths. Carboniferous source rocks are assumed to be present throughout the entire study area, but may be over-mature in the Dutch Central Graben. Zechstein salt often forms a barrier between these source rocks and the Volpriehausen sandstones. Therefore, the presence of migration paths forms the largest uncertainty concerning the charge aspect. When a salt window is visible on seismic or fault movement was large enough that the reservoir is juxtaposed against pre-Zechstein stratigraphy, a migration path may be present. Even then, still the lower Bunter Shale, Zechstein Claystone and Slochteren shale need to be crossed. A vast majority of the well locations shows a faulted Zechstein sequence on seismic, but lacks juxtaposition of pre- and post-Zechstein sediments. In these cases it is uncertain whether a migration path is present. Beneath E09-02 and E09-03 Zechstein salt seems to be thin on seismic, however, no gas has been encountered. Near A18-01 and F04-01 the Zechstein seems to be grounding, but also no gas has been encountered in these wells. According the EBN database, no gas shows are present in drilled Volpriehausen Sandstones in the study area. Only in F04-03 and G07-02 (Figure 52) trace gas was encountered, which indicates that it is or has been possible for gas to migrate into or along the Volpriehausen Formation at these locations.

Figure 53 shows the seal presence and effectiveness. The Volpriehausen Clay-Siltstone Member is overlying the Volpriehausen Sandstone Member in most cases, which acts as top-seal if not breached. Faults, if present, form a risk as possible migration paths to shallower levels. Salt walls can act as side-seal (F04-02-A, F05-02, G07-02) and a (partly) salt-plugged reservoir can also be an effective side-seal. In three wells (E09-02, E09-03 and F10-01) the Volpriehausen Sandstone reservoir is cut off by Cretaceous sediments at an unconformity, where the Vlieland Claystones can be top-sealing. The Volpriehausen Clay-Siltstone Member is overlying the reservoir in these three wells without breaches.

The wells E09-03, F04-01, F04-03 and F05-02 are evaluated to be a valid negative test. In all these wells it is questionable whether charge is taking or has taken place, but the other aspects (trap, reservoir, seal) were tested positive. It should be noted that the seal of F04-01 and F04-03 might be breached a little, as can be seen on seismic, but uncertain is whether this actually provides a leaking path to shallower levels. The valid negative tested wells are indicated in Figure 54.

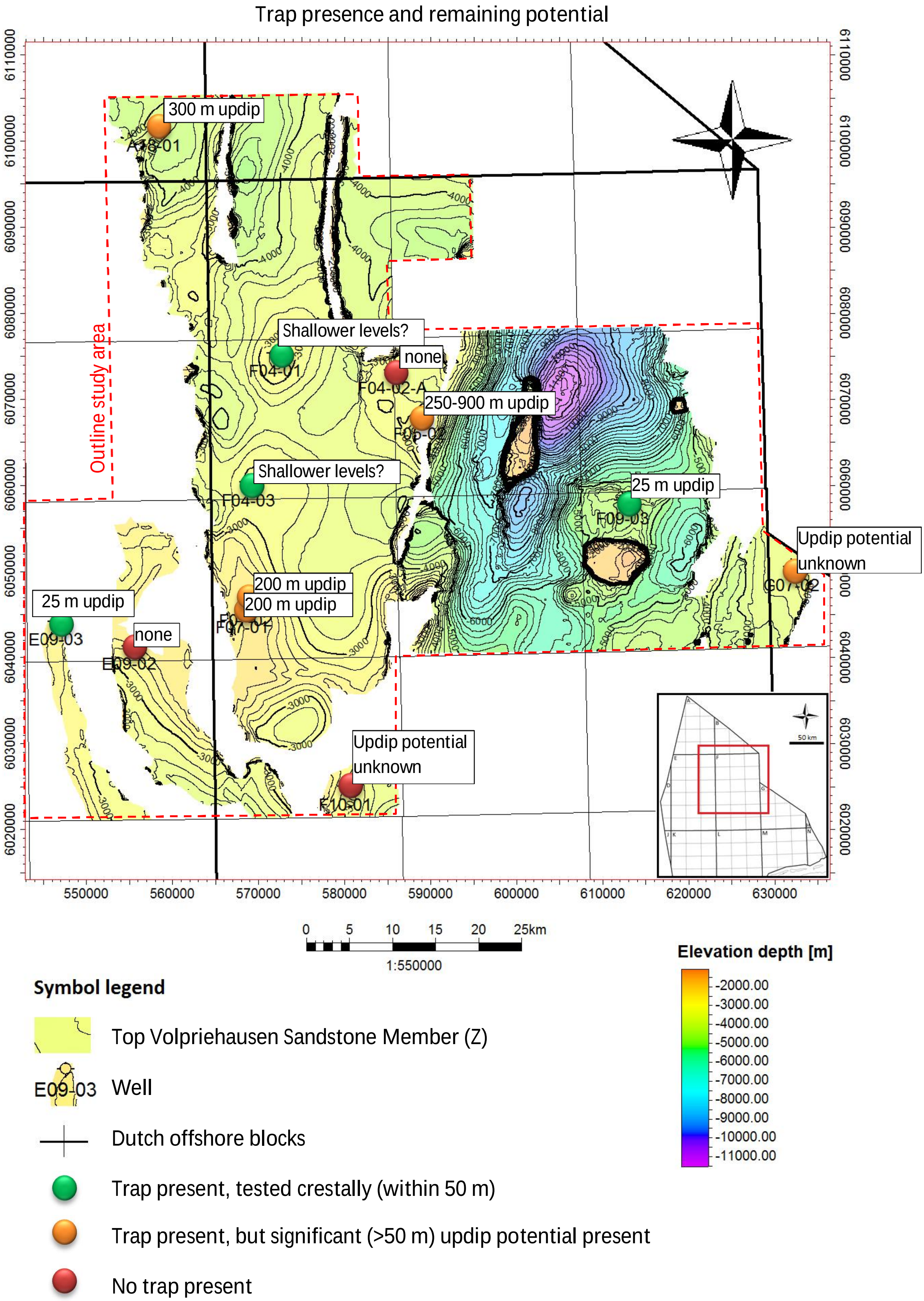


Figure 49 - Depth map of the Top Volpriehausen Sandstone Member, showing the trap presence at 12 well locations in the study area. A green dot indicates a valid trap, which has been tested within 50 m of the crest. An orange dot indicates a trap present, but with significant updip potential from the entry depth to the crest (>50 m). A red dot indicates trap absence at the well location, or the structure is unknown due to contours exceeding the DEF survey (F10-01). Updip potential is also partly unknown for G07-02, as no German seismic data are available north of G07-02. Textboxes at the well locations indicate the amount of updip potential. 'Shallower levels' means that the well was drilled at the crest of the structure, but due to a possibly breached top-seal there is a remaining potential at shallower lithostratigraphic levels.

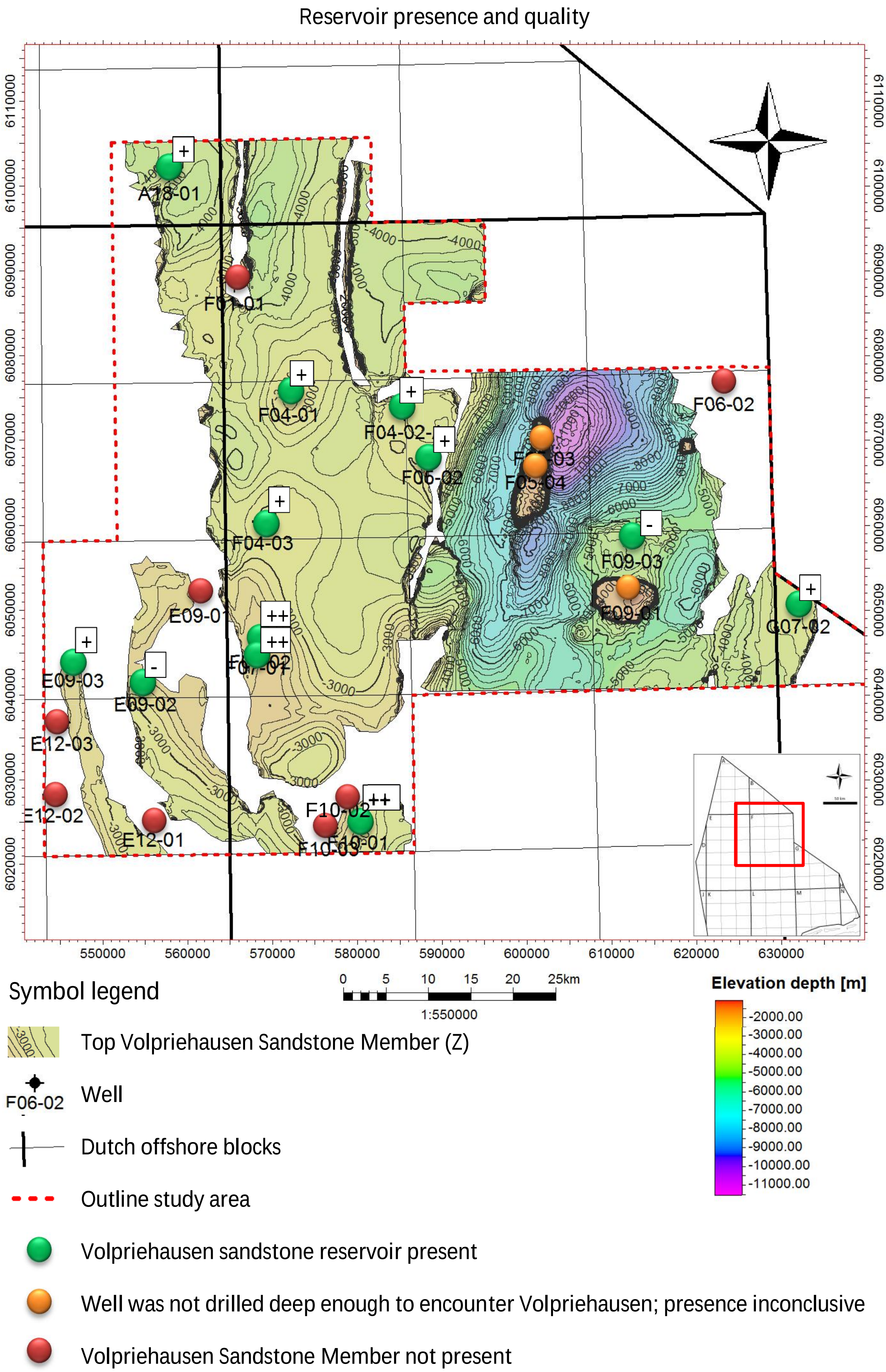


Figure 50 - Depth map of the Top Volpriehausen Sandstone Member, showing the reservoir presence at well locations in the study area. A green dot indicates the presence of a Volpriehausen Sandstone reservoir. The plusses and minuses indicate the reservoir quality at these locations, corresponding to a good (+), very good (++) and less (-) reservoir quality. It should be noted that the reservoirs marked by a minus are not completely tight, and therefore may not be excluded from the possibility of partial gas fill. An orange dot indicates the presence of a well, but that the well was not drilled deep enough to encounter Volpriehausen. A red dot indicates the absence of a Volpriehausen Sandstone reservoir at this well location.

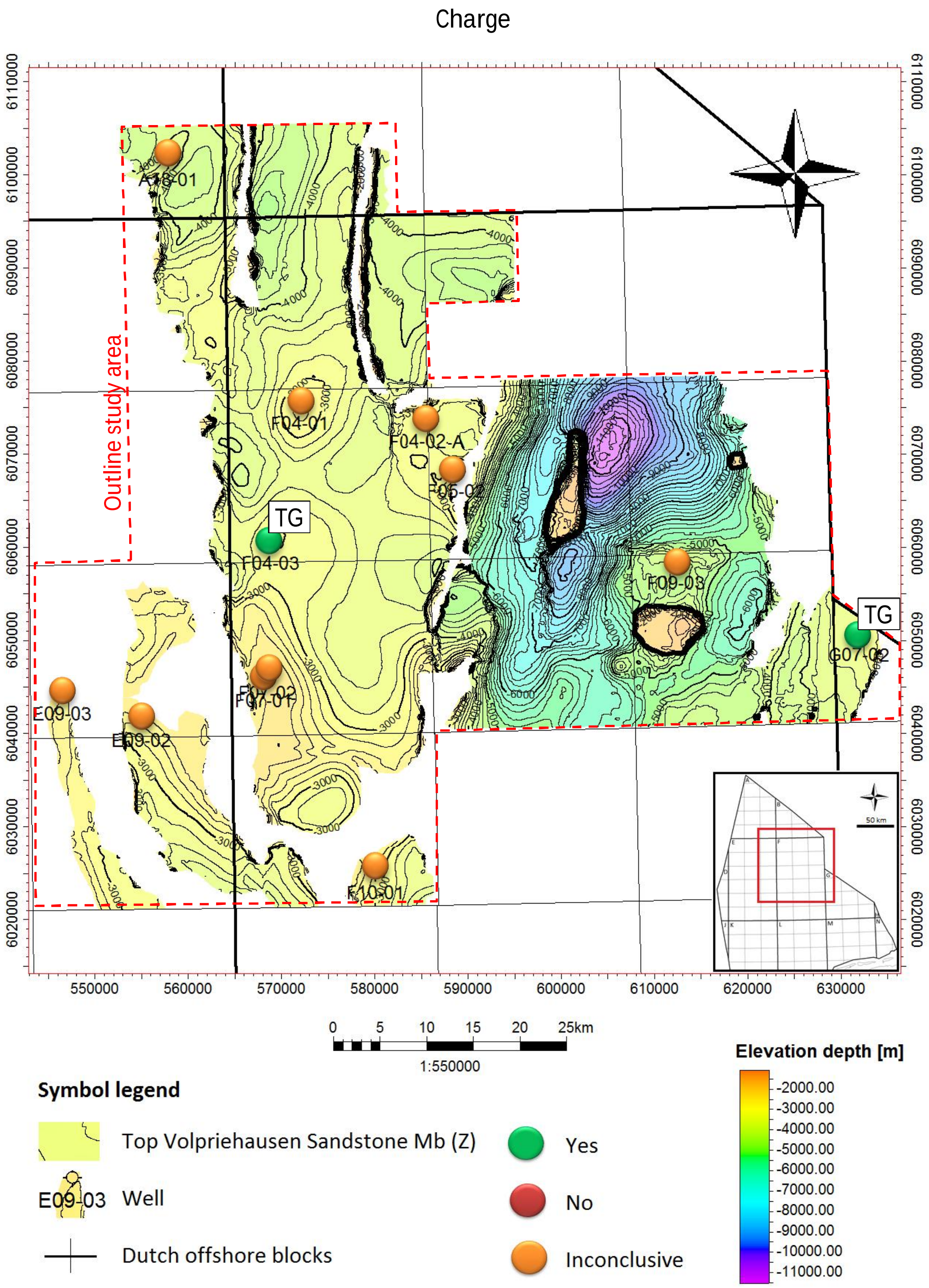


Figure 51 – Depth map of the Top Volpriehausen Sandstone Member, showing charge (with the presence of migration paths as decisive factor), indicated by colored dots at well locations. Green dots indicate that indications exist that there has been charge (TG=trace gas), red dots indicate that charge was not possible, and orange dots indicate that it is uncertain whether charge was possible or not. The latter is true for most cases. Except for the trace gas found in F04-03 and G07-02, no wells have gas/oil shows in the Volpriehausen (EBN database).

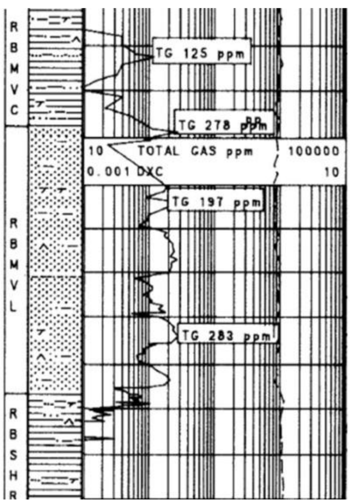


Figure 52 - Formation evaluation log (from NLOG) of the G07-02 well showing trace gas readings in the Volpriehausen Sandstone (RBMVL), on a logarithmic scale. This indicates it is or was possible for gas to migrate into/along the Volpriehausen Formation.

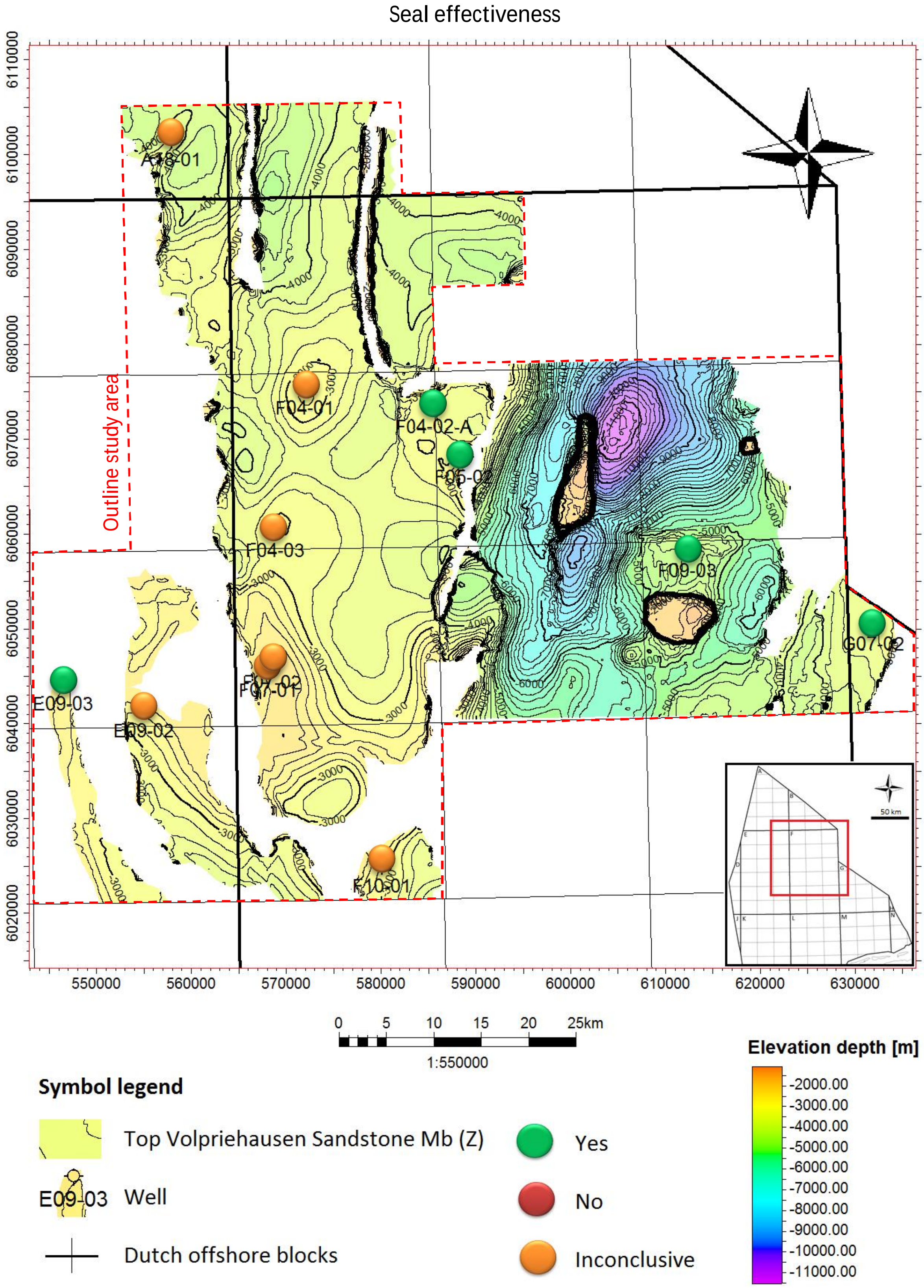


Figure 53 – Depth map of the Top Volpriehausen Sandstone Member, showing the seal effectiveness at well locations, indicated by colored dots. A green dot indicates an effective seal, a red dot indicates the absence of a seal, and orange dots indicate that the seal effectiveness is uncertain.

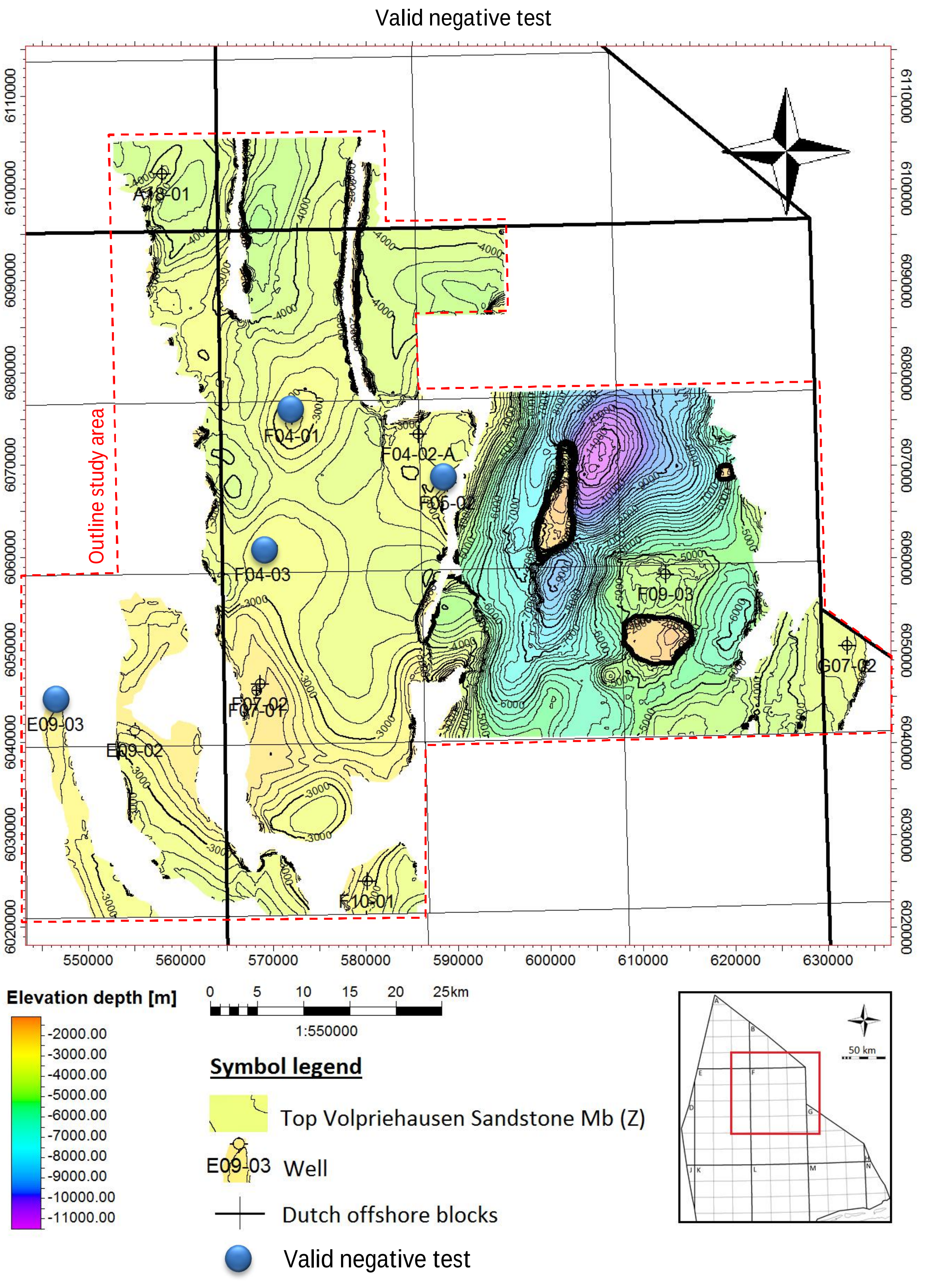


Figure 54 - Depth map showing the wells with a valid negative test, indicated with blue dots. For further explanation, see text.

7.7 Salt plugging

The reservoir quality of the Volpriehausen sandstones can be reduced locally due salt plugging. Cementation of predominantly halite, anhydrite and dolomite can decrease porosity and permeability by significant amounts. It occurs in reservoirs overlying salt or juxtaposed to salt diapirs. Salt plugging is of secondary origin, since no indications exist for primary evaporite deposition in the Volpriehausen (Dronkert et al., 1989), and seepage of overlying Röt salt seems unlikely due to intermediate clay and silt barriers. Therefore, it is most likely that salt precipitated when salt structures pierced the Triassic formations during the Late Jurassic, and the Main Buntsandstein came in close contact with Zechstein salt (Dronkert & Remmelts, 1996). Additionally, flowing of Zechstein salt results in accumulation in diapirs and depletion of salt between diapirs. This can create migration paths for hydrocarbons, but also for saturated brines from the underlying Silverpit Formation into the permeable Volpriehausen sandstones. This results in a lateral flow in the reservoir towards the diapirs. A temperature decrease towards the salt diapir causes the brine to cool down and precipitate, resulting in salt plugging of the pores. The amount of salt plugging decreases with distance from the diapir (Van Bergen & De Leeuw, 2001). According to Dronkert & Remmelts (1996) salt plugging is restricted to less than 1.5 km from the salt dome or ridge, at a depth of 1-2 km. Salt plugging in the Buntsandstein occurs primarily by halite, anhydrite and dolomite cementation. Halite and anhydrite cementation is texturally selective, and generally occurs in the lithofacies with the best primary porosity and permeability characteristics. Consequently, dune sandstones, which are the best reservoirs, are cemented first by halite. Sand sheets or damp aeolian sandflats are mainly cemented by anhydrite. Dolomite is often enclosed by both anhydrite and halite, and occurs predominantly in finer grained laminae (Purvis & Okkerman, 1996).

Salt plugging of the Volpriehausen sandstones in the Northern Dutch offshore has been detected in the F15-A, L2-FA, L5-FA, and the M4 fields (Brown et al., 2001) (See chapter 7.5). A partly salt plugged reservoir can still be a good reservoir, which is, for example, the case at the F15-A field. Moreover, a completely salt plugged part of the reservoir can act as a seal for underlying reservoir rocks.

Salt plugging may be recognized on seismic. An amplitude decrease and seismic phase change can be an indication of salt plugging. Polarity reversal can occur when the reservoir is completely salt plugged. However, it remains difficult to recognize a salt plugged reservoir without well data, because high amplitudes can also indicate a gas-filled reservoir or a reservoir with good porosity (EBN database). However, a gas-filled reservoir is represented by a soft-kick, whereas a completely salt plugged reservoir is represented by a hard-kick (if interpreted correctly). According to an operator in the Netherlands the top of a salt-plugged Volpriehausen Sandstone reservoir is characterized by a clear through, followed by a peak (Figure 58). If a salt-plugged Volpriehausen Sandstone reservoir is picked incorrectly, the Top Volpriehausen Sandstone Member is a clear peak, followed by low energy events. To find out where in the study area salt plugging could be present an amplitude extraction was done in a window of 20 ms above the interpreted Top Volpriehausen (Figure 55) and at the interpreted Top Volpriehausen Sandstone (Figure 56), assuming this method may be valid in the study area. Areas showing a clear through (high red amplitudes) in Figure 55 and also a clear peak in Figure 56 are areas with a risk of being salt plugged, indicated in Figure 57. In these 'risk areas' other indications of salt plugging were searched for on seismic, but polarity reversals are difficult to detect, especially if lithologies are breached.

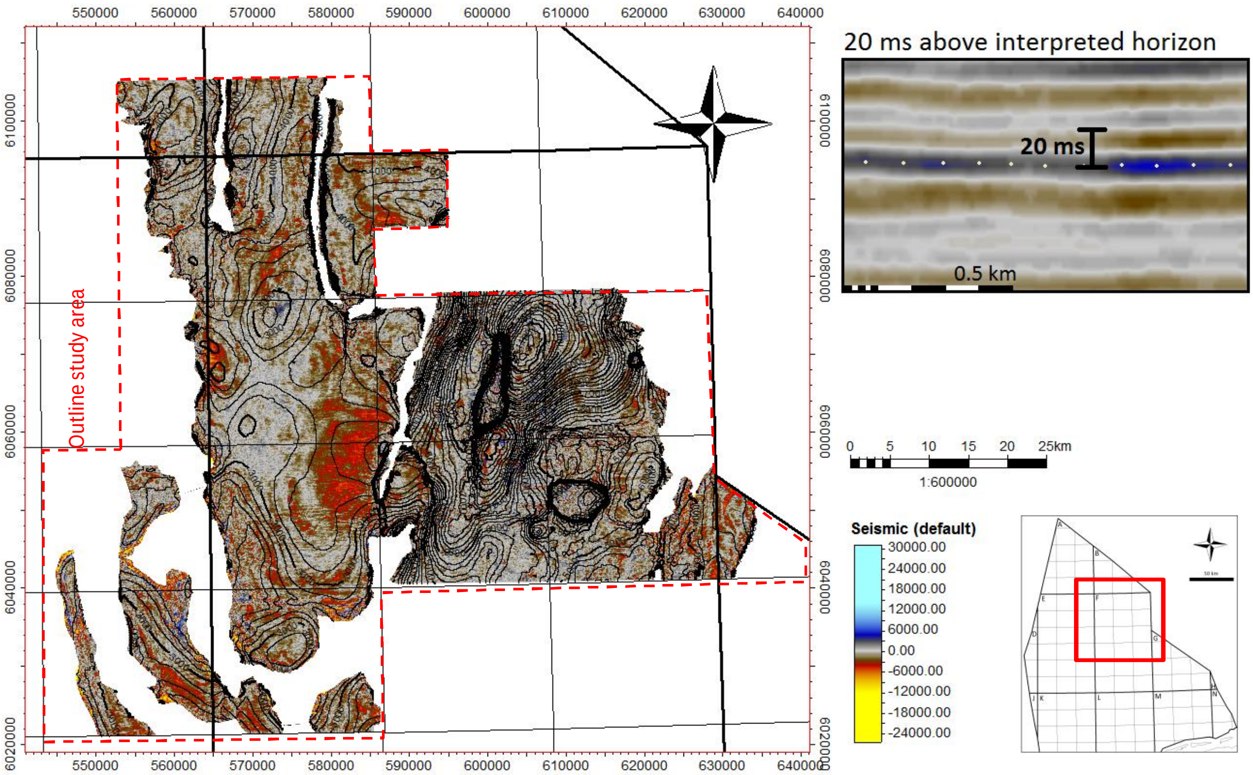


Figure 55 - Extracted amplitude in window of 20 ms above interpreted Top Volpriehausen Sandstone Member. Red amplitude indicates trough. Depth contours have an interval of 100 m.

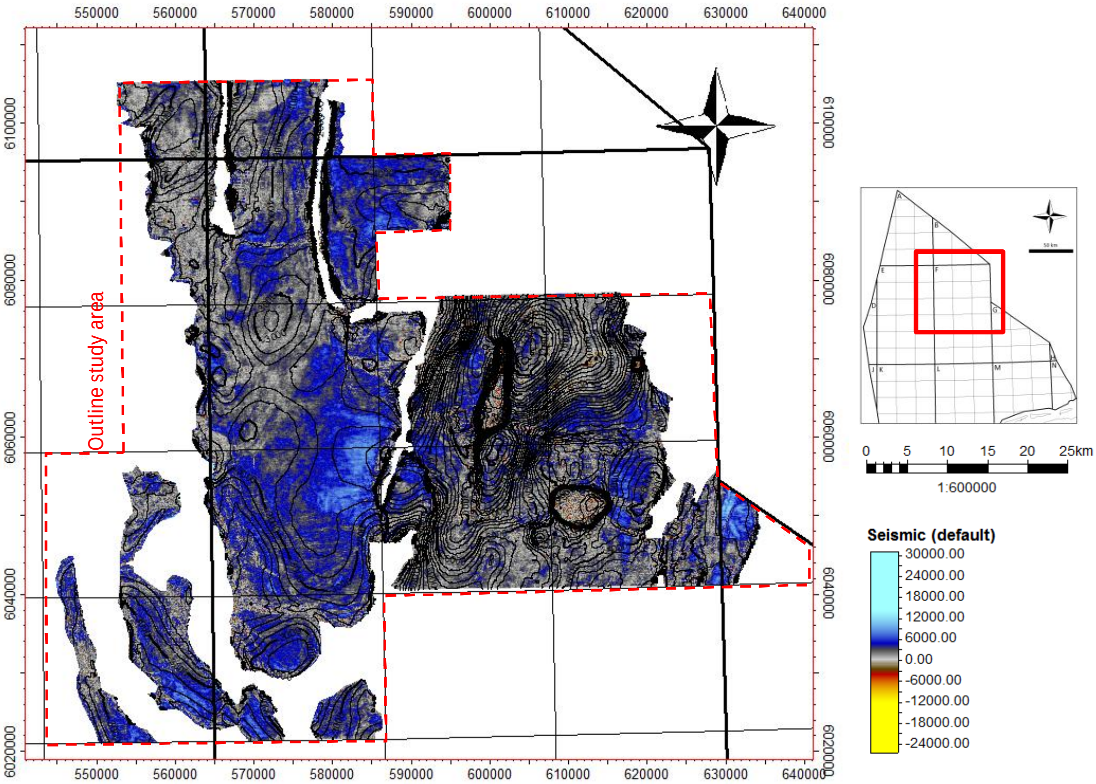


Figure 56 - Extracted amplitude at interpreted Top Volpriehausen Sandstone Member (no window). Blue amplitude indicates peak. Depth contours have an interval of 100 m.

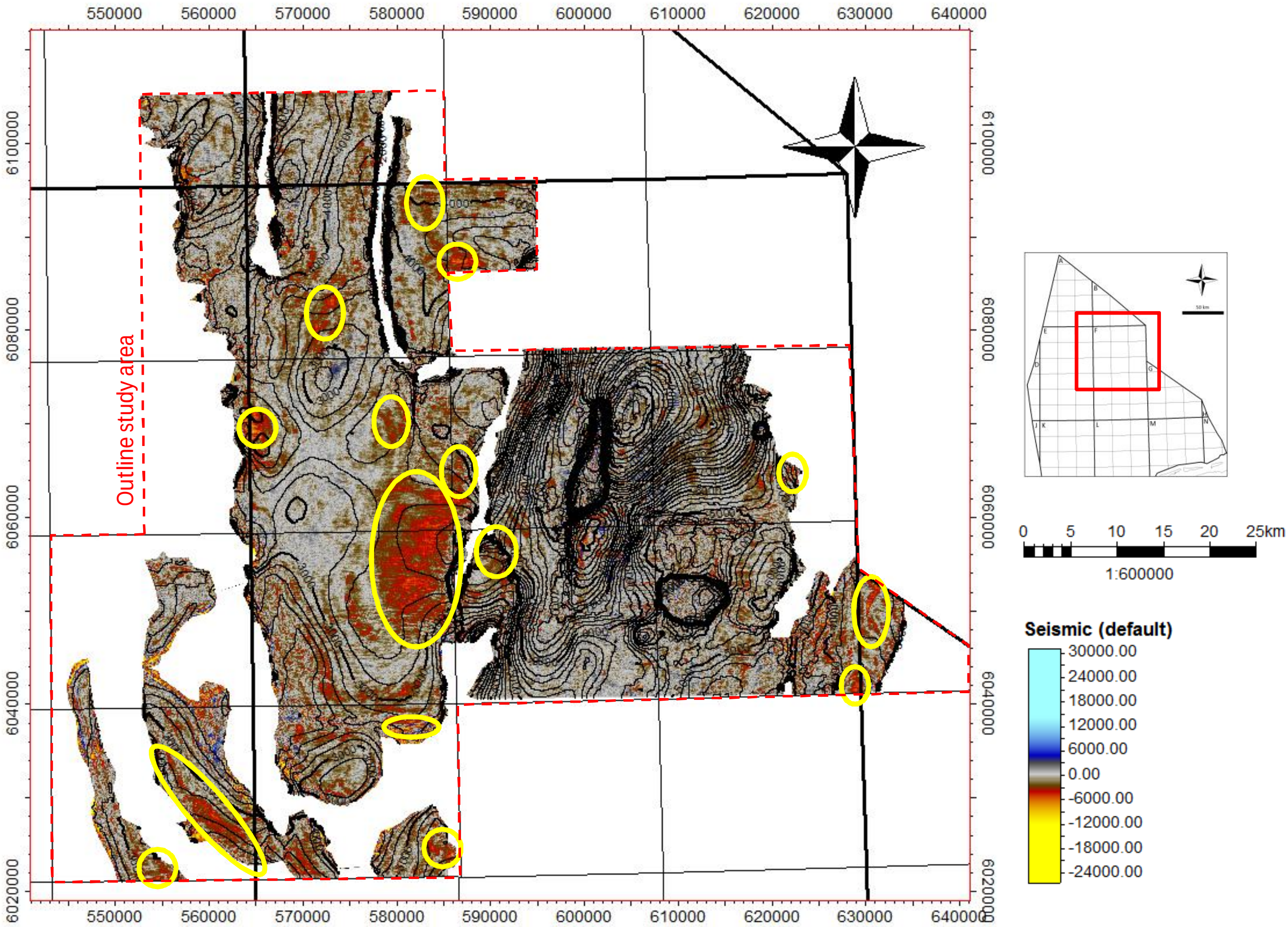


Figure 57 - Maximum amplitude map (window: 0/+20 ms) showing the risk areas for salt plugging, indicated with yellow circles, based on amplitudes. In this map red amplitudes indicate troughs. Depth contours have an interval of 100 m.

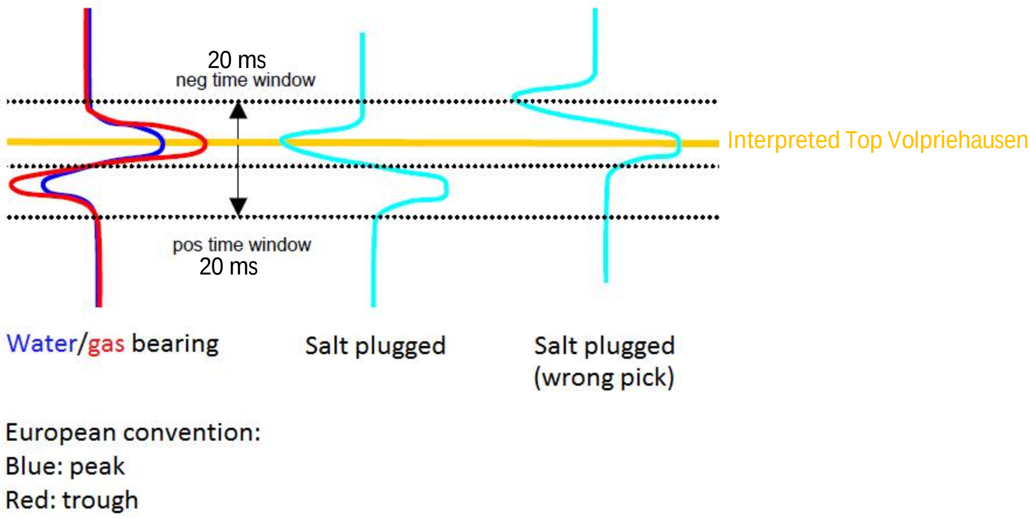


Figure 58 - Seismic characteristics of Volpriehausen Sandstone reservoirs. A good quality reservoir (porous and water/gas bearing) has a peak, followed by a clear trough. A gas-bearing reservoir is brighter than a water filled reservoir. A salt-plugged reservoir is characterized by a trough, followed by a peak. A correctly picked salt-plugged reservoir is picked at the trough and has a strong peak below, a wrongly picked salt-plugged reservoir is picked at the peak and has a strong trough above. The amplitude extraction of figures 52-54 is based on the wrongly picked salt-plugged reservoir characteristics.

8. Prospectivity Review

In this chapter the prospectivity of the Volpriehausen Sandstone in the study area will be shown in the form of 16 leads. These leads are undrilled closures and updip potentials of dry wells (chapter 7.6, Appendix A5). The locations of the leads are shown in Figure 59 and Table 5 gives an overview of their characteristics. Amplitude maps and associated seismic sections for each lead are enclosed in Appendix A6. Along the edges of the interpreted Volpriehausen Sandstone Member, bordering salt walls, are elevations resulting from 3D auto-tracking during seismic interpretation (orange borders in Figure 59). These elevated areas have been studied and are ignored in this prospectivity review if not a valid lead. Nine leads have a 3-way dip closure against a salt wall as structure, six are 4-way dip-closures, and one lead is a truncation trap below the Base Cretaceous unconformity (Table 5). Amplitudes were checked for structural conformity. Reservoir thickness was estimated based on the thickness map of the Volpriehausen Sandstone Member (Figure 9), and height of the structure was determined from the top Volpriehausen depth map. Table 5 shows the main risk for each lead. Charge is a risk for the entire study area and is therefore mentioned at every lead.

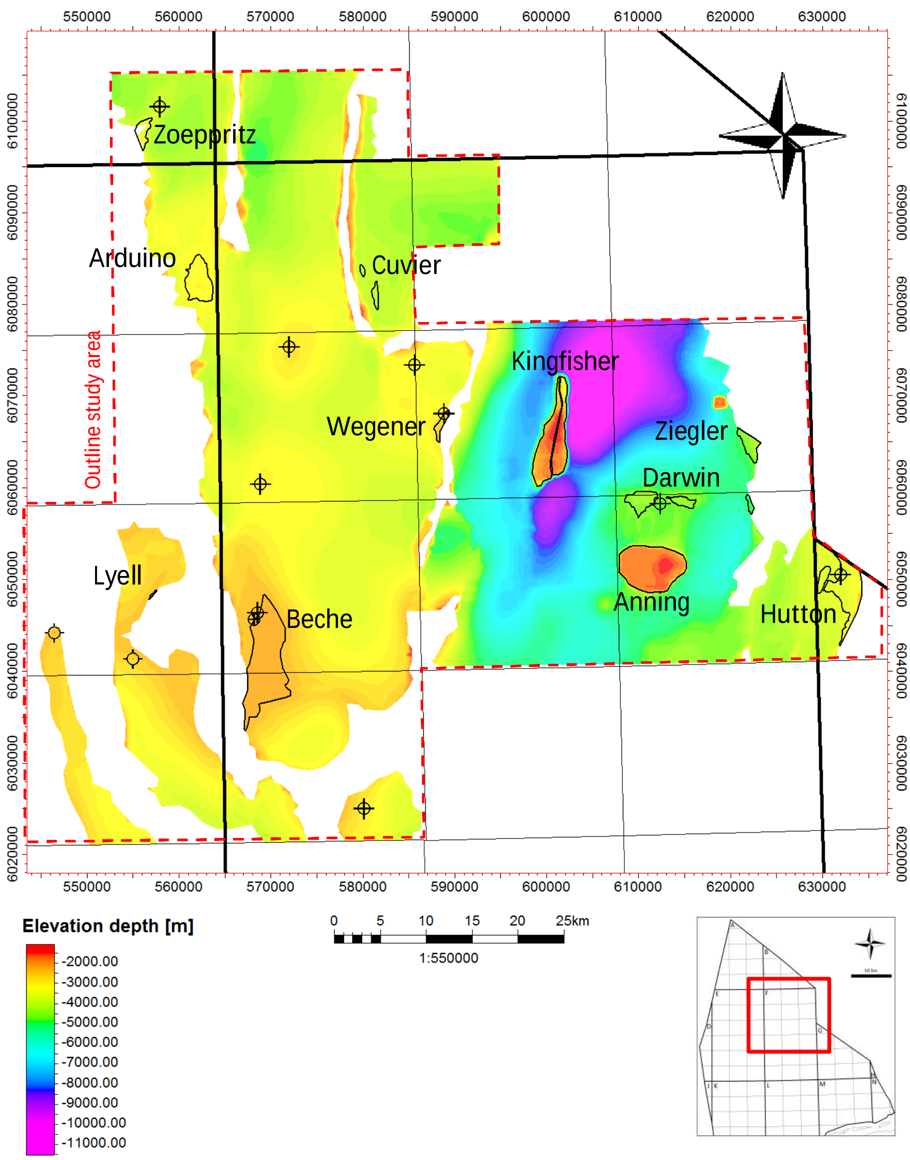


Figure 59 - Depth map with location and size of leads indicated. Exact size of the leads are listed in table 5.

Table 5 - Leads and their characteristics. Note that the Kingfisher and Anning leads have depths indicated in ms instead of m.

No	Lead name	Off-shore block	Description	Amplitude	Reservoir thickness	Height	Area (km^2)	Depth Top Volp Sst. (m)	Risk
1	Hutton 1	G7	3-way dip closure against fault	High amplitudes structural conformable	30 m	40 m	2.15	-3480	Fault may not be completely sealing
2	Hutton 2	G7	Closure against salt wall in the east, and fault in the west. Closure unknown in the north	Medium-high amplitudes Structural conformable	30 m	1250 m	≥15.28	-2240	Uncertainty due to lack of German data in the north
3	Wegener	F5	Updip of F05-02: 3-way closing contours against salt wall	Medium amplitudes not structural conformable	54 m	325 m	1.89	-2375	Charge Salt plugging
4	Beche	F7, F10	Updip of F07-01 and F07-02: 3-way closure against salt wall (fault)	Low-medium amplitudes not structural conformable	52 m	150 m	40.79	-2000	Charge Seal (faulted)
5	Ziegler	F6	3-way dip closure at salt wall	Medium-high amplitudes Structural conformable Polarity reversal: indication of salt plugging	40 m	700 m	4.14	-3970	Charge Salt plugging Overmature SR Trap (Poor seismic due to salt close-by) Seal due to faulting
6	Zoeppritz	A18	3-way dip closure against salt wall	Low amplitudes not structural conformable	17 m	≥720 m	3.33	≤-3130	Charge Salt plugging
7	Kingfisher 1	F5	3-way dip closure against salt (fault)	Low amplitudes not structural conformable	50 m	*625 ms*	13.45	*-3685 ms*	Charge Overmature SR Salt plugging
8	Kingfisher 2	F5	3-way dip closure against salt (fault)	Low amplitudes not structural conformable	50 m	*325 ms*	9.97	*-4450 ms*	Charge Overmature SR Salt plugging
9	Cuvier 1	F1	4-way dip closure	High amplitudes structural conformable	45 m	10 m	0.49	-3820	Charge
10	Cuvier 2	F1	4-way dip closure	Medium-high amplitudes structural conformable	45 m	15 m	1.36	-3840	Charge Salt plugging
11	Arduino	E3	4-way dip closure	Low-medium amplitudes not structural conformable	42 m	100 m	10.76	-2990	Charge
12	Darwin 1	F6, F9	4-way dip closure	Low-medium amplitudes not structural conformable	50 m	250 m	5.45	-4270	Charge Overmature SR Seal
13	Darwin 2	F9	4-way dip closure	Low-medium amplitudes not structural conformable	50 m	150 m	2.31	-4300	Charge Overmature SR Seal
14	Darwin 3	F9	3-way dip closure against salt wall	Medium amplitudes not structural conformable	40 m	350 m	0.88	-4710	Charge Overmature SR Salt plugging
15	Anning	F9	4-way dip closure	Not visible on seismic	40 m	*650 ms*	28.69	*-2660 ms*	Charge Structure Overmature SR Reservoir quality seal
16	Lyell	E9	Unconformity trap	High amplitudes medium structural conformable	48 m	25 m	0.17	-2260	Charge Seal

The Hutton lead can be divided into two leads, separated by the G07-02 dry well. The Hutton 1 is a 3-way dip-closure against a NNE-SSW trending fault, which is visible in the amplitude map (Fig. A.53 in Appendix A6). Amplitudes are high and structural conformable. The main risk is the sealing capacity of the fault. Updip from this fault well G07-02 was drilled, which was dry at Volpriehausen Sandstone level. However, low gas readings were measured (Figure 52), which indicates it is or has been possible for gas to migrate into or along the Volpriehausen sandstone reservoir at this location. Updip from G07-02 is therefore another lead (Hutton 2), but it should be noted that it is uncertain whether this lead has closing contours in the north, due to the lack of German seismic data here. In the west the structure is dip closed and against a fault, in the east the lead borders a salt wall. If contours are closing in the north at German territory, this structure has an area of at least 15.28 km^2 with a height of 1250 m. Also in this lead amplitudes are high and structural conformable, except near the salt wall where the height of the amplitudes decreased due to the salt.

The Wegener lead is the updip potential of F05-02 and is trapped in a 3-way dip-closure against a salt wall in the F5 block (Figure A.54 (A6)). The amplitudes are not structural conformable, the structure is 325 m high and has an area of 1.89 km^2. Salt plugging is one of the main risks, because the reservoir is bordering a salt wall in the east. It is not certain whether charge has taken place. In the F05-02 well no gas readings were measured, and therefore charge is considered as the other main risk.

The Beche lead shows the updip potential of the F07-01 and F07-02 dry wells. The 150 m high structure has a 3-way dip-closure against a salt wall in the southwest. The Beche lead is with an area of 40.79 km^2 the largest lead of this project. However, the amplitudes are not high and not structural conformable in this area. The largest risks concerning this lead are the sealing capacity of the overlying claystones which are rather strongly faulted on the seismic sections (Figure A.55 in Appendix A6), and the presence of charge. No gas readings were measured in F07-01 and F07-02 which supports charge as one of the main risks.

The Ziegler lead in F6 is a steep dipping, 3-way dip-closure against a salt wall, showing medium to high and structural conformable amplitudes. The structure is at least 700 m high and has a 2D area of 4.14 km^2. On seismic (A6) a polarity reversal is visible, which could be an indication for salt plugging. The seismic quality is poor in this area due to salt, which forms a risk, and together with the chance of salt plugging, the possible absence of charge, and uncertainties regarding the trap and the sealing capacities of the overlying lithology, this is a lead with many risks.

The Zoeppritz lead is located in the north of the study area and forms the updip potential of the dry A18-01 well. Since the original seismic interpretation was done on regional scale, some details were added on lead scale, as indicated on Figure A.57 (Appendix A6). This has resulted in an area of 3.33 km^2 for the Zoeppritz lead, with a height of at least 720 m. However, the seismic interpretation remains very uncertain, and the trap has a very high structural uncertainty. The amplitudes are low and not structural conformable in this area. Since the structure as mapped is a 3-way dip-closure against a salt wall, salt plugging may form one of the main risks. In A18-01 no shows were measured, which supports charge as another major risk. However, the faulted Zechstein may have provided a charge window into the Zoeppritz lead, updip of A18-01.

The two Kingfisher leads are both 3-way dip-closures against the same N-S trending fault. Along this fault salt has migrated upwards to form a salt dome above the Volpriehausen level. On seismic and the depth map (Figure A.58 (A6)) the Volpriehausen Sandstone Member has an exaggerated amount of updip, due to this salt dome above, which also makes the details of the interpretation somewhat speculative. In reality the Volpriehausen is expected to have a less extreme dipping structure, where the sandstones end against the fault, as indicated in the schematic representation (Figure 60). The height of the structure is hard to estimate and is therefore indicated in ms in Table 5. The amplitudes are low and not structural conformable. The Kingfisher 1 lead has an area of 13.45 km^2, and the Kingfisher 2 lead occupies an area of almost 10 km^2. The main risk for both leads is salt plugging, and uncertainties remain about the presence of charge, on top of the structural uncertainty. Due to the large offset of the fault separating the two leads, lateral hydrocarbon migration from Jurassic rocks into the Volpriehausen of the Kingfisher 1 lead might be possible. The fault itself also may provide a charge window into both leads.

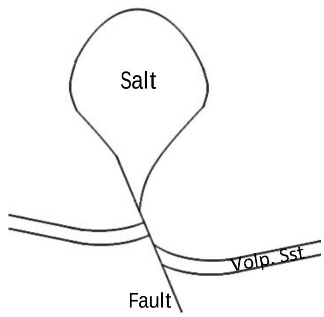


Figure 60 - Expected structure at Kingfisher lead. Structure of Volpriehausen is uncertain due to salt above.

In the north of the study area, in the F1 block, the small Cuvier leads are located. The deepest 4-way closing contour of the Cuvier lead is at -3830 m (Figure A.59 (A6)). The result is two 4-way dip-closures with high amplitudes that are structural conformable, and together extend over 1.85 km^2. A drawback is the low relief of the structure, which is only 10-15 m high. However, in the optimistic case that both the fault south of Cuvier and the salt wall in the west are sealing, the Cuvier lead can be extended significantly, forming a fault-dip closure. In this scenario the area is 28 km^2 and the height of the structure is at least 150 m (Appendix A6). Its main risk is considered to be charge, as well as salt plugging since the Cuvier lead is located near salt walls. In the optimistic scenario the sealing capacity of the fault south of the lead and the salt wall in the west form an additional risk.

Arduino is a lead in the E3 block with a 4-way dip closure and encloses an area of 10.76 km^2 (Figure A.60 (A6)). The height from the spill point to the crest is approximately 100 m. Amplitudes in this area are low and not structural conformable. Charge is considered to be the main risk in this lead. Zechstein is continuously present underneath and from seismic it seems unlikely that a migration path is present. The lead might be extended assuming that the salt wall northeast of Arduino is sealing. However, sealing at the salt wall forms a large uncertainty in this scenario. The optimistic case is indicated on Figure A.60 (A6).

The Darwin lead is subdivided in three leads, separated by the dry F09-03 well. The Darwin 1 lead is located west of well F09-03 and is the largest of the three with an area of 5.45 km^2. It is a 4-way dip closure and has low to medium amplitudes which are not structural conformable. The Darwin 2 lead is also a 4-way dip-closure, has a height of 150 m and an area of 2.31 km^2. The Darwin 3 lead is the smallest of the three, and is a 3-way dip-closure against a salt wall in the east. Its height is 350 m and spreads over an area of 0.88 km^2. Of all three Darwin leads the main risk is considered to be charge. Other risks are the sealing capacity of the overlying lithology, trap and salt plugging (Darwin 3). Since the seismic quality is poor in this area, these risks cannot be excluded.

The Anning lead is an undrilled very poorly imaged structure in the F9 block, in an area where the seismic has been negatively influenced by salt. A simplified interpretation has been made, showing the trap as a 4-way dip closure (A6 in Appendix), to indicate an estimation of its potential size. The Volpriehausen Sandstone is not visible on seismic in this lead, due to salt above the structure.

Anning covers an area of 28.69 km^2. Sealing capacities of the overlying lithology, charge and reservoir quality (e.g. salt plugging) are seen as main risks of this lead, on top of the very significant structural risk. As by the Kingfisher lead, the height of the structure is uncertain and is therefore indicated in ms in table 5. The F15-A field forms an analogue for the Anning lead, although F15-A is deeper, but the structure and salt plugging is comparable.

Lyell is a small subcrop lead below the Base Cretaceous unconformity in the E9 block. It has an area of 0.17 km^2 and a height of 25 m, but it has high amplitudes that show some structural conformity and form an analogue to the G16-B gas field southeast of the study area. The sealing capacity of the overlying lithologies is uncertain, and together with charge, this forms the main risk of this lead.

9. Discussion

9.1 Thickness

A thickness map of the Volpriehausen Sandstone Member has been created, based on well data in the study area (Figure 9). This map shows similarities in general trends, but also differences compared to the thickness map created by Geluk (2005) (Figure 61). The Geluk (2005) map shows a decrease in thickness towards the southeast and northwest, similar to the thickness map created in this study. Also, the areas of absent Volpriehausen roughly correspond. Overall, the map of Geluk is less detailed and thicknesses are higher compared to thicknesses resulting from this study. Geluk (2005) shows a thickness of 60 m in the DCG, compared to a thickness of 51 m in Figure 9. However, it should be noted that data are limited in this area. Thickness on the Schill Grund High agrees (30 m). The largest differences are in the Step Graben. The Geluk (2005) map indicates a thickness of 70 m while in Figure 9 not more than 54 m was found. However, in F10-01 71 m of Volpriehausen Sandstone was encountered according to this study, whereas Geluk indicated a 60 m thickness here. As indicated in Figure 9, a thickness of 36 m is present in F04-03, which is not shown on the map of Geluk. Also, the 17 m thickness in A18-01 is not included in the thickness map of Geluk. However, the decreasing thickness trend towards the northwest is shown in Figure 61, as well as Figure 9.

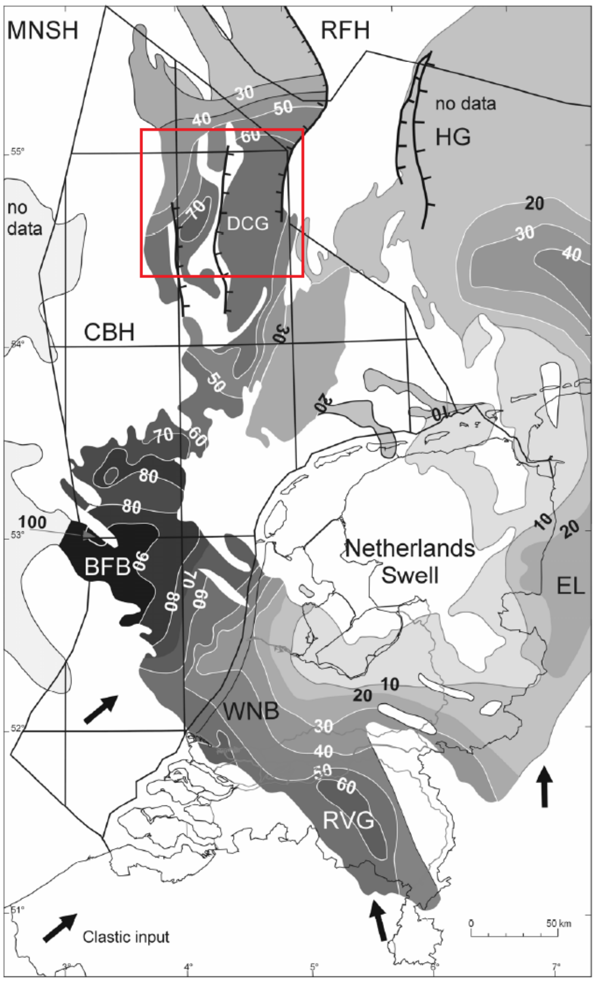


Figure 61 - Thickness map of the Volpriehausen Sandstone in the Netherlands. From: Geluk (2005). The red box indicates the location of the study area for this study.

9.2 Clay-content

The thickness of the Volpriehausen Sandstone Member varies over the study area, thinning towards the north, northwest and east. The well logs in the study area (chapter 7.2 and Appendix A4) show three to four distinguishable sand units, separated by clay beds. These sand units are traceable over large distances within the study area. The top sand unit is generally the thickest (5-30 m), followed by the second sand unit (4-15 m). The sand unit at the base of the Sandstone Member is usually the thinnest (2-4 m). The clay-content within the Sandstone Member varies between 6-36% (Figure 47), with a significant higher clay-content in the northern half of the study area, compared to the southern half. Compared to the Volpriehausen sandstones south of the study area, the clay-content within the Volpriehausen Sandstone Member is significantly higher. The Sandstone Member in the gas fields consists of one sandstone unit, without interbedded clay-stone. The intermediate clay-beds as present in the study area decrease the vertical permeability substantially. This trend of increasing clay-content towards the north can be explained by the depositional model. The fluvial system in which the Volpriehausen sediments were deposited, tends to build out northwards. This resulted in northward thinning sandstone units and increasing clay-content, as observed in the study area.

9.3 Porosity

Porosity data availability is limited in the study area, with just four locations of known porosity, and three additional locations with only an indication of the porosity available. No trend in porosity is observed, partly due to lacking of additional data. When comparing porosity values of the study area and the Volpriehausen gas fields south of the study area, it is remarkable that the latter (7-18%) are lower than the former (14-28%). Because, based on the well logs, the opposite is expected. When considering the higher clay-content within the Sandstone Member in the study area, it is likely that the high porosity in the study area was measured at a point in a sandstone unit, opposed to bulk porosities in the fields south of the study area, what would explain the difference. When plotting the porosities of the study area and of the fields south of the study area against depth, a trend is observed of decreasing porosity with depth (Figure 62). The majority of the Volpriehausen fields have greater depths than the Volpriehausen in the study area, as well as a lower porosity. However, since these fields are all currently producing gas fields, this proves that despite high depths or porosities below 15% the reservoir quality can still be high enough to be a produceable gas reservoir. Porosity is influenced by depth and related compaction, but is also influenced by regional diagenesis, including salt plugging. The porosities in Figure 62 were used to draw a trend line, as indicated in Figure 63. Depths of the Top Volpriehausen Sandstone Member in the leads (Table 5) are plotted on this porosity trend line, in order to estimate their porosity. If this estimation is approximately correct, it becomes clear that the leads in the Step Graben, on the Schill Grund High and on the Cleaver Bank High (Figure 2) have the highest porosities, opposed to the leads in the Dutch Central Graben, which have estimated porosities of less than 7%. However, in the M1-A and L5-FA gas fields similar porosities have been measured. Since these are produceable gas reservoirs, the low porosities of the leads in the Dutch Central Graben are not expected to be a problem.

9.4 Compaction

The amount of compaction increases with depth, which is visible on the DT logs in the study area. The deeper the Volpriehausen, the lower the DT. In F09-03 and A18-01 the Volpriehausen is deepest in the study area, in F07-01 and F07-02 the Volpriehausen is situated the shallowest. The DT logs of these wells show significant differences, which can be explained by the different amount of compaction that has taken place. With an increasing amount of compaction the water-content decreases, as reflected by the DT logs. This strong effect on DT will also affect the amplitude response. Forward modelling is essential, and is therefore recommended.

The amount of compaction is also related to the amount of burial. The Step Graben and the Dutch Central Graben experienced a different amount of burial. This most likely influenced the maturity of the Carboniferous source rocks. Due to the deeper burial of the Dutch Central Graben overmaturity of the Carboniferous source rocks is expected to form a risk here, opposed to the shallower and less deep buried Step Graben.

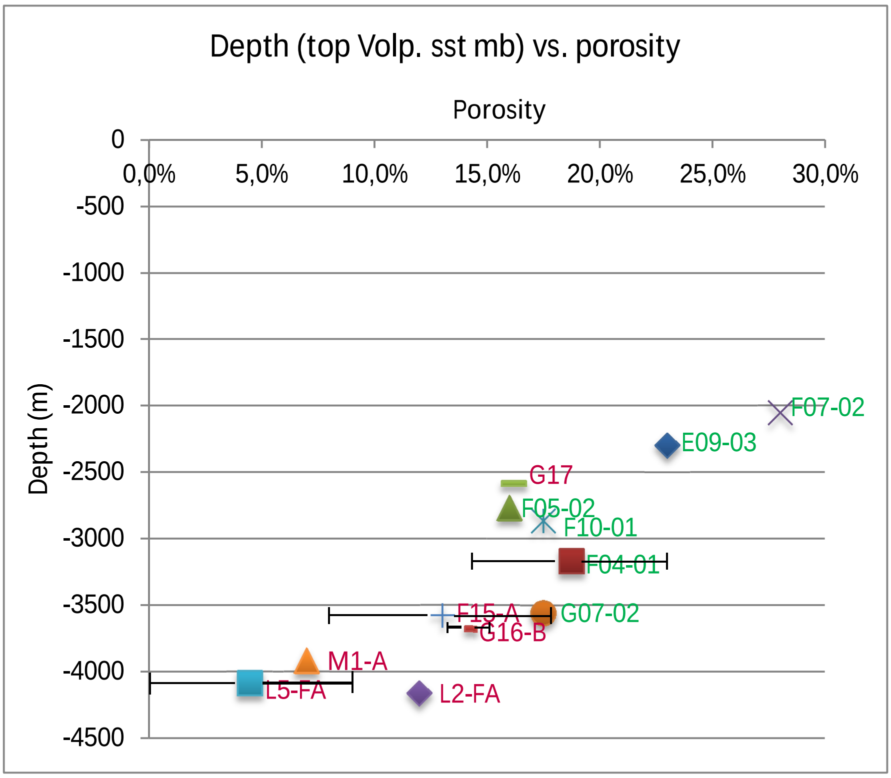


Figure 62 - Graph showing depth of the Top Volpriehausen Sandstone Member against porosity (%). A decreasing trend is observed in porosity with increasing depth. Error bars indicate a range of porosity measured in wells of that field. Labels indicate the location of the porosity measurement, green labels indicate well locations inside the study area, red indicates a field south of the study area.

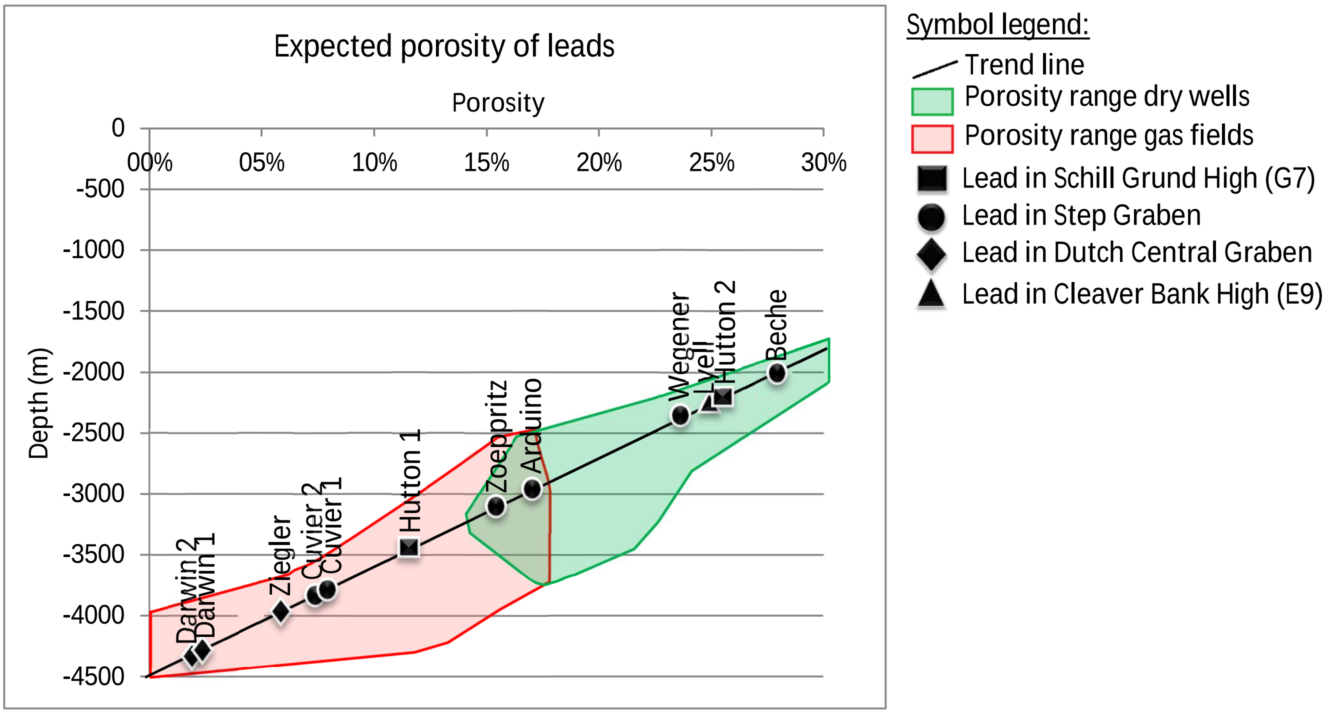


Figure 63 – Graph showing the estimated porosities of the leads. The red and green polygons show the range of porosities of the gas fields outside the study area and dry wells in the study area, respectively (Figure 62). A trend line has been drawn through these porosities, indicated by the black line. The depths of the Top Volpriehausen Sandstone Member per lead are plotted on this line, to give an estimated porosity. The names of the leads are indicated.

9.5 Seismic interpretation

The seismic interpretation of the Volpriehausen Sandstone Member has been done on a regional scale. This may have led to inaccuracies locally, especially where the Volpriehausen Sandstone abuts salt walls. For example the Zoeppritz lead (block A18) has been extended towards the salt dome, based on the interpretation at lead scale.

During the interpretation uncertainties about the presence of the Volpriehausen Formation were encountered. In areas, e.g. between salt walls, where the interpretation cannot be linked to a well or other interpretations, and the seismic character differs from the typical Lower Germanic Trias character, it is uncertain whether the Volpriehausen is present and which reflector represents the Top Volpriehausen Sandstone Member. However, its presence cannot be excluded. Between E09-03 and E09-02 is such an area (Appendix Figures: A.26 and A.27, line F (A5)), as well as east of G07-02.

9.6 Amplitudes

The seismic amplitude, reflecting the difference in acoustic impedance between two units, can be influenced by several factors. First, it is influenced by lithology. Transitions in lithologies such as chalk, salt, clay or sands reflect differences in acoustic impedance, resulting in high amplitude reflectors. Facies changes, e.g. changes in clay-content, can also cause this effect. A salt plugged reservoir can cause polarity reversal. The amplitude is also affected by porosity. Generally, high porosity sandstones show high amplitudes. Also, pore fluids, including type and saturation of the fluid, can influence the amplitudes, with hydrocarbon-filled reservoir normally displaying the highest amplitudes (Figure 58). This usually results in structural conformable amplitudes, with a “switch-off” of amplitudes at the gas-water contact. Another factor that may affect amplitudes is the (effective) pressure, which influences the seismic wave velocity, and therefore the amplitude. In addition, faults and fractures and reflector geometry may also influence the height of amplitudes locally, as well as a high amplitude event above the reflector of interest, which may cause low frequency shadow zones (assuming no processing issues). Furthermore, the processing of the seismic data may result in dimming or brightening of reflectors. This results in non-structural conformable amplitudes. Amplitudes can also be influenced by tuning, an effect where the seismic signal of two lithological interfaces interfere where they are very close. If the spacing is less than ¼ wavelength, two reflectors interfere and produce a single event of high amplitude. The thickness at which two events become indistinguishable on seismic is called the tuning thickness. The generally strong reflector which is interpreted as the Top Volpriehausen Sandstone Member results from a tuning effect where waves interfere due to the closely spaced top and base of the Volpriehausen Sandstone Member. Finally, the bed thickness influences the amplitude. The Volpriehausen Sandstone generally decreases towards the north. North of the study area the Volpriehausen Sandstone becomes very thin, resulting in a reduced seismic expression. When the bed thickness becomes too thin, the Volpriehausen Sandstone is no longer visible on seismic, and therefore, amplitude anomalies are also not visible. Thereby, uncertainties arise about the reliability of the methods used to detect good quality reservoirs and salt plugged reservoirs in areas with thin Volpriehausen Sandstones, since these methods were originally used on Volpriehausen Sandstones with higher thicknesses, south of the study area. In order to be certain that these methods are reliable in areas with thin Volpriehausen in and north of the study area, it should be modelled with the appropriate parameters.

9.7 Salt affecting the seismic signal

Salt has a low density and high seismic wave velocity. Since salt is highly reflective, it acts as a barrier to seismic signal penetration, and therefore the layering below overhanging salt is not clearly visible and not fully reliable on (post-stack) seismic. This effect has also been encountered in the study area, near and below salt overhangs, where the strength of the seismic signal (brightness of the reflectors) of the Volpriehausen Sandstone has decreased, as well as of over- and underlying lithologies. This has led to uncertainties in seismic interpretation in these areas. Simplified interpretations have been made in these cases (e.g. the Anning lead). These interpretations are somewhat schematic and speculative, and may not correctly represent the subsurface. It should also be taken into account that the strong velocity contrast between the salt and the surrounding sediments results in a distorted picture of the structure (height, steepness of the layers), as can be seen on the depth map, in the form of exaggerated shallowness of three salt domes in the Dutch Central Graben and the steep dipping layers bordering salt walls (Figure 10). These salt domes and borders are the main cause of differences in the time (Figure 8) and depth (Figure 10) maps. In order to understand the structures near and below the Zechstein salt, pre-stack data should be studied, since pre-stack migration images the reflections from the salt boundaries better. Also the visualization of sub-salt layering is expected to improve on pre-stack data.

9.8 Salt plugging

Completely salt plugged reservoirs may cause polarity reversal, as seen in the Ziegler lead. It cannot be excluded that polarity reversals in the study area due to salt plugging of the Volpriehausen Sandstone Member have been overlooked, since they are difficult to detect, especially if lithologies are breached or the reflectors have low amplitudes. As described in the result chapter, salt plugging has been detected outside the study area in the F15-A, L2-FA, L5-FA and M4 fields, however, since these are all producing gas fields, this proves that the presence of anhydrite in the Volpriehausen Sandstone does not necessarily exclude the sandstone from being a suitable gas producing reservoir rock. An attribute analysis was used to detect areas in the study area with a risk of salt plugging (Figure 56). However, there are some drawbacks to this method. Areas which might be salt plugged, but have poor seismic signal, do not come forward, as well as areas where salt influenced the seismic signal. For example, from the dry well analysis salt plugging is expected to have influenced the reservoir quality of the Volpriehausen Sandstone Member in well F09-03, but this area has not come forward as ‘risk area’ by this method, due to the poor seismic signal in this area. Another drawback that should be taken into account is that the areas resulting from the attribute analysis to locate good quality reservoirs (Figure 27) and ‘risk areas’ for salt plugging (Figure 57) sometimes overlap. This is the case for the areas indicated in green on the map in Figure 64. These areas might suffer from other factors influencing the amplitude on seismic, as discussed in chapter 9.6.

9.9 DHI’s

The Volpriehausen Sandstone gas fields south of the study area all show high amplitude reflectors, which serve as direct hydrocarbon indicators (DHI’s). Insufficient information is available in the public domain on the structural conformity of these DHI’s, but it seems that structural conformity is not so obvious for all fields. The switch-off of amplitudes for the L2-FA fields is very clearly structurally conformable. These bright spots result from local amplitude anomalies due to a larger difference in acoustic impedance between the overlying shale and the sandstone, caused by hydrocarbons (gas) in the sandstone reservoir. However, bright spots are not fully reliable as DHI,

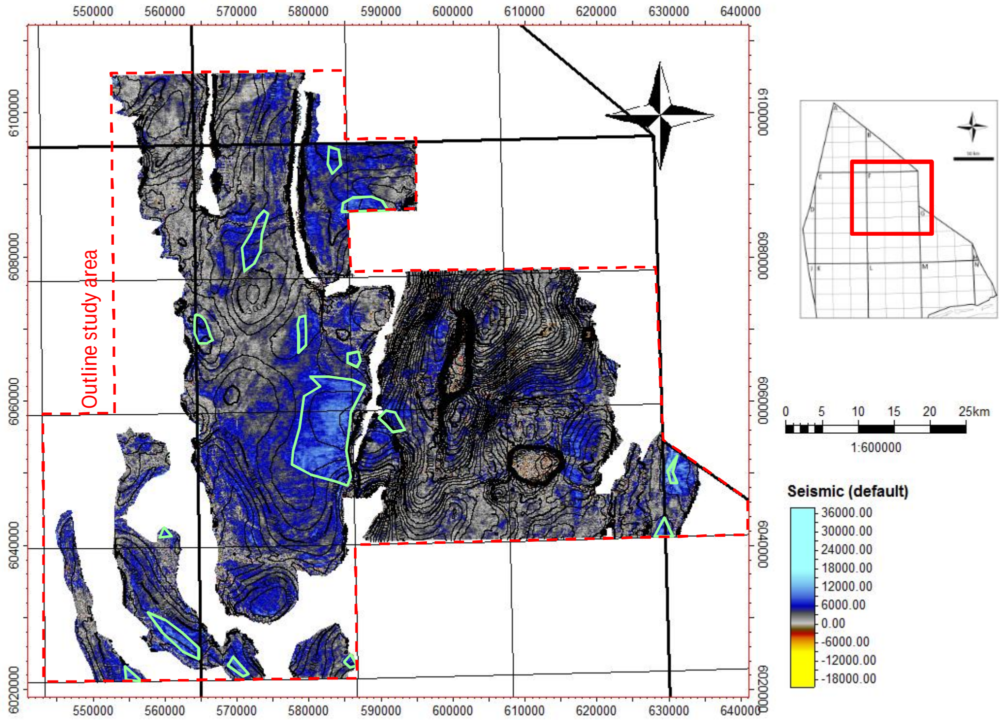


Figure 64 - Amplitude extraction map at interpreted Top Volpriehausen Sandstone, showing the overlap between salt plugging risk areas and good quality reservoirs, both resulting from attribute analysis. These overlapping areas might suffer from other factors influencing seismic amplitudes.

since the reflector strength can also be influenced by other factors than gas fill, such as salt plugging or tuning (chapter 9.6). No standard seismic character can be determined for a gas-filled reservoir in the Volpriehausen Sandstones, because not all of the evaluated fields have the same amplitude character, some have a peak as top high amplitude reflector, and others a trough (Table 4).

9.10 Comparison of leads and gas fields

Leads resulting from the prospectivity review (chapter 8) show similarities with the gas fields south of the study area. The trapping style of L2-FA (3-way dip-closure against salt wall) is comparable to the trapping style of the Hutton 2, Wegener, Beche, Ziegler, Zoeppritz and Darwin 3 leads. It shows that this type of trap can be effective in the Volpriehausen Sandstone Member. This also applies to the unconformity trap of the G14-G17 gas field, which serves as an analogue for the Lyell lead in E09, also an unconformity trap, as well as the fields south of the study area with a turtle-back anticline (F15-A and L5-FA), which may serve as analogue for leads with a 4-way dip-closure, which are the Cuvier 1 and 2, Arduino, Darwin 1 and 2, and Anning leads. With F15-A as analogue, the potential of the Anning lead increases. In F15 also areas with poor seismic signal are present, and salt plugging forms a main risk. This is similar to the situation of the Anning lead in F9, which contributes to the potential of this lead. The Hutton 1 and Kingfisher 1 and 2 leads are 3-way dip-closures against faults, for which none of the evaluated gas fields forms an analogue. But that does not preclude this trap type from being a possible effective trap in the Volpriehausen. The depths of the gas fields are comparable to depths of the leads in the study area, or deeper. Also the reservoir thicknesses are comparable, varying generally between 30-50 m, with a few exceptions. The fields all show high amplitudes at locations of gas filled reservoirs (in L2-FA also structural conformable), as do the Hutton, Cuvier, Ziegler and Lyell leads. The other leads have low amplitudes which are not structural conformable. Based on this, the Hutton, Cuvier, Ziegler and Lyell leads are considered as most promising. However, the other leads, especially the Kingfisher and Anning leads in the Dutch Central Graben should not be ruled out. They might not have high structural conformable amplitudes, but this results from poor seismic image due to salt above. Hence, these leads should also be taken into consideration as high potential leads. On the other hand, the sometimes poor seismic definition at Volpriehausen, especially close to salt domes and below salt overhangs, implies a sometimes considerable risk for no trap.

9.11 Controls on hydrocarbon distribution

The hydrocarbon distribution in the Volpriehausen Sandstone Member in the northern Dutch offshore is controlled by several factors.

9.11.1 Reservoir

First, the presence and quality of the reservoir. Reasons for absence can be that (1) no sediments were deposited, (2) it has been pierced by salt and/or (3) it has been eroded. The quality of the reservoir depends on the thickness, porosity, permeability and clay-content. Salt plugging of the Volpriehausen reservoir forms a risk, especially near salt domes, walls and overhangs.

9.11.2 Trap

Halokinesis is an important factor for trap formation in Mesozoic sediments. Proven valid salt-related traps in Volpriehausen Sandstones are 3-way dip-closures against salt walls, turtle-back anticlines, and 4-way dip-closures above salt structures. For some of the leads (e.g. Anning, Zoeppritz, Darwin) trap is a major risk. The Volpriehausen has another geometry in these leads, due to a bad definition of the Volpriehausen reflector.

9.11.3 Seal

Another factor controlling the hydrocarbon distribution, is the sealing capacity of the overlying lithology. In order to be fully sealing, the Volpriehausen Claystone Member must overly the Sandstone Member normally and must not be breached, in order to be fully sealing. If breached, hydrocarbons may migrate to shallower stratigraphic levels. In case of an unconformity trap, not only the Volpriehausen Claystone Member must be sealing, but also the lithology encountering the Volpriehausen Sandstones at the unconformity. If the Volpriehausen Sandstones are trapped against a salt dome, the salt or (partly) salt-plugged reservoir may act as a seal.

9.11.4 Charge

The last main control on hydrocarbon distribution is the presence of charge. Mature source rocks must be present, and the timing of charge and migration has to be during and/or after trap formation. Additionally, migration paths have to be present, in order for hydrocarbons to be able to migrate into the Volpriehausen Sandstone Member. Charge windows might be created by the reactivation of faults due to halokinesis. The presence of Zechstein salt beneath the Triassic may prevent migration, or provide migration paths in the case of grounding or touchdown of Zechstein. In order for hydrocarbons to be able to migrate into Volpriehausen reservoirs, the underlying Main Claystone Member (a.k.a. Lower Bunter Shales), Slochteren Shale and Zechstein Claystone must be faulted, or the Volpriehausen Sandstone Member must be otherwise in contact with pre-Zechstein sediments to create a migration path. In the part of the Dutch Central Graben that lies in the study area, the presence of charge (into the Volpriehausen) has not been proven. However, it is also not certain that charge is absent in this area (Figure 51). The general assumption that there is no charge in this part of the Dutch Central Graben results from the lack of well data at depths of the Volpriehausen Sandstone Member. Drilling more wells into the Volpriehausen Sandstone is the only way to gain knowledge about the presence of charge in the Dutch Central Graben.

10. Conclusions

Hydrocarbon distribution in the Volpriehausen Sandstone Member in the northern Dutch offshore is controlled by:

- *Reservoir*. The Volpriehausen sandstone reservoir is present in the entire study area, except in salt pierced areas, and where it has been eroded (in the west of the study area and locally in E9 and F10). The reservoir quality is good with porosities between 14-28%. Following the decreasing porosity with depth trend, leads in the DCG are expected to have porosities below 7%. Leads in the Step Graben, on the Schill Grund High and Cleaver Bank High are expected to have higher porosities. A trend of decreasing reservoir quality is observed towards the north, due to decreasing thickness of the Volpriehausen Sandstone Member and increasing clay-content in northern direction. This trend is consistent with the depositional model of a fluvial system building out northwards, resulting in thinning sandstone units and increasing clay content in this direction.
- *Halokinesis*. The movement of salt has resulted in several types of traps in the Volpriehausen, including turtle-back anticlines (e.g. the F15-A and L5-FA fields), 3-way dip-closures against salt walls (as shown in the L2-FA, M1-A and G16-B fields, and in the Hutton, Wegener, Beche, Ziegler, Zoeppritz, Darwin 3 and Kingfisher leads), and 4-way dip-closures above salt structures (as seen in the Cuvier, Arduino, Darwin 1&2 and Anning leads). Halokinesis may also reactivate faults and create zones with thin or absent Zechstein salt (‘touchdown’/‘grounded’), both may provide migration paths for hydrocarbons.
- *Salt plugging*. Salt plugging of the pores decreases the reservoir quality, but a (partly) salt-plugged reservoir may also provide a side-seal for the rest of the reservoir, as shown in field M1-A. If the reservoir is not completely salt-plugged, the rest of the reservoir can still be a producible gas reservoir, as shown in fields F15-A, L2-FA and L5-FA.
- *Zechstein (salt) presence underneath*. If Zechstein salt is continuously present underneath the Volpriehausen Sandstone Member, it can prevent migration of hydrocarbons into the reservoir. However, if grounded or faulted, it may provide a migration path for hydrocarbons. Near wells A18-01 and F04-01 the Zechstein is grounding. Near wells E09-02, F04-03, G07-02 and the Zoeppritz and Kingfisher leads the Zechstein is faulted, providing possible charge windows.
- *Sealing capacity of overlying lithology*. The Volpriehausen Claystone Member generally acts as top seal in the study area. It overlies the Volpriehausen Sandstone Member in the entire study area, except at unconformities (E09, F10), where its thickness is less or the member might be absent due to erosion. Breaches and faults in the overlying Claystone Member provide possible migration paths for hydrocarbons out of the Volpriehausen Sandstone Member, which possibly occured in the F04-01 and F04-03 four-way dip-closures in the study area. In F04-01 bright spots are present at levels above the Volpriehausen, possibly indicating gas that was not trapped in the Volpriehausen and migrated through leak-paths to shallower levels. In case of an unconformity trap (E09-03 and F10-01), the overlying lithology (Lower Cretaceous shales) at the unconformity must also be sealing, additionally to the Volpriehausen Claystone Member. The G14-G17 gas field, which is also overlain by an unconformity and serves as an analogue for Volpriehausen unconformity traps (E09-03, F10-01 and Lyell lead) demonstrates the possible success of this trap type in the Volpriehausen. In the L2-FA, M1-A and G16-B fields the hydrocarbons are trapped against a salt dome or wall, where the salt (or partly salt-plugged reservoir) is acting as side-seal,

additionally to the top-sealing Claystone Member. These fields are analogue to the Hutton, Wegener, Beche, Ziegler, Zoeppritz, Kingfisher and Darwin 3 leads, where similar sealing situations are expected to be present. However, comparable structures were drilled in wells A18-01, F05-02, F07-01 and F07-02, which were all dry.

- *Charge*. Charge forms the highest risk in the study area, since much is unknown or uncertain in this part of the Dutch offshore. In order to provide charge, mature source rocks must be present below the Volpriehausen Sandstone Member. Uncertainties exist about the maturity of the Carboniferous source rocks in the study area. Due to the difference in amount of burial between the Step Graben and the Central Graben, differences in maturity are likely. The Dutch Central Graben has experienced deeper burial than the Step Graben. Therefore, overmaturity of Carboniferous source rocks in the DCG forms a risk. The F15-A gas field is the northernmost Volpriehausen gas field in the Dutch offshore. Not much is known about charge from Carboniferous source rocks into the Volpriehausen Sandstone Member north of F15 at this time. Another factor contributing to successful charge is the timing and migration, which should be after trap formation in the Volpriehausen Formation. Also, migration paths must be present in order for hydrocarbons to migrate from the source rock into the Volpriehausen Sandstone Member. Not only the Zechstein salt, but also the Slochteren Shale, Zechstein Claystone and Lower Bunter Shales need to be crossed. Therefore, the presence of charge into the Volpriehausen forms a large uncertainty in the study area. Even in areas with thin Zechstein salt (e.g. in the E09 area) no gas has been encountered in the Volpriehausen Sandstone Member, which confirms the difficulty of charge into the Volpriehausen in this area. In wells F04-03 and G07-02 trace gas was encountered, which implies that charge is or has been possible at these locations. It could be possible that hydrocarbons migrate(d) laterally from Jurassic source rocks (Posidonia Formation) into the Volpriehausen Sandstones at large faults where the Jurassic rocks are being juxtaposed against Triassic Volpriehausen sandstones. For example at the Kingfisher 1 lead, where a large offset has resulted in the juxtaposition of the Volpriehausen against the Altena Group.

The Volpriehausen Sandstone gas fields south of the study area all show high amplitude reflectors, which serve as direct hydrocarbon indicators (DHI's), but structural conformity is only obvious in L2-FA. These bright spots are caused by the presence of gas in the sandstone reservoir. However, bright spots are not fully reliable as DHI, since the reflector strength can also be influenced by other factors than gas fill, including salt plugging, porosity, tuning, processing, and lithology transitions. No standard seismic character can be determined for a gas-filled reservoir in the Volpriehausen Sandstone Member, because not all of the evaluated fields have the same amplitude character. F15-A, M1-A and G16-B have a trough as top high amplitude reflector, L2-FA, L5-FA and G14-G17 a peak.

Analysis of seismic and well data of the Volpriehausen Sandstone Member in the northern Dutch offshore has resulted in a prospect inventory, of which the Hutton, Cuvier, Ziegler and Lyell leads are considered to be the most promising. However, the Anning and Kingfisher leads in the Dutch Central Graben should also be taken into account, despite the poor seismic image that is influenced by salt. The presence of charge is considered to be the main risk for these leads. A distinction is made between the Step Graben and the Dutch Central Graben, due to their difference in burial. For leads located in the Dutch Central Graben, where a large amount of burial has taken place, overmaturity of the source rocks is expected to form a risk.

11. Recommendations

To improve the confidence in the seismic interpretation and mapping of structures near and below salt domes and walls, pre-stack depth migration is recommended, as it is expected that this will image the reflections from salt boundaries in a better way. Additionally, the visualization of layering below salt overhangs is expected to improve on pre-stack depth migrated data. Subsequently, the seismic interpretation can then be detailed, especially near and above salt structures, where large uncertainties exist at this time. It is also recommended that for all wells a consistent porosity calculation will be performed with similar intervals for each well, preferentially by a petrophysicist, in order to be able to make an equivalent comparison between the different wells. Modelling is also recommended based on parameters optimized for the study area, since compaction of reservoir and overlying seal has not only a strong effect on DT logs, but will also affect the amplitude response. Also the lithology of the reservoir and sealing lithology may be (slightly) different, influencing the input parameters. Furthermore, knowledge about the Volpriehausen Sandstone Member in the northern Dutch offshore may only be extended when more wells are drilled and logs are acquired covering the Volpriehausen Formation. In addition, in the sector of the Dutch Central Graben that overlaps with the study area, a need exists for better understanding of hydrocarbon charge, since its presence is not proven but can also not be excluded in this area at this time. It is also recommended that this study will be extended to the west (D and E blocks), for which also high quality 3D seismic data are available. It is also possible to extend this study to the north (A and B blocks), however, reservoir quality is expected to decrease further towards the north, following the northward decreasing thickness and increasing clay-content trends, as found in this study.

12. Acknowledgements

I would like to thank EBN for giving me the opportunity to do a graduation internship in this environment full of expertise, providing me the chance to work on an interesting and challenging project for six months, and giving me valuable insights in the Dutch E&P industry. Special thanks go to my daily supervisor Eveline Rosendaal for her support, input and supervision throughout the entire project. Jan de Jager, John Reijmer and Guido Hoetz are also thanked for their supervision. Walter Eikelenboom is thanked for his help with Petrel, especially with velocity modelling. Also Bastiaan Jaarsma, Roberta Guarnieri, Annemiek Asschert, Jan Lutgert, Mijke van den Boogaard and all the other colleagues and interns are thanked for their help and the great time at EBN. I wish Mijke good luck with expanding the Volpriehausen Prospectivity Review in the northern Dutch offshore.

13. References

Bloch, G., and Egele, P., 1993. Technical Review of the Volpriehausen Play, Dutch Central and Northern Offshore. NAM Report No: 21.893.

Brown, C., McAfee, A., and Phillips, I., July 2001: Petrographical investigation of Volpriehausen core samples from blocks L02, L05 & L04, offshore Dutch Sector. Prepared for the NAM by Core Laboratories Advanced Technology Centre.

Clyde Petroleum Exploratie B.V., January 2000: Geoscience evaluation G17.

De Jager, J., 2007. Geological Development. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds.): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences, 5-26.

Dost, B., and Haak, H.W., 2007. Natural and induced seismicity. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (Amsterdam): 223–239.

Dronkert, H., and Remmelts, G., 1996. Influence of salt structures on reservoir rocks in Block L2, Dutch continental shelf. In: Rondeel, H.E., Batjes, D.A.J., Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands, Kluwer (Dordrecht): 159–166.

Dronkert, H., Nio, S.D., Kouwe, W., van der Poel, N., and Baumfalk, Y., 1989. Buntsandstein of the Netherlands offshore. International Geoservices. (Report EP890020, EBN00012389)

Fontaine, J.M., Guastella, G., Jouault, P., and De la Vega, P. 1993. F15-A: a Triassic gas field on the eastern limit of the Dutch Central Graben. In: Parker, J.R. (ed.) Petroleum Geology of Northwest Europe, Proc. 4th Conf, Geol. Soc. (London): 583–593.

Frost, R.T.C., Fitch, F.J. and Miller, J.A., 1981. The age and nature of the crystalline basement of the North Sea Basin. In: Illing, L.V. & Hobson, G.D. (eds): Petroleum Geology of the Continental Shelf of North-West Europe. Heyden (London). 43–57.

GDF Suez, October 2012: G16a TCM Fall.

Geluk M.C., and Rohling H.-G. 1999. High-resolution sequence stratigraphy of the Lower Triassic Buntsandstein: a new tool for basin analysis. In: Bachmann, G.H. & I. Lerche (eds): The Epicontinental Triassic, Zentralblatt fur Geologie und Palaontology 1998: 545–570.

Geluk, M. C., 2005. Stratigraphy and tectonics of Permo-Triassic basins in the Netherlands and surrounding areas. (Proefschrift)

Geluk, M.C., and Rohling, H.-G. 1997. High-resolution sequence stratigraphy of the Lower Triassic 'Buntsandstein' in the Netherlands and Northwestern Germany. Geologie en Mijnbouw 76: 227–246.

Gianolla, P., and Jacquin, Th., 1998. Triassic sequence stratigraphic framework of Western European Basins. Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication 60: 643–650.

Guterch, A., Wybraniec, S., Grad, M., Chadwick, R.A., Krawczyk, C.M., Ziegler, P.A., Thybo, H., and De Vos, W., 2010. Crustal structure and structural framework. In: Doornenbal, J.C. and Stevenson, A.G. (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 11-23.

ICS, 2003. International Stratigraphic Chart. International Commission on Stratigraphy.

Intergeos B.V. 1989. Buntsandstein of the Netherlands offshore. International Geoservices, report no. EP890020 (Leiderdorp): 80 pp.

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

Kombrink, H., Doornenbal, J.C., Duin, E.J.T., Den Dulk, M., Van Gessel, S.F., Ten Veen, J.H., and Witmans, N., 2012. New insights into the geological structure of the Netherlands; results of a detailed mapping project. Netherlands Journal of Geosciences-Geologie en Mijnbouw 91.4: 419.

Kozur, H., 1999. The correlation of the Germanic Buntsandstein and Muschelkalk with the Tethyan scale. In: Bachmann, G.H. & I. Lerche (eds) The Epicontinental Triassic, Zentralblatt fur Geologie und Palaontology 1998: 701–725.

Moreau, P., Neumann, C., Chennaux, G., and G. Perrin, G., 1990. Well F15a-7 - Biostratigraphy, sedimentology, mineral geochemistry, structural analysis. Offshore Netherlands. EP/S/EXP/Lab.Pau 90/54RP.

Pharaoh, P., England, R. and Lee, M., 1995. The concealed Caledonide basement of eastern England and the southern North Sea – a review. Studia geoph. et geod. 39: 330–346.

Pharaoh, T.C., Dusar, M., Geluk, M.C., Kockel, F., Krawczyk, C.M., Krzywiec, P., Scheck-Wenderoth, M., Thybo, H.,Vejbæk, O.V., and Van Wees, J.D., 2010. Tectonic evolution. In: Doornenbal, J.C. and Stevenson, A.G. (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 25-57.

Purvis, K., and Okkerman, J.A., 1996. Inversion of reservoir quality by early diagenesis: an example from the Triassic Buntsandstein, offshore the Netherlands. In: Rondeel, H.E., Batjes, D.A.J., Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands, Kluwer (Dordrecht), 179-189.

Remmelts, G., 1996. Salt tectonics in the southern North Sea, the Netherlands. In: Rondeel, H.E., Batjes, D.A.J., Nieuwenhuijs, W.H. (eds): Geology of gas and oil under the Netherlands, Kluwer (Dordrecht). 143–158.

Röhling, H.-G., 1991. A lithostratigraphic subdivision of the Early Triassic in the Northwest German Lowlands and the German Sector of the North Sea, based on Gamma Ray and Sonic Logs. Geologisches Jahrbuch A 119: 3-23.

Van Adrichem Boogaert, H.A., and Kouwe, W.F.P. (compilers), 1993–1997. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst 50.

Van Bergen, F., and De Leeuw, K., 2001. Mechanism proposed to explain salt cementation near salt domes. TNO-NITG-Information (May), 19-20.

Van Dalfsen, W., Van Gessel, S.F., Doornenbal, J.C., 2007. TNO report: Velmod-2 Joint Industry Project.

Vittori, J., Mathis, B., Neumann, C., Rebelle, M., 1990. Layering of Volpriehausen sandstones (Lower Triassic) F15-4, F15-5 and F15a-7 wells. Pau, July 1990. EP/S/EXP/Lab. Pau n° 90/144 RP.

Wong, Th.E., Batjes, D.A.J. and De Jager, J., 2007: Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences.

Wride, V. C., 1995. Structural features and structural styles from the Five Countries Area of the North Sea Central Graben. First Break 13.10.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe (2nd edition). Geological Society Publishing House, Bath, 239 pp.

Websites:

www.dinoloket.nl/Triassic

www.nlog.nl