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TNO report

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Stringers in Salt as a Drilling Risk

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Summary

This report describes the results of the project ‘Stringers in Salt as a Drilling Risk’, commissioned to TNO Advisory Group Economic Affairs (TNO AGE) by the State Supervisory of Mines (SodM). The project focussed on anomalous formation pressures associated with stringers that can be encountered when drilling through the (Permian) Zechstein salt in the Netherlands.

Stringers are layers or fragments of rock mainly consisting of minerals other than halite (e.g., anhydrite, carbonate) that are embedded in evaporites that mainly consist of halite and have different mechanical and flow properties than the salt. Anomalous pressures in stringers can pose a drilling risk as they may lead to losses of drilling fluids (mud losses) or flow of gas or brine from stringers (kicks) into the borehole. Both mud losses and kicks may affect well control and drilling safety.

The goal of the research is (1) to understand the formation of stringers, (2) to identify preferred locations and geological setting of stringers in the Dutch subsurface (on- and offshore), (3) to review the causes and effects of overpressures and pore fluid content of stringers, and (4) to provide an overview of drilling risks and possible risk mitigation measures associated with overpressures and pore fluid content of stringers.

Data inventory indicated that a total of 2575 wells have been drilled through the Zechstein formation in the Netherlands. The occurrence of drilling events has been analyzed for a total of 921 unique wells. 62 wells with reported drilling events have been identified and investigated. 32 formation pressures were analyzed for the 62 wells.

The main conclusions of the study can be summarized as: (1) stringers in the Zechstein mainly originate from Z2 and Z3 lithologies with most of the stringers consisting of Z3 anhydrite-carbonate (Z3AC) stringers, (2) hard overpressures (i.e. formation pressures that are close to lithostatic pressure) are mainly associated with anhydrite and carbonate lithologies, (3) ~80% of stringers associated with drilling events are visible on seismic data and most stringers that caused drilling events could have been seen on seismic before drilling commenced. Nevertheless quality of seismic data is an important factor in identifying stringers and predicting potential drilling issues prior to drilling, (4) overpressures can be up to the maximum overpressure constrained by the lithostatic pressure, in particular overpressures in carbonate and anhydrite formations tend to be close to the maximum overpressure constraint, (5) maximum possible overpressure is increasing with depth without a clear trend of overpressure with the relative position within the local Zechstein formation, (6) best option for planning a well trajectory is to avoid folded tilted stringers and to avoid areas where the base Zechstein is faulted or areas below the flanks of folded top Zechstein.

Measures to mitigate stringer-related drilling risks may be improved by (1) new techniques for the interpretation of seismic surveys to improve the identification, imaging and mapping of stringers and surrounding salt boundaries, (2) better constraints on pore pressure within stringers and expected volume of brine or gas influx using predictive models to map out areas in the Zechstein with high probabilities for the presence of overpressured stringers, (3) compiling guidelines with best practices for handling pressure kicks, drilling trajectories, locations of casing shoes and timing of casing cementation.

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1 Introduction

This report describes the results of the project ‘Stringers in Salt as a drilling risk’, commissioned to TNO Advisory Group Economic Affairs (TNO AGE) by the State Supervisory of Mines (SodM). The project focussed on anomalous formation pressures associated with stringers that can be encountered when drilling through the (Permian) Zechstein salt in the Netherlands.

Stringers are layers or fragments of rock mainly consisting of minerals other than halite (e.g., anhydrite, carbonate) that are embedded in evaporites that mainly consist of halite, and have different mechanical and flow properties than the salt. The stringers most commonly consist of strata originally interbedded within salt (Talbot and Jackson, 1987). The stringers are sometimes also referred to as floaters or floating blocks, but *stringers* is the preferred term used in this report. The anomalous pressures in the stringers can pose a drilling risk as they may lead to losses of drilling fluids (mud losses) or flow of gas or brine from the stringers (kicks) into the borehole. Both mud losses and kicks may cause affect well control and drilling safety.

The goal of the research is (1) to understand the formation of the stringers, (2) to identify preferred locations and geological setting of stringers in the Dutch subsurface (on- and offshore), (3) to review the causes and effects of overpressures and pore fluid content of the stringers, and (4) to provide an overview of drilling risks and possible risk mitigation measures associated with overpressures and pore fluid content of the stringers.

2 Geological description of Zechstein and stringers

2.1 Brief geological description of Zechstein lithologies

In the Netherlands the Zechstein lithostratigraphy may consists of several formations (Z1 to Z5, Figure 1). The Z1-Z3 formations can contain lithologies that were deposited following a clastic carbonate-evaporite cycle with claystone, carbonate, gypsum/anhydrite, halite and K-Mg salt rocks. The Z4-Z5 formation are characterized by playa-type deposits with increasing amounts of siliciclastic impurities (Geluk, 2000; Geluk et al., 2007). The Z2 and Z3 formations contain the thickest salt units. The Z2 salt with salt content of >95% (mainly halite) can cover two-thirds of the entire Zechstein salt thickness and can be more than 1 km thick. Most of the stringers identified within the Zechstein of the Dutch subsurface are Z3 anhydrite-carbonate (Z3AC) stringers (Geluk et al., 2007; Strozyk, 2017).

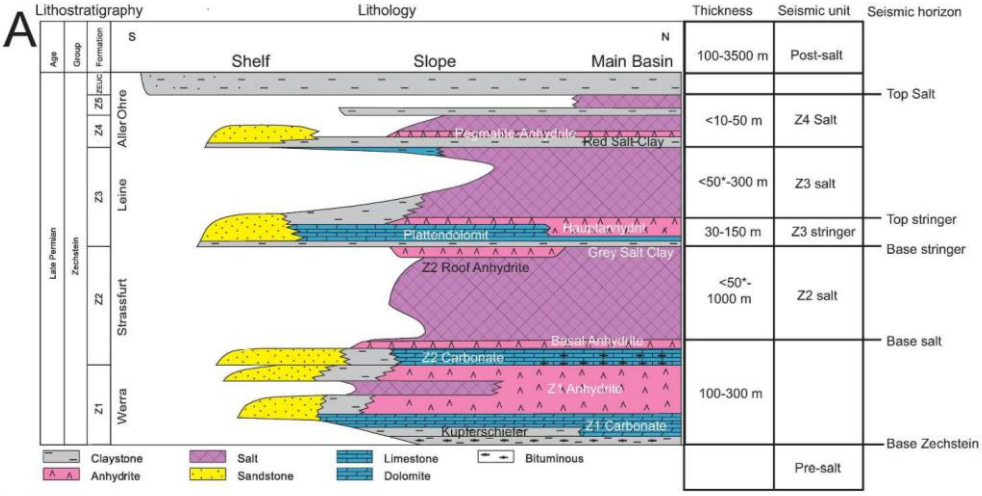


Figure 1 Stratigraphy of the Zechstein the in Dutch subsurface (modified from Geluk, 2007).

2.2 Z3AC lithology and depositional environment

The Z3AC lithology is usually composed of 15–130 m thick Hauptanhydrite at the top, 0.5–20 m thick Platy Dolomite Member in the middle and the very thin (5-10 m) Gray Salt Clay at the bottom. The Gray Salt Clay lithology is characterized by high gamma ray values. Z3AC is only deposited on the slope and in the basin at the northern part of Z3 carbonate platforms, (Geluk, 2007, Figure 1). The platform facies dominantly consists of grey microcrystalline dolomites and algal boundstones. Off-platform shoals have been encountered on the Groningen High. The slope facies comprises laminated and bioturbated carbonate mudstones and silty dolomites with a thickness of up to 40 m. Oolitic and bioclastic grainstones locally occur in the area adjacent to the slope (Van Adrichem Boogaert & Burgers, 1983; Baird, 1993), and on the landward margin of the platform. In the basin the carbonate consists of a few meters thick dark-colored limestone. In the western offshore area the carbonate transitions to fluvial sandstones (Geluk et al., 1997).

2.3 Stratigraphic position of the Z3AC stringers

According to Strozyk (2017), Z3AC stringers are stratigraphically located in the middle to the upper third of the salt section. Relative location in the salt is controlled by the thickness of the Z2 (below) and Z3 salt (above). Since the Z2 salt is much thicker than the Z3 salt, Z3AC is mostly located within the upper third of the entire section. Some of the Z3AC fragments are close to base salt (Figure 2).

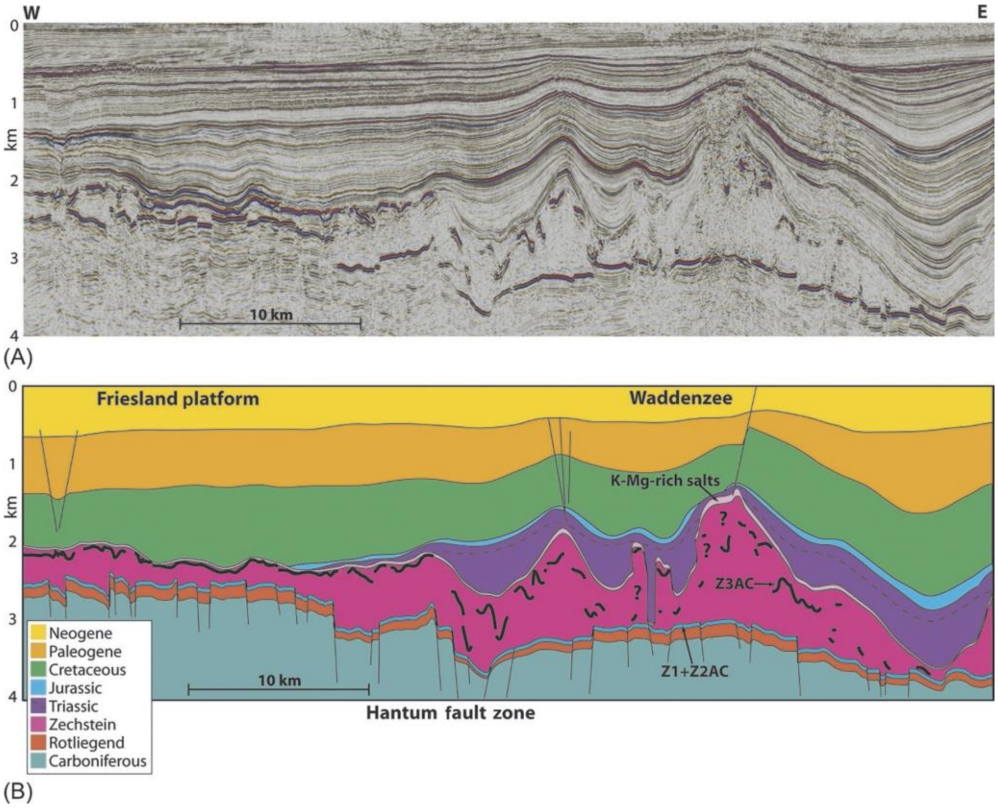


Figure 2 E-W seismic section (A; Vertical axis 5x horizontal) and its seismo-stratigraphic interpretation sketch (B) trending from the Friesland Platform (left) into the Waddenzee area (right). The strong variation in thickness and deformation of the Zechstein section clearly correlates to the complexity of intrasalt structures, imaged by the interpreted Z3AC reflections (black): a thin, layered salt and less deformed Z3AC on the Friesland Platform highly contrasts with the thick, diapiric salt and the highly fragmented and folded Z3AC in the Waddenzee. Note how the Z3AC is highly discontinuous and is intensively folded within the salt crest on the right-hand side (B). From Strozyk (2017).

2.4 Geographic distribution of Z3AC stringers

The Z3AC lithologies are assumed to initially have formed a continuous layer across large part of the Zechstein Basin, especially in the southern part of the southern Permian Basin currently located in the subsurface of the Netherlands (Geluk, 2007). Further North (basinward), the thickness of Z3AC decreases. Stringers have been identified from the Cleaver Bank Platform to the West to the Ameland Platform to the East and are well developed in the Northern Coastal/ Waddenzee area (Strozyk et al. 2012; Strozyk, 2017).

2.5 Structure of the Z3AC stringers

Van Gent *et al.* (2011) show that the Z3AC stringers are on average 40–50 m thick and have a complex structure dominated by boudinage and folding (Figure 3). Strozyk et al. (2014) indicated that these stringers have blocky thickness anomalies of up to 150 m. They are commonly broken into mappable fragments of varying size but are most likely still arranged along the deformed boundary between the Z2 and Z3 salt, with a trend generally following the shape of top Zechstein (Strozyk, 2017). In some areas the salt and the imbedded Z3AC stringers are almost undeformed (for example at the Friesland Platform), while in other areas stringers are very fragmented (for example, in the Waddenzee area, Figure 2).

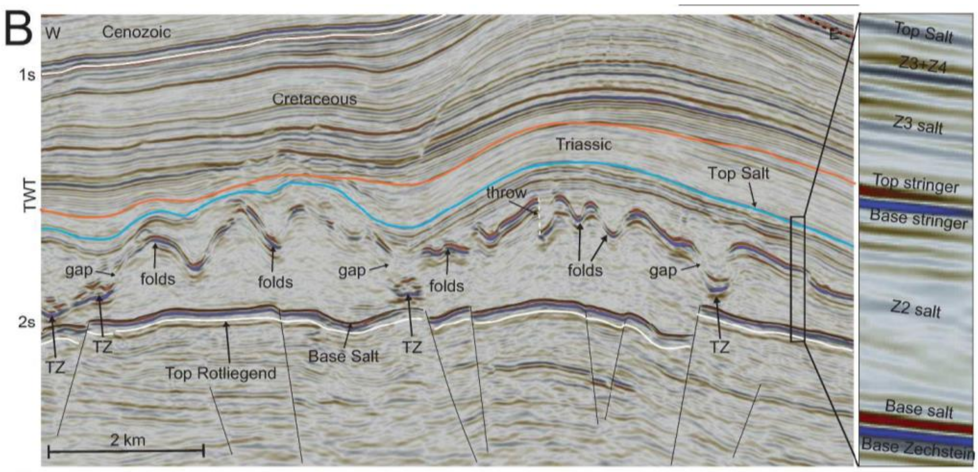


Figure 3 E-W seismic section (5x exaggerated) from the Groningen High showing the highly folded and ruptured Z3AC stringer and thicker zones (TZs) in the Zechstein section as well as a rough stratigraphic interpretation of the supra-salt. The cropped part of the section on the right highlights the seismically resolved part of the Zechstein stratigraphy Strozyk *et al.* (2014).

2.6 Mechanisms controlling movement of stringers

Movement of salt bodies, such as the Zechstein evaporites, that dominantly consist of rocksalt is controlled by the deformation of rocksalt. Deformation of rocksalt is ductile below depths of ~800 meter (> 65 bar confining pressure, Peach et al. 2001), i.e. under these conditions rocksalt flows and its strength is controlled by grain-scale deformation mechanisms (Figure 4, Ter Heege et al. 2005a, b, Urai et al. 2008). Two main types of deformation mechanisms control the flow behaviour or rheology of rocksalt. The mechanical behaviour of both carbonate and anhydrite is different from rocksalt. Under conditions relevant for deformation of stringers, rocksalt tends to be ductile while carbonates and anhydrite tend to be more brittle. It basically means the depth or confining pressure for the transition between brittle and ductile deformation is larger for carbonates and anhydrite than for rocksalt. It also means that at larger depths, the rate of ductile deformation is lower for carbonate and anhydrite than for rocksalt at similar flow stress (i.e. stress-strain relations for carbonate and anhydrite plot to the right and top in Figure 4).

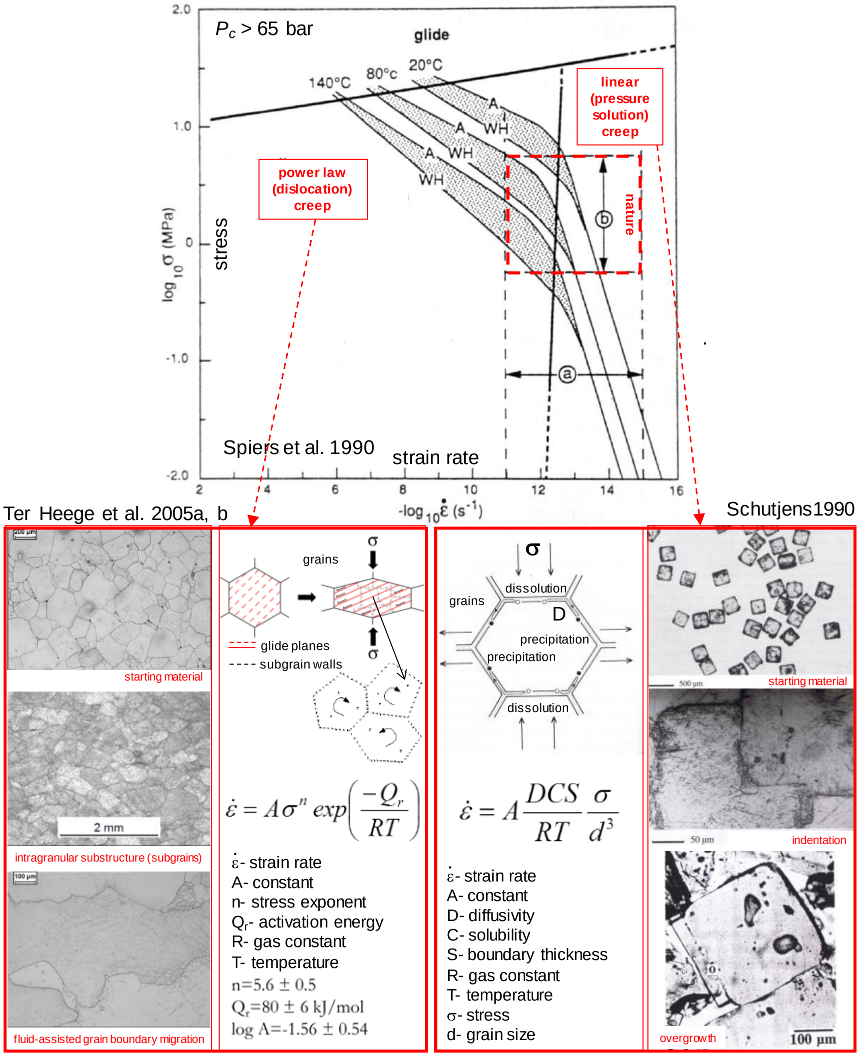


Figure 4 Overview of deformation mechanisms and processes in rocksalt as observed in laboratory experiments. *Top figure*: Deformation mechanism map that describes the relation between flow stress (σ) and the rate of deformation ($\dot{\varepsilon}$, strain rate) at temperatures between 20 and 140°C for confining pressures (P_c) above 65 bar (solid black lines indicate stress-strain rate relations at different temperatures with shaded area between lines indicating the variation for different salt types, A-Asse, WH-West Hackberry, Spiers et al. 1990). Two deformation mechanisms (dislocation creep and pressure solution creep) may be active, depending on stress, strain rate, temperature and grain size (bottom figures). *Bottom left figure*: Typical microstructures indicating dislocation processes and dynamic recrystallization by fluid-assisted grain boundary migration. A schematic diagram explaining the grain-scale dislocation processes, and a general constitutive equation for power law dislocation creep (Ter Heege et al. 2005a, b) are also indicated. The mechanical behaviour resembles that of materials with non-Newtonian viscosity. Note that the values for stress exponent, activation energy and pre-exponential constant are for steady state deformation of rocksalt that includes both dislocation and pressure solution mechanisms as well as fluid-assisted grain boundary migration (Ter Heege et al. 2005b). *Bottom right figure*: Typical microstructures, schematic diagram of grain-scale solution-precipitation processes, and constitutive equation for linear pressure solution creep (Schutjens 1990). The mechanical behaviour resembles that of materials with Newtonian viscosity. See also Urai et al. (2008) for more details.

These findings are important as they can be used to quantify deformation conditions (stress and strain) and styles (brittle or ductile) during halokinesis as well as at present day. For example, the observation that stringers have not sunk to the bottom of the Zechstein evaporites has been used as evidence the Zechstein rocksalt exhibits non-Newtonian viscosity and likely deforms by dislocation creep over geological timescales (Li and Urai 2016).

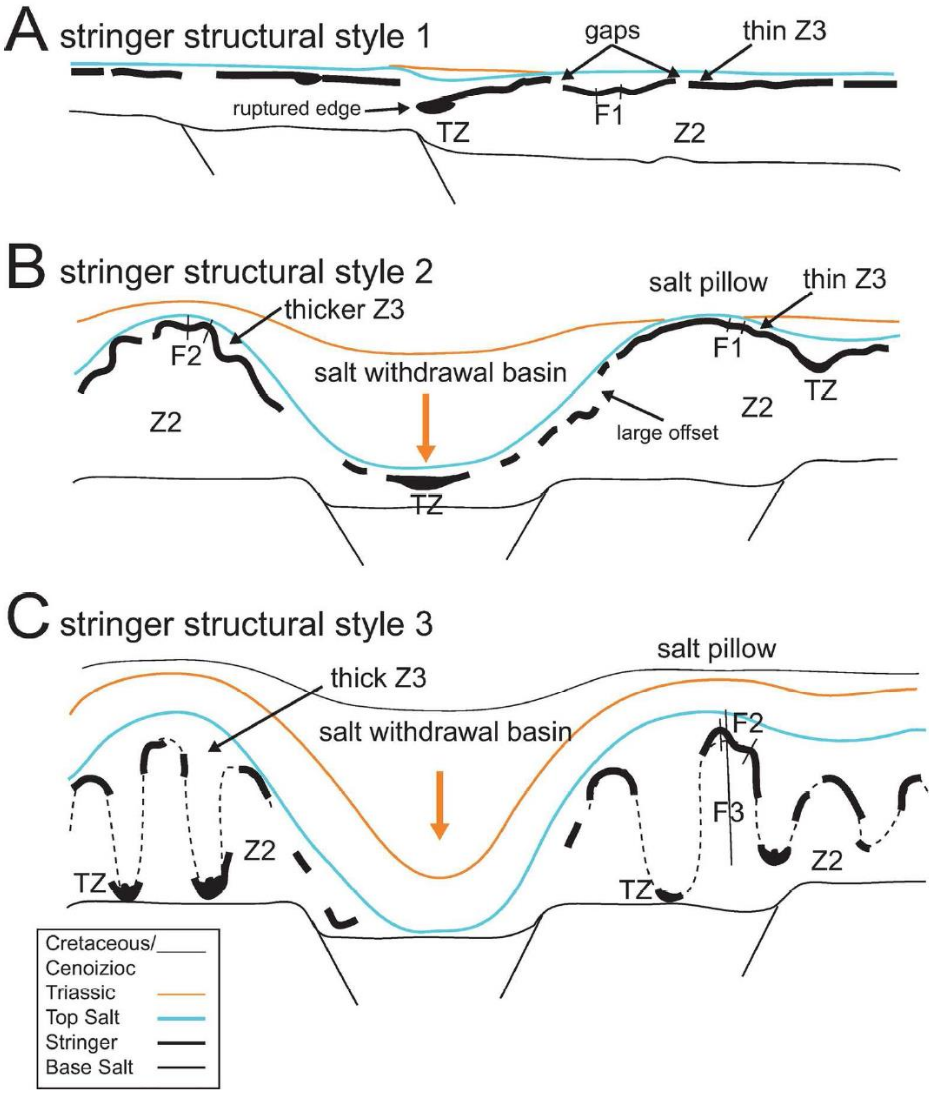


Figure 5 Sketches (not to scale) illustrating the geometries attributed to structural styles 1-3 (for details see text); **A)** The stringer follows Top Salt, it is frequently ruptured and forms F1 folds. Edges of Thicker Zones (TZ) are preferred points of rupture. The Z3 salt layer above the stringer is thin; **B)** The stringer generally follows the deformed Top Salt, it is broken to boudins along flanks of salt structures and below sediment basins. F1 folds occur where the Z3 salt is thin, and F2 folds where it is thick. Thicker Zones (TZ) are often disconnected and located below sedimentary basins; **C)** The stringer does not follow the deformed Top Salt and it is almost completely removed below large sedimentary basins. In the salt highs it is highly ruptured to fragments. The interpolation surface of the fragments image large F3 folds. TZs often represent syncline hinges of these folds. From Strozyk *et al.* (2014).

Movement of salt is driven by tectonics in combination with passive diapirism (Geluk et al. 2007, Strozyk 2017). Movement of the Permian Zechstein evaporites in the Northern Netherlands has been attributed to fault reactivation and differential loading of sediments that caused salt withdrawal and passive diapirism during regional Triassic extensional tectonics. Subsequent movement during Late Cretaceous and Cenozoic regional contractional tectonics has been attributed to basin inversion. Apart from some diapir movement that caused drape folds in Neogene sediments, most parts of the Zechstein in the Netherlands have not been moving over the last 20-30 Ma.

The Z3AC Member was dragged along with the salt during successive halokinetic movements (extension, rafting, and differential loading during Middle-Upper Triassic and Jurassic) (Strozyk, 2017). The strong rheological difference existing between the relatively brittle stringer layer and the surrounding halite results in a very complex deformation pattern comprising shear zones, folding and boudinage. Salt flows caused rupture and folding of the Z3AC on a wide range of scales (Figure 5) (Strozyk*,* 2014). The Z3AC stringers that are physically isolated in the salt have been used as gauges of the rheology of the Zechstein salt with respect to geological strain rates (Li et al., 2012). Li *et al.* (2012) numerically tested whether the high-density contrast between representative blocks of anhydrite and the surrounding rock downward movement of the blocks. These authors show that in contrast to the halite the anhydrite blocks (stringers) show elastic to brittle behavior and move with a much higher viscosity. This also implies massive changes in the mechanics of the rock salt with a Newtonian behavior and large strains at high stresses during tectonically active phases and non-Newtonian behavior preventing significant strain and sinking of brittle inclusions during low stresses in tectonically quiescent times.

2.7 Relation between stringer deformation and generation of overpressures

A consequence of differences in mechanical behaviour of rocksalt, carbonate and anhydrite is that stringers more or less passively move with the flowing salt during halokinesis. Nevertheless, local stresses within and around the stringers develop during halokinesis. These stresses result in the deformation of stringers including fracturing, folding and boudinage (Van Gent et al. 2011). It also means that types of deformation depend on the position and orientation of stringers within the salt body. Strongly fractured or folded stringers have been reported to be prone to overpressures, probably due to enhanced permeability along interconnected fracture networks. Large vertical movements of stringers associated with extensive salt flow along the boundaries of structurally highs and lows may lead to dense fracture networks with overpressures in the stringers (Strozyk 2017). These fracture networks can hydrologically connect stringer compartments that were previously isolated, hence creating a permeable fracture network throughout the stringer. If encountered during drilling larger volumes of fluids or gas can flow into the wellbore for these fractured stringers. In parts of the salt body where salt flow is limited or absent, differential stresses are expected to be low. Finite element modelling of stringer movement after salt tectonics has stopped suggest that differential stresses are on the order of 1 bar (Li and Urai 2016). At such stress levels, pressure solution may be the only active deformation mechanism provided some water is present. Pressure solution can lead to reduction in porosity and hence permeability, which may lead to compartmentalization and lower hydrologically connected stringer volumes. If these stringers are encountered during drilling the probability that large volumes of fluids or gas flow into the wellbore will be lower.

2.8 Relation between pore fluid composition, overpressures and risks of drilling stringers

Pore fluids of stringers have been reported to contain brine, natural gas (mainly methane, CH_4), oil, and sour gas (H_2S). In addition, varying proportions of carbon dioxide (CO_2), nitrogen (N_2), and hydrogen (H_2) may be present as dispersed and free gas in salt formations (Warren 2006, Kukla et al. 2011). Dewatering of gypsum during transformation to anhydrite may add to the overpressure in stringers with brine as pore fluid. Hydrocarbon generation may lead to additional overpressures if the stringers have moved to the oil or gas maturation window during their burial history. H_2S can be generated due to bacterial or thermochemical sulphate reduction associated with breakdown or maturation of organic material. In general, influx of fluids are less problematic for drilling than influx of gases. Brine influx can usually be handled by changing mud weights or by incremental depletion of brine accumulations (Williamson et al. 1997). Possibilities to change mud weights are limited for openhole sections as mud weight increase may lead to mud losses elsewhere along the borehole. The result may be the exchange of fluids between formations at different depths. Installing an (additional) casing shoe and cementation of shallower parts of the well may prevent such exchange. Expansion of gas during gas influx may have a large effect on mud properties, and may locally result in pressures below hydrostatic. As a result, formation fluids may start flowing into the well, and maintaining well control may be an issue. As H_2S is toxic and corrosive, special measures are required to protect personnel and casing steels. Ultimately, extensive influx of brine or gas could require the depletion of fluids, (temporary) shut-in, or even plugging and abandonment of wells.

3 Identification and imaging of Zechstein stringers

Stringers in the Zechstein can be identified in both well and seismic data. Figure 6 shows a stringer in well M09-01 and the corresponding seismic image. On seismic the large contrast in acoustic impedance between the stacked carbonate and anhydrite with the surrounding rock salt produces high-amplitude reflections of the layer's top and base in the seismic data (Figure 7). The high reflectivity allows continuous 3D tracking of the layer across very large areas with high accuracy. However the stringer may become seismically invisible inside larger salt pillows and diapirs where the signal-to-noise-ratio is generally low and very complex intra-salt structures are to be expected (Strozyk *et al.,* 2012). According to Strozyk *et al.* (2014) due to limitations of the seismic data and a threshold of about 20-30 m tuning thickness (also depending on the vintage and quality of the seismic volumes) parts of the stringer with a reduced thickness, size, or very steep dips are generally assumed to drop below seismic resolution (van Gent et al., 2011; and Strozyk *et al.,* 2012). In some cases the existence of the stringer can only be checked using well data. The orientation of the stringers may also affect the capacity to image them on seismic. Highly tilted or vertical stringers may be seismically invisible, yet they can be drilling risks when encountered.

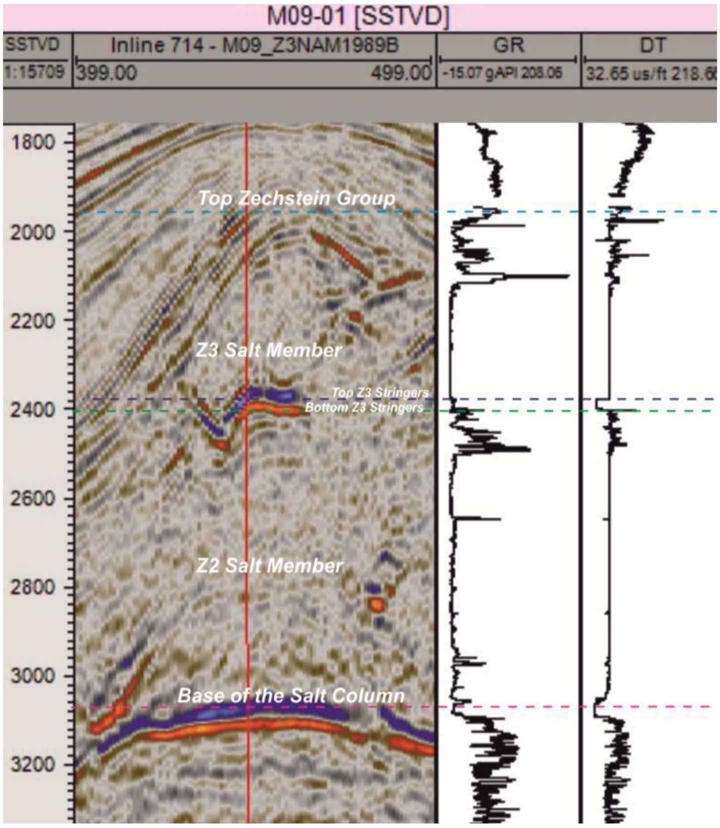


Figure 6 Seismic imaging of a Z3AC stringer encountered in Well M09-01. The pick in Gamma Ray can be seen at the lower part of the stringer, corresponding to the Basal Clay Member. From Masiero, 2015 (TNO unpublished data).

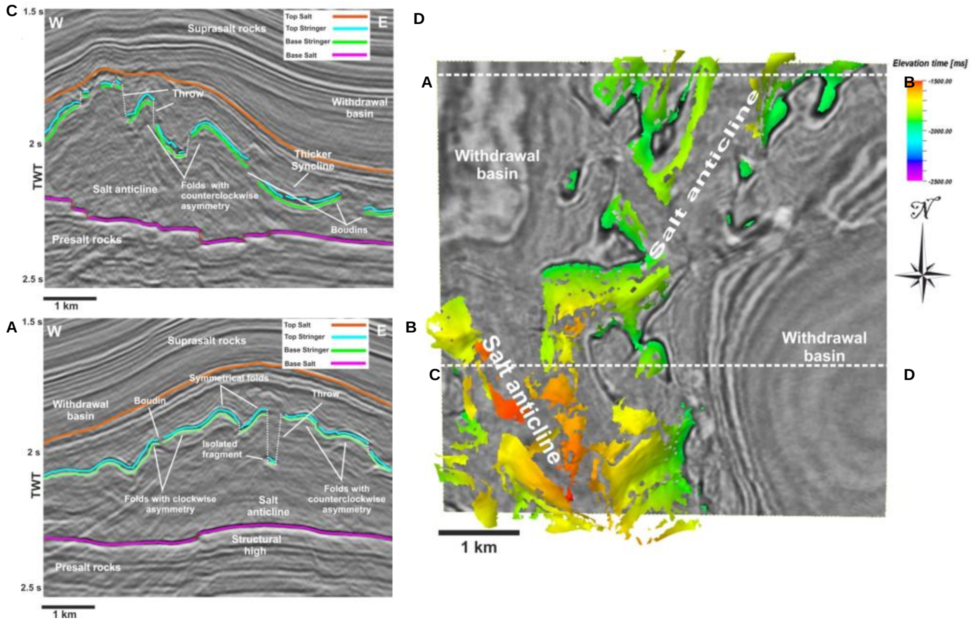


Figure 7 Seismic lines (left) and time slice (right) showing deformed Z3AC Member on the Ameland Plaform. From Masiero, 2015 (TNO unpublished data).

4 Potential issues with drilling salt or stringers

4.1 Issues with drilling salt

Key problems associated with drilling through salt and stringers include:

1. Reduced well control due to abrupt variation in formation fluid pressures associated with non-evaporite inclusions (e.g. stringers) or brine/gas pockets (mainly Z2 and Z3 formations).
2. Borehole closure and stuck drill strings due to salt creep after drilling
3. Washouts, stuck or buckled casings, and problematic cementation due to the presence of highly soluble squeezing salts (e.g., K-Mg rich carnallite and bischofite salt layers, mainly in the Z2 and Z3 formations).
4. Changes in the rate of penetration during drilling and borehole deviation in preferred directions due to variation in salt lithology and associated mechanical properties (Israel et *al.*, 2008).

Accordingly, drilling issues associated with stringers are mainly differences in mechanical properties and anomalous fluid pressures. Incidents related to pressure kicks associated with stringers in the Zechstein formation are the main focus of this report.

Pressure kicks (i.e., sudden inflow of gas or fluids) or mud losses have been mainly encountered in the carbonate members of the Z1, Z2 and Z3 formations. Anomalous fluid pressures in stringers are especially problematic when both overpressures and underpressures are encountered in the same well as no single mud weight is appropriate to handle both in a single well (Jackson and Hudec, 2017). In comparison to the base Zechstein carbonates (Z1C, Z2C) kicks in the Z3 anhydrite-carbonate (Z3AC) occur less frequently. However, if Z3AC kicks are encountered they may produce high overpressures and associated fluid flow (Strozyk, 2017). Some of these carbonate members (especially for the Z3 formations) can be highly deformed and may have significantly migrated within the Zechstein evaporites. Some of the drilling issues can be predicted through seismic observations (Jackson and Hudec, 2017).

4.2 Mechanisms leading to overpressures in stringers

Burial and movement of stringers within the Zechstein salt may lead to pore pressures above or below the hydrostatic pressure gradient. If pore pressures in stringers encountered during drilling exceed the hydrostatic gradient (i.e. the stringers have overpressures), fluids or gases may flow into the well (brine or gas kicks). Stringers with overpressures may lead to drilling problems caused by changing mud properties, increasing well pressures and exchange of fluids between drilled formations at different depths. If pore pressures in the stringers are below the hydrostatic gradient (i.e. the stringers have underpressures), drilling mud may flow into the stringer. Stringers with underpressures may lead to drilling problems caused by mud losses.

Pore pressures in Zechstein stringers are mainly controlled by the geological (burial) history of the Zechstein evaporites, the movement of the stringers within the Zechstein, and the specific mechanical and sealing properties of the salt surrounding the stringers. The lithology of the Zechstein (Z1-Z5) mainly consist of anhydrite, carbonate, dolomite and claystone formations that are interbedded in rocksalt (Figure 1). Stringers mainly originate from Z2 and Z3 lithologies (Williamson et al. 1997, Van Gent et al. 2011, Strozyk 2017). Overpressures have been mainly associated with the ZEZ2 Salt (ZEZ2H), Carbonate (ZEZ2C) and Basal

(ZEZ2A) and Roof (ZEZ2T) Anhydrite Members, and with the ZEZ3 Salt (ZEZ3H) and Main Anhydrite (ZEZ3A) Members, although overpressures have also been reported for the ZEZ1 Carbonate (ZEZ1C) and Anhydrite (ZEZ1A) Members. The anhydrite and carbonate lithologies are prone to hard overpressures (close to the lithostatic pressure). The burial history determines the evolution of pressure, temperature and stresses in these lithologies and stringers. Overpressures can develop by the following main processes (Williamson et al. 1997, Swarbrick et al. 2002; Kukla et al. 2011):

1. Rapid compaction during burial leading to non-hydrostatic pore pressures
2. Sealing of carbonates by overlying anhydrite, and cementation leading to compartmentalization by seepage of anhydrite into the carbonate
3. Changes in pore fluid composition, for example due to the generation of hydrocarbons that act as an additional source of fluid or gas
4. Mineral transformations, for example dewatering of gypsum may generate additional pore water during transformation to anhydrite
5. Pressure- an temperature-induced changes in the density of pore fluids
6. Stress-induced porosity reduction due to poroelastic effects or pressure solution

Most of these processes only generate significant overpressures if the stringers are hydrologically disconnected (sealed off) from their surroundings by impermeable salt (Figure 8).
During burial, movement of the rocksalt (halokinesis) may lead to intense deformation of the anhydrite, dolomite and claystone formations that cause fragments (stringers) of these formations to become surrounded by impermeable salt. As a result, pore pressures in the stringers can increase above the hydrostatic pore pressure gradient, and may even reach the lithostatic gradient.

4.3 Theoretical constraints on maximum expected pore pressure in stringers

The maximum pore pressures in the stringers can be constrained on the basis of an analysis of local stresses. Local stress conditions can be described using the orientation and magnitudes of three principal stresses ($S_1 = S_v$, $S_2 = S_{Hmax}$, $S_3 = S_{hmin}$ for a normal faulting regime, cf. Zoback 2007). In general, the total vertical stress (S_v) can be determined using if the variation of bulk density (ρ) with depth (z) is known:

$$S_v = \int_0^z \rho(z) \cdot g \cdot z \, dz \tag{1}$$

with gravitational acceleration g=9.8 m/s^2. The location-specific variation of bulk density with depth can be determined using the density well log. Stress conditions in the Netherlands are relatively uniform and can be characterized by a normal faulting regime ($S_v > S_{Hmax} > S_{hmin}$) with a relatively uniform NW-SE trend (strikes 120-180°) for the maximum horizontal stress (Van Eijs et al. 2004). For a normal faulting regime, constraints for the minimum (S_{hmin}) and maximum (S_{Hmax}) horizontal stress can be determined using the Poisson effect of overburden weight. In absence of tectonic stresses, and assuming linear elastic deformation and lateral constrained formations, horizontal stresses (S_{hor} indicating S_{hmin} or S_{Hmax}) can be related to overburden weight:

$$S_{hor} = \frac{\nu}{(1-\nu)}\left(S_v - \alpha_{Biot} P_p\right) + \alpha_{Biot} P_p \tag{2}$$

with Biot coefficient α_{Biot} and pore pressure P_p.

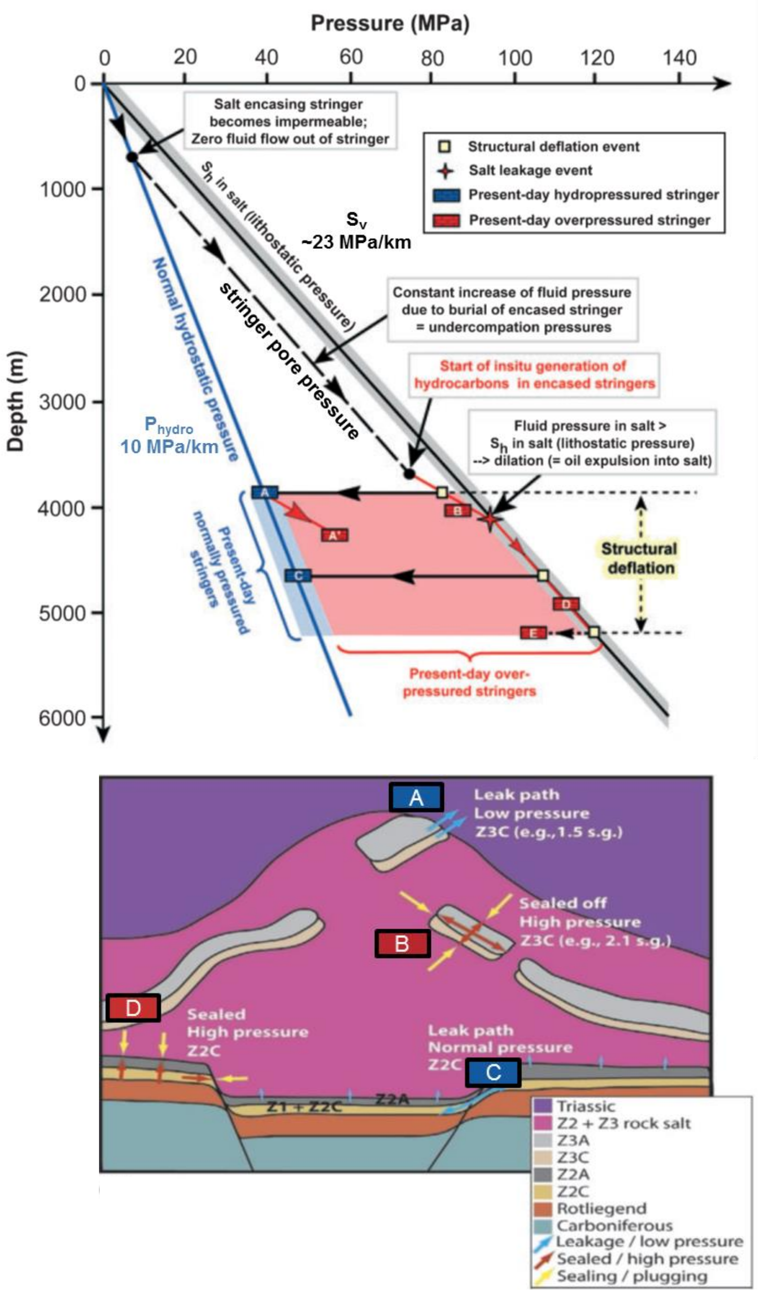


Figure 8 Schematic diagrams showing different scenarios for the evolution of pore pressure in a stringer (*top*), depending on the hydrological connection (sealed/leak path) of the stringer with surrounding formations (right). In the left diagram, burial (black dashed line), the hydrostatic pressure gradient (P_{hydro},blue solid line) and an average lithostatic pressure gradient (S_v, black solid line) are indicated (after Kukla et al. 2011). In the bottom diagram, different scenarios for the hydrological connection between stringers and surrounding formations (boxes labelled A-D) are indicated (after Strozyk 2017).

Viscous rock materials, such as rocksalt, undergo time-dependent (creep) deformation under differential stress ($\Delta S = S_v - S_{hor}$, cf. section 2.6). The result is that over geological timescales and in absence of pressure perturbations by subsurface operations (e.g., drilling or gas production), differential stress in a rocksalt formation will tend to be zero, i.e. $S_v = S_{Hmax} = S_{hmin}$ (also referred to as an isotropic stress state). S_v is related to overburden density and depth alone (Eq. 1) which is constant at relevant timescales (i.e. timescales at which creep processes can relax differential stresses). Therefore, at present day, horizontal stresses in the salt formation are elevated compared to the (non-viscous) under- and overburden (cf. Eq. 2). Pore pressures (P_p) are generally between the hydrostatic pressure gradient ($\Delta P_{hydro}/\Delta z = 100$ bar/km) and the lithostatic pressure gradient ($\Delta P_{lith}/\Delta z = \Delta S_v/\Delta z$). If $P_p > S_{hmin}$, tensile fracturing will occur and fluid will escape from the formation through the fracture until fractures close, approximately at $P_p = S_{hmin}$ (Zoback 2007, Schoenherr et al. 2007). As $S_{hmin} \approx S_v$ in rocksalt, the lithostatic pressure ($P_{lith} = S_v$) can be regarded as an upper bound for pore pressure in a stringer.

For a typical density of sedimentary rocks ($2.0 < \rho_r < 2.3$ kg/m^3), the lithostatic pressure gradient is between 196 and 225 bar/km. In absence of well log data, an average gradient of ~220 bar/km is often used. Accordingly, a rough upper bound for pore pressure in stringers (P_s) is given by the lithostatic pressure ($P_s = 225\ z_s$ with depth z_s in km). Tighter constraints can be determined by using the variation of density with depth from density logs, and if data on pore pressures in the over- or underburden is available. The actual pore pressure in a stringer critically depends on the timing and depth at which the stringer became hydrologically disconnected from surrounding permeable formations. Therefore, the original location of the stringer lithology (Figure 8) and the current location of the stringer could be used to further constrain pore pressures. Four end member cases can be defined (Figure 8):

1. A stringer that is detached from its source formation and in hydrological connection with a permeable formation in the overburden (case A). If overburden pressure $P_o = P_{hydro}$, the stringer will have a pore pressure of $P_s = P_o = 100\ z_s$ (with depth z_s in km).
2. A stringer that is “floating” in the Zechstein salt at and sealed off from surrounding formations (case B). In this case, the stringer can have a maximum pore pressure equal to the lithostatic pressure, $P_{smax} = P_{lith} = (\Delta P_{lith}/\Delta z)z_s$.
3. A stringer that is detached from its source formation and in hydrological connection with a permeable formation in the underburden (case C). Due to the presence of the Zechstein, underburden pressure P_u is not likely to be hydrostatic. If a hydrological connection with formations at hydrostatic pressure is absent, the most likely scenario is that $P_{hydro} < P_s < P_{lith}$.
4. A stringer that is connected to and in hydrological connection with its source formation (case D). Analogous to case B, the stringer can have a maximum pore pressure equal to the lithostatic pressure, $P_{smax} = P_{lith} = (\Delta P_{lith}/\Delta z)z_s$. In addition, a higher volume of fluid influx can be expected compared to case B when drilled as a larger volume of formation is connected.

Pore pressure predictions for these end member cases can be evaluated against actual pore pressure data collected during drilling (cf. section 5.3).

5 Analysis of Zechstein drilling events in the Dutch subsurface

5.1 Data sources

In previous years there have been a number of projects which investigated drilling risks in Zechstein as well as (anomalous) formation pressures. The projects that have been used as the basic source of data for this research are:

- ‘Drilling Hazards Information System for the Netherlands – pilot project’ (Kortekaas 2013). A drilling hazard database set up after screening by eleven operators of 102 wells for geological incidents. In total 49 incidents extracted for this study.
- Pressure SNS 2014 (Verweij 2014). Investigation of all documented formation pressures in the Dutch subsurface. The project resulted in a tool which can be found on nlog.nl For this project a total of 1145 wells were investigated. A selection was made on overpressures within the Zechstein, which led to 32 incidents used for this project.
- EBN Drilling Hazard Database (Hoetz et al. 2013; Hoetz 2017, *pers. comm.*). A drilling hazard database that is continuously updated by EBN. Currently 860 wells are included, with more coming each year. From this database an extraction was made for any drilling incident reported within the Zechstein formation and of these the anomalous pressure occurrences are used in this project. In total 46 incidents extracted. We thank EBN and Guido Hoetz for this data an appreciate the cooperation on this subject.
- Stringers in Salt Expert meeting on February 6th 2018 (Appendix B Expert Meeting Results). To get an overview of the current state of knowledge on drilling stringers in Zechstein salt in the Netherlands an expert meeting was organized. For this expert meeting oil & gas operators active in the Netherlands as well as AkzoNobel were invited to share their experiences. Operators showed various cases where drilling issues were encountered when drilling in salt (see Appendix B Expert Meeting Results for program and results).

Data from these projects was used together with additional analysis within the current study to compile an inventory of Zechstein drilling events in the Netherlands.

5.2 Approach

The data inventory and analysis in this study indicated that a total of 2575 wells drilled the Zechstein formation in the Netherlands. In the 4 previous projects combined (section 5.1), the occurrence of drilling events has been analyzed for a total of 921 unique wells. Of these wells 62 wells with reported drilling events have been investigated in this study. It should be emphasized that the 62 wells are a selection based on expert knowledge, and *not* based on a thorough screening of all 2575 wells for reported drilling events. Note that this means that not all Zechstein well reports have been investigated. If all end of well reports of each Dutch Zeichstein well were to be included, more stringers in salt would potentially have been found. Another option for detecting more drilled stringers would be to go through available seismic and cross-check with wells that are drilled through stringers visible on seismics. Therefore, the number of events likely is a lower estimate of all events that occurred during drilling of the Zechstein in the

Netherlands (Appendix A). Moreover, stringers are deposited throughout the Zechstein Basin, and therefore the number of drilled stringers will be larger than 62. However, if drilling a stringer did not lead to a drilling problem or the event has not been reported, the wells are not investigated in this study.

For the events in the selected 62 wells the main characteristics of the well and event has been investigated, including reported overpressure, location, spud date, depth of the Zechstein, formation pressure and drilling issues such as downtime or modification to drilling fluids. Moreover for each well seismic data is analyzed to determine the location of the stringer with respect to the base and top of the Zechstein, and to determine the visibility of the stringer on seismic (see Appendix C). In this study, 2D and 3D seismics were used that is publicly available (www.nlog.nl). The seismic data is used without further reprocessing. The key features that were determined for each case are:

1. Reported (over-)pressures that were observed in wells during the drilling event.
2. Seismic visibility of the stringer, classified as low, medium and high that roughly correlates with (i) cases where stringers are not or poorly visible on seismic or are at locations where seismic data is of bad quality, (ii) cases where the presence of stringers can be detected using seismic, and (iii) cases where stringers can be mapped and their structures analyzed.
3. Continuity of the stringer, classified as low, medium and high that roughly correlated with (i) cases where stringers are fragmented or faulted, (ii) cases where stringers are isolated but not fragmented or faulted, and (iii) cases where stringers is continuous over a larger area on seismic sections.
4. Orientation of the stringer, classified as dominantly horizontal or tilted.
5. Character of the base and top of the Zechstein formation. A faulted, flat or unspecified (n/a) base of Zechstein is distinguished. An anticline, flank and syncline structure of the top Zechstein is distinguished.
6. Type of structural setting of the stringer (cf. Figure 5, Strozyk 2014)

5.3 Overpressures associated with Zechstein drilling events

A total of 32 formation pressures were collected for the 62 wells with reported drilling events (Figure 9). The formation pressures can be used to evaluate pore pressure predictions from theoretical constraints on maximum expected pore pressure in stringers (section 4.3). In addition, trends in overpressure with depth or relative position within the Zechstein can be explored (Figure 10).

The most important observations are that:

1. All reported overpressures are above ~1/3 and up to the maximum overpressure constrained by the lithostatic pressure (P_{lith} - P_{hydro}).
2. All reported Zechstein lithologies (ZEZ1-ZEZ3) can develop overpressures, with most reported overpressures in ZEZ2 and ZEZ3. Overpressures in all reported Zechstein lithologies can be close to the upper bound constrained by the lithostatic pressure. There is no clear difference of maximum overpressure between the different lithologies.

3. Overpressures in carbonate and anhydrite formations tend to plot at the high end of overpressures encountered in salt (close to the upper bound).
4. Most reported kicks are from influx of brine or unknown fluids. Gas kicks are observed in 3 carbonate and anhydrite formations.
5. There is a clear trend of maximum possible overpressure with increasing depth (as the hydrostatic and lithostatic pressure gradients diverge with depth). There is no clear trend of maximum possible overpressure with relative position within the local Zechstein formation (note that local thickness and depth can vary).

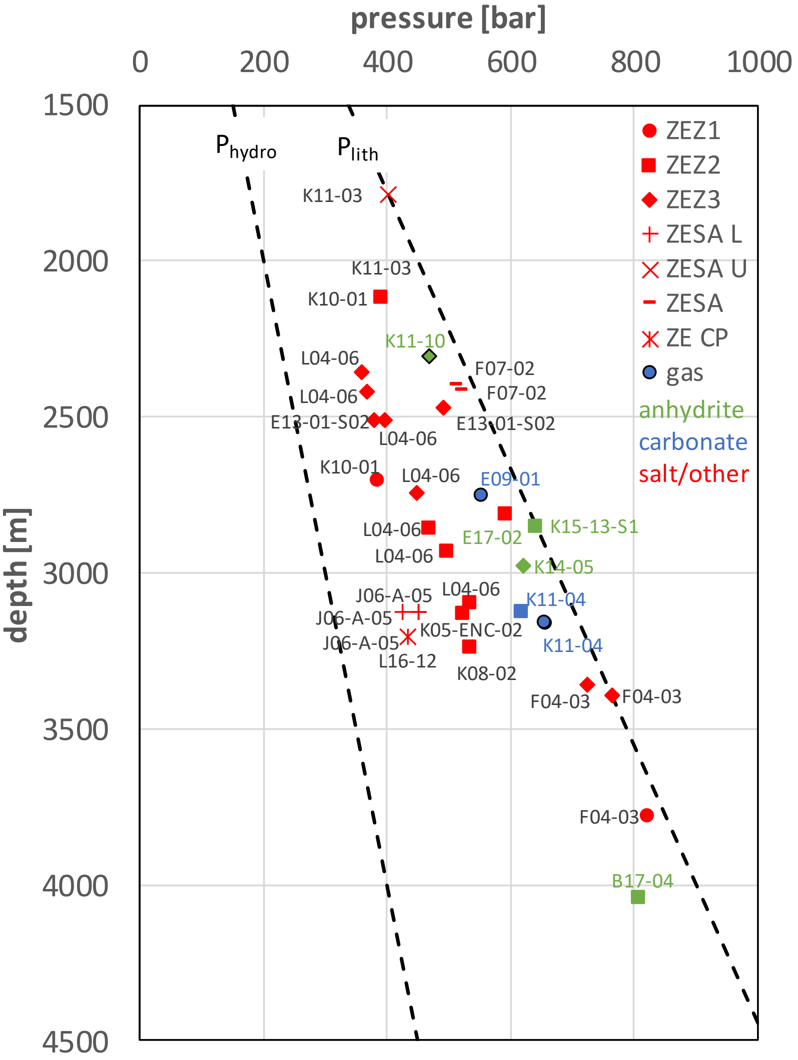


Figure 9 Formation pressures (32 data points) from different wells (indicated by labels), collected during drilling of the Zechstein. Bounds on formation pressures given by the hydrostatic (P_{hydro} with $\Delta P_{lith}/\Delta z$ = 100 bar/km) and lithostatic (P_{lith} with $\Delta P_{lith}/\Delta z$ =225 bar/km) pressure gradients (black dashed lines), reported lithology (different symbols) and rock type (colours) are indicated. Only wells with kicks are indicated. 18 out of 32 kicks are from stringers as confirmed using seismics, others are unclear or seismics are absent. 4 kicks are in Z1 formation, 10 are in Z2 formation, 10 are in Z3 formation, 8 have different lithological labels (cf. Figure 1). 3 out of 32 are gas kicks (symbols enclosed by black lines) in carbonate or anhydrite formations, others are brines or unknown.

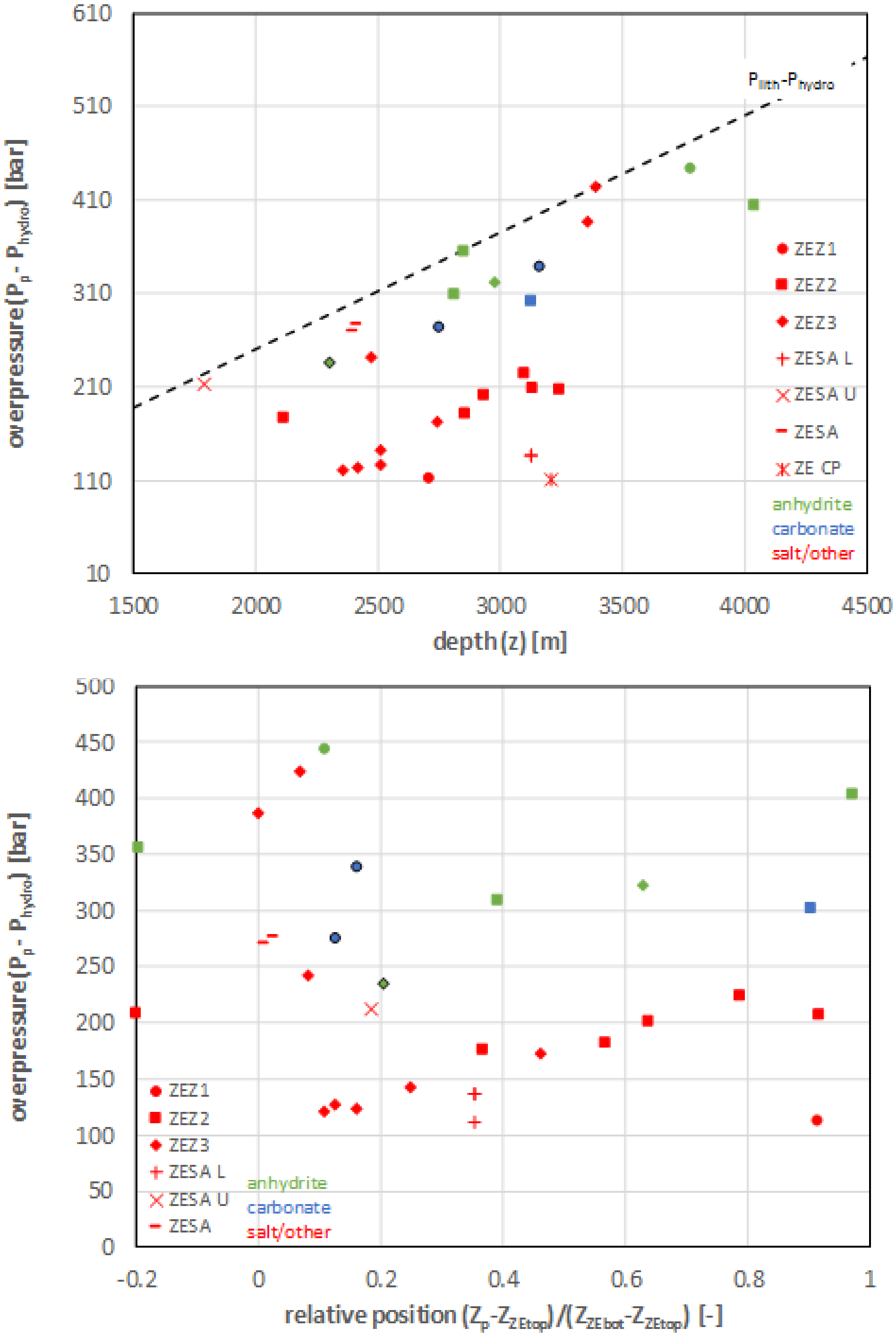


Figure 10 Trends of formation overpressure with depth (top figure) and relative position within the Zechstein (bottom figure). Symbols and labels are similar to Figure 9.

5.4 Characteristics of Zechstein drilling events and stringers

Zechstein drilling events

Based on the analysis of the 62 wells with reported drilling events, 84 events could be identified (Figure 11). Accordingly some wells show multiple events. The geographical distribution of drilling events seems to correlate with palaeography during deposition of the Z3C Member with most drilling events linked to Z3C carbonates deposited in slope or basin facies extending northward (

Figure 13). The temporal distribution of drilling events indicates drilling events occurred over the last 65 years, mainly between 1972 and 2012 (Figure 14). The last 5 years only 1 event is reported.

For 66 drilling events in 62 wells, the reported event type could be classified into (i) Pressure kicks (42, 64%), (ii) brine influx (15, 23%), (iii) mud losses (5, 7%), and (iv) gas influx (4, 6%), see Figure 12. Pressure kicks indicate influx of fluid or gas which is unspecified in the reports. Accordingly, combined pressure kicks and brine/gas influx (61, 92%) are much more frequent than losses. Unexpected gas influx poses a higher risk due to volume expansion with pressure decrease.

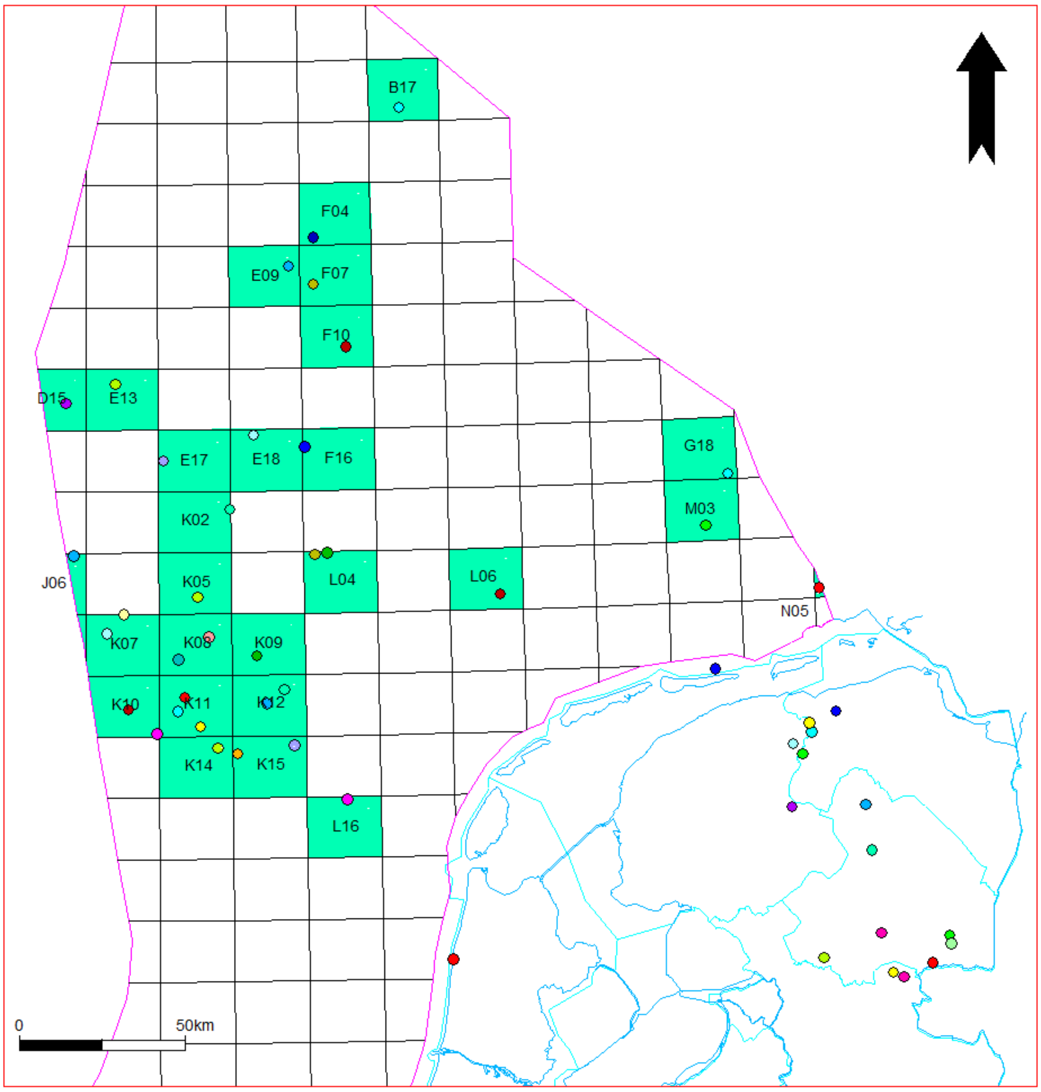


Figure 11 Overview of well locations with Zechstein drilling events in the Dutch subsurface. In total 84 drilling events were identified in 62 wells.

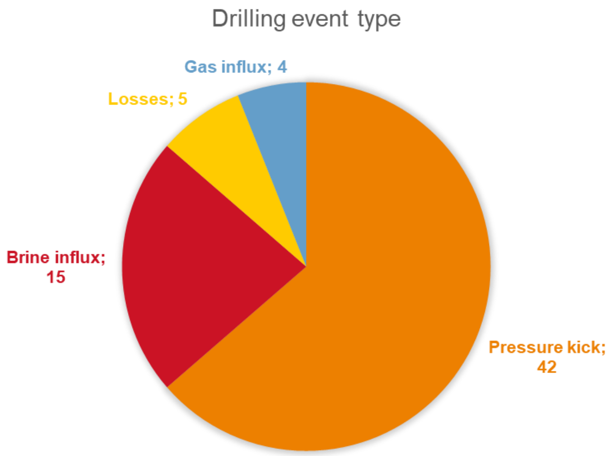


Figure 12 Number of events for different drilling event types of 66 events in 62 wells.

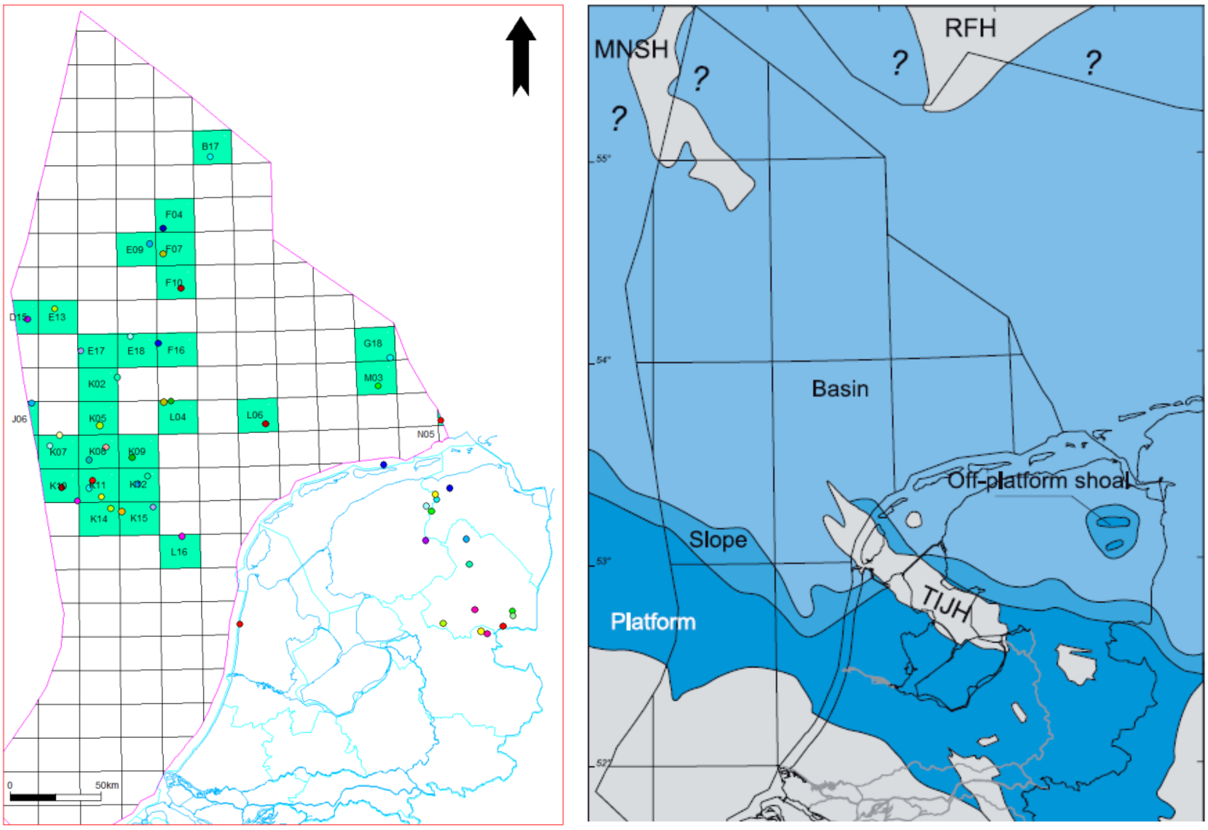


Figure 13 Locations of wells with Zechstein drilling events (*left*) and facies map of the Z3C Member consisting of carbonate deposits (*right*). MNSH- Mid North Sea High, RFH- Ringkøbing-Fyn High, TIJH-Texel-Ijsselmeer High (from Geluk 2007).

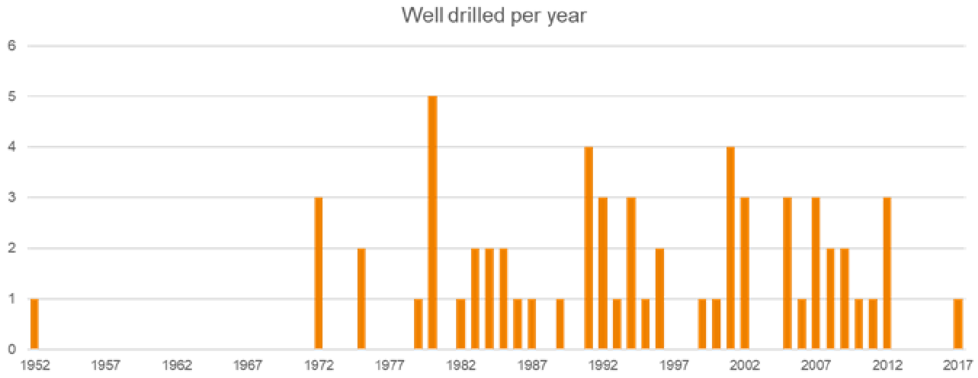


Figure 14 Number of wells with Zechstein drilling events (drilling incidents or anomalous pressure in the Zechstein) through time (year wells were drilled).

For 54 out of 62 wells (88%) a stringer is visible and interpreted on 2D or 3D seismic (Appendix C). For 45 out of 62 wells (72%) the depth of the recorded drilling events correlates with the depth of a stringer on seismic. For these 45 wells, stringer characteristics have been analyzed.

Stringer visibility

The distribution of stringer visibility for the 45 wells drilled through stringers show a positive correlation between drilling events and visibility on seismics (Figure 15A). As ~80% of stringers are visible on seismics, most stringers that caused drilling events could have been spotted on seismic before drilling commenced. The data also shows that for more than half of the events that cannot be correlated to a stringer seismics are of bad quality. For the other stringers with low visibility stringers cannot be identified on seismics or the reported drilling event is not related to a stringer.

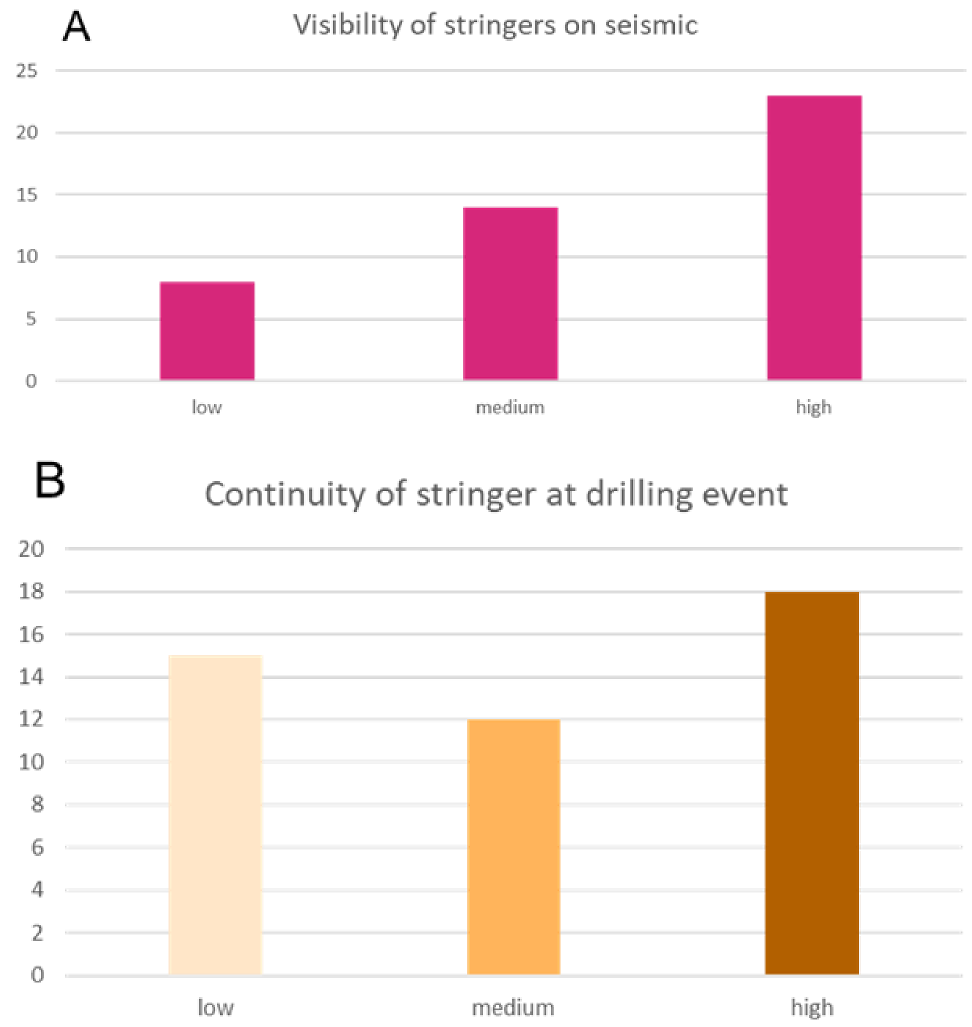


Figure 15 A) Visibility of a stringer on the available seismics. B) Continuity of the stringers.

Stringer continuity, folding, orientation and structural type

The distribution of stringer continuity for the 45 wells drilled through stringers show no clear correlation between drilling events and level of continuity (Figure 15B). Accordingly, the continuity (on seismic) of a stringer is a poor indicator for the probability of encountering a stringer-related drilling event. The number of drilling events associated with folded and tilted stringers (58%) is higher than for flat and horizontal stringers (42%, A, B). The overall structure of the wider stringer area affects the number of drilling events (C). A higher number of drilling events are associated with folded stringers following the top salt (structural types A and B) compared to the more intensely folded and fragmented stringers not following the top salt (structural type C, cf. Figure 5, Strozyk 2014). Despite the higher occurrence of drilling events associated with folded and tilted stringers following the top salt, the small differences suggest that stringer structure types are not good indicators for the probability of encountering a stringer-related drilling event.

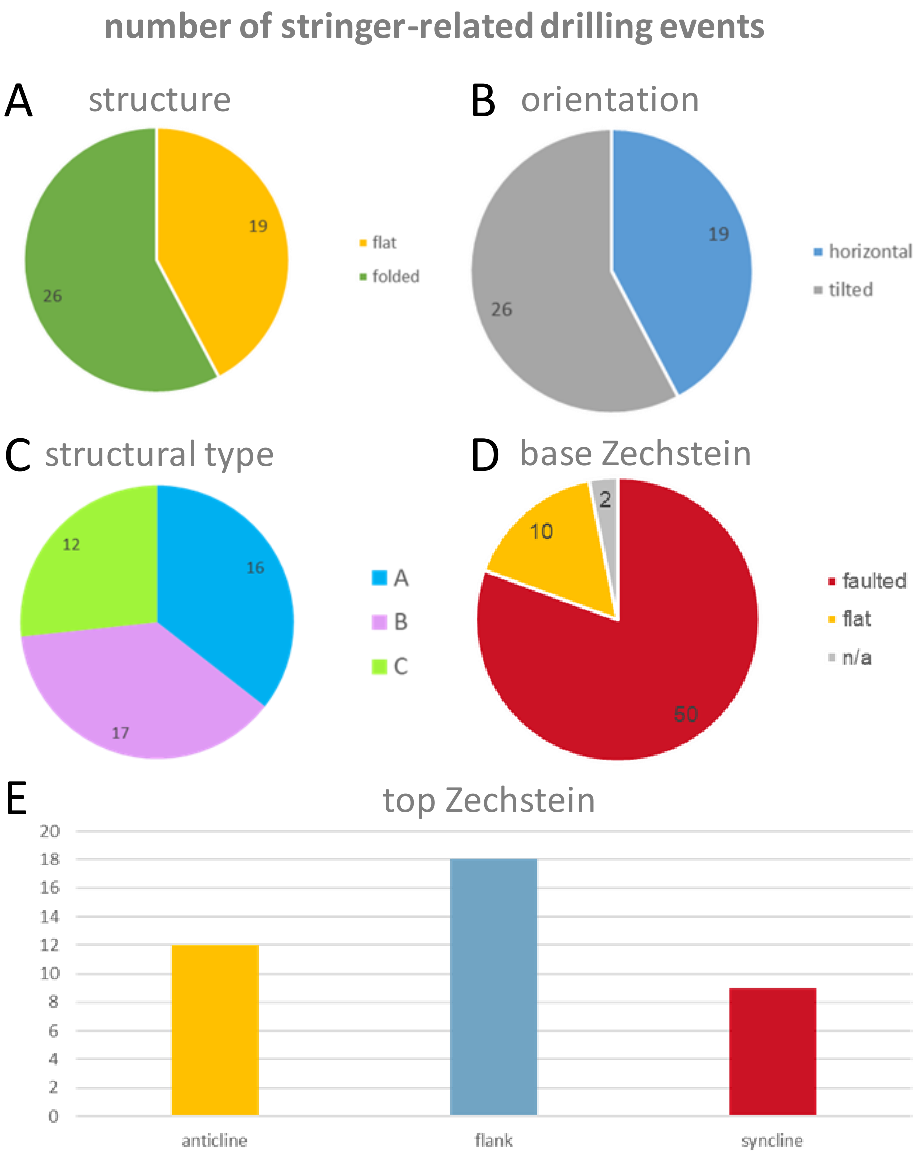


Figure 16 Correlation between drilling events and stringer characteristics (number of drilling events). A) Number of flat or folded stringers. B) Number of horizontal or tilted stringers. C) Number of stringers with specific structure type (cf. Figure 5). Stringer character, orientation and structure determined using seismics. D) Structure of the base Zechstein. E) Structure of top Zechstein.

Character of the base and top of the Zechstein formation

The structural character of the base Zechstein has been analyzed for the 62 wells with drilling events (Figure 16D). A high number (80%) of drilling events is associated with faulted base Zechstein compared to a base Zechstein that is flat (16%) or unspecified (4% n/a). For 39 drilling events, the structural character of the top Zechstein has been analyzed (Figure 16E). More drilling events occur when drilling in the area below the flank of a folded top Zechstein surface than when drilling in the area below the anticlines or synclines. Although comparable with drilled anticlines, drilled synclines show the lowest number of drilling events. Based on this analysis it is recommended to avoid drilling areas near faulted base Zechstein and flanks of folded top Zechstein (when different drilling trajectories are possible).

6 Risk assessment and mitigation of risks

6.1 Definition of impacts, hazards and risks

The terms hazards and risks are often used interchangeably to indicate the potential occurrence of incidents. It is therefore good to first provide some definitions of these concepts. Within the context of this report, *impacts* are considered as effects resulting from drilling operations, *hazards* as potential incidents caused by drilling operations that *may* affect drilling safety or efficiency. Hazards and incidents are defined on the basis of their causes and effects. To define an appropriate risk assessment framework, it is important to emphasize the difference between hazards or incidents and risks (e.g., Okrent 1980; Smith 2013). Throughout the report risks are defined as the combination of the *probability or likelihood* of the occurrence of an incident or hazardous event (e.g., a gas kick) and the (severity of) *impacts or effects* that the incident has (e.g., loss of well control).

6.2 Risk assessment methodology

Risk assessment was based on the following two approaches: (1) a bow-tie approach to describe incidents in terms of its causes and effects with associated preventive and control measures (Figure 17, Van Thienen-Visser et al. 2013; De Waal et al. 2017), and (2) a risk assessment matrix that classifies risks according to their probability of occurrence and effects (Energy Institute 2008; De Waal et al. 2017).

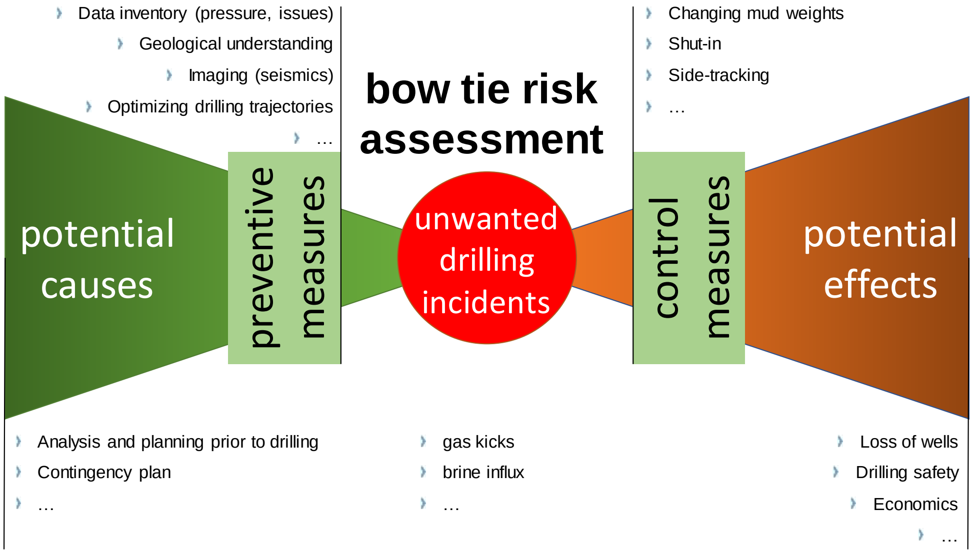
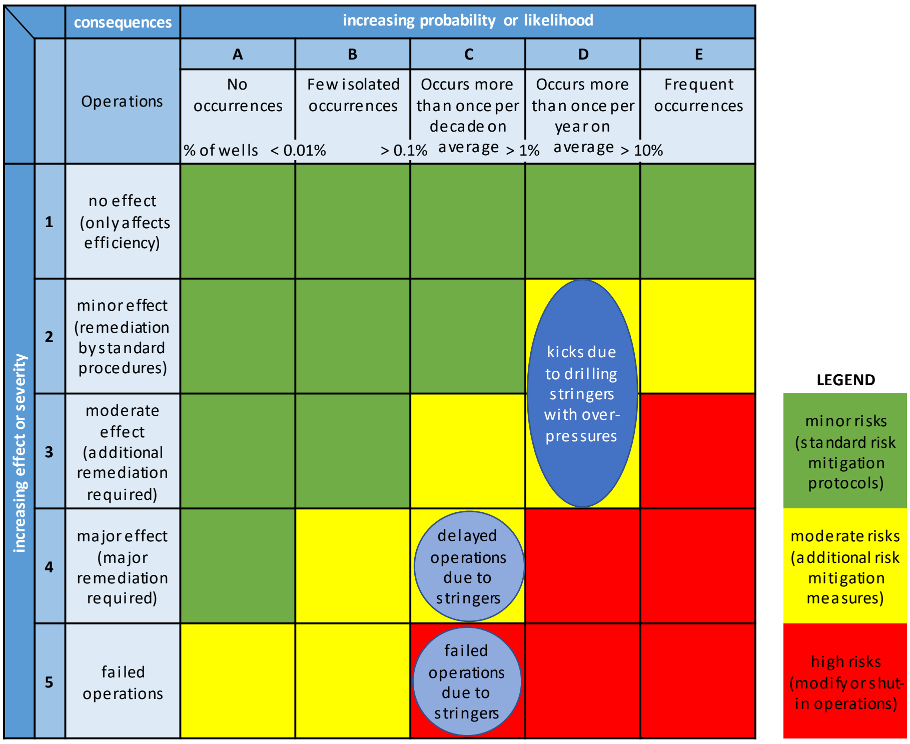


Figure 17 Bow-tie approach for risk assessment describing an incident in terms of its potential causes and effects with associated preventive and control measures (Van Thienen-Visser et al. 2013; De Waal et al. 2017). Some key examples relevant to drilling stringers in salt are also indicated.



consequences		increasing probability or likelihood				
		A	**B**	**C**	**D**	**E**
	Operations	No occurrences	Few isolated occurrences	Occurs more than once per decade on average	Occurs more than once per year on average	Frequent occurrences
	% of wells	< 0.01%	> 0.1%	> 1%	> 10%	
1	no effect (only affects efficiency)	🟩	🟩	🟩	🟩	🟩
2	minor effect (remediation by standard procedures)	🟩	🟩	🟩	🟨 kicks due to drilling stringers with over-pressures	🟨
3	moderate effect (additional remediation required)	🟩	🟩	🟨	🟨	🟥
4	major effect (major remediation required)	🟩	🟨	🟨 delayed operations due to stringers	🟥	🟥
5	failed operations	🟨	🟨	🟥 failed operations due to stringers	🟥	🟥

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- 🟩 minor risks (standard risk mitigation protocols)
- 🟨 moderate risks (additional risk mitigation measures)
- 🟥 high risks (modify or shut-in operations)

Figure 18 Example of a risk assessment matrix that classifies risks (minor to high) according to their probability or likelihood of occurrence (class A-E, based on the number of wells and frequency of occurrence) and the severity of impacts or effects (class 1-5, based on the effect on operations). Modified after Energy Institute (2008).

6.3 Risk assessment of drilling the Zechstein

The risk assessment matrix is useful to compare the relative importance of different events and incidents that may be encountered when drilling through the Zechstein. Following the risk assessment methodology outlined above, the relative importance of risks associated with drilling through stringers in salt is determined by the likelihood of encountering brine or gas influx while drilling through the Zechstein, and by the effect of brine or gas influx on drilling safety and operations.

The division of probability classes is based on the number of incidents relative to the number of wells drilled in the Zechstein Formation (% of wells). Drilling events were reported in 62 wells with the occurrence of drilling events has been analyzed for a total of 921 unique wells out of 2575 wells that drilled the Zechstein formation in the Netherlands (section 5.2). Again, it should be emphasized that the 62 wells with drilling events are *not* based on a thorough screening of all 2575 wells. Also, it is unsure if more events would be found if reports of all 2575 wells were to be screened as in selecting the 62 wells there has been a focus in the current and previous projects on the wells with known drilling events. Therefore, we regard the 62 wells with drilling events as a lower estimate of all events that occurred during drilling of the Zechstein in the Netherlands.

Severity of effects are classified in terms of reported impacts of drilling incidents. Brine or gas influx that requires changes in mud weights can be regarded as a minor effect. Delay of operations (lost time) caused by temporary shut-in of wells or installation of additional casing shoes can be regarded as a major effect. Plugging and abandonment (and potentially side-tracking) of wells can be regarded as afailed operations. The combination of probability and impacts determines the risk class (minor to high). Although the division in classes can vary according to expert opinion, the matrix is useful to compare the relative importance of incidents and risks.

The most frequent incident that may occur if stringers in salt are encountered while drilling through the Zechstein is influx of brine or gas due to overpressures in the stringers (section 5.4, Figure 12). The data inventory of 921 unique wells (out of 2575 wells drilled through the Zechstein) indicated that 81 pressure anomalies were observed in 61 wells. Therefore, a lower estimate for the probability of encountering a pressure anomaly when drilling the Zechstein in the Netherland is ~2.3% of all wells drilled. For 54 wells (~2.1% of all wells drilled) a stringer was observed on seismics, and for 45 wells (~1.7% of all wells drilled) the depth of the recorded drilling events correlated with the depth of a stringer on seismics. The effects are mostly unstable well pressures that can be handled by increasing mud weights or well depletion (minor to moderate effect, class 2-3). The overall risk of drilling stringers with overpressures in the Zechstein that can be handled by increasing mud weights or well depletion can be classified as moderate (position D2-D3 in Figure 18). In the data inventory, 5 cases (~0.2% of all wells drilled) have been reported where drilling of stringers have caused a significant delay in operations (lost time), which can be regarded as a major effect (class 4). Accordingly, the risk of drilling stringers with overpressures in the Zechstein that cause significant delay in operations can be classified as moderate (position C4 in Figure 18). In the data inventory, 4-5 cases (~0.2% of all wells drilled) have been reported where drilling of stringers have led to failed operations (e.g., shut-in, plugging and abandonment, and side-tracking of wells, class 5). Accordingly, the risk of drilling stringers with overpressures in the Zechstein that led to failed operations can be classified as high (position C5 in Figure 18).

6.4 Mitigation of drilling risks associated with stringers in salt

The bow-tie approach can account for two types of mitigation measures that lower risks associated with drilling incidents (Figure 17, Table 1): (1) Preventive measures that mainly lower the probability of incident occurrence (e.g., analysis prior to drilling), and (2) control measures that mainly lower the effects of incidents after they occurred (e.g., changing mud weights after brine or gas kicks).

One of the problems with improving preventive measures to mitigate stringer-related drilling risks is that there are few good indicators that are available prior to drilling (section 5.4). The best options (when different drilling trajectories are possible) is to avoid folded, tilted stringers, and to avoid areas where the base Zechstein is faulted or areas below the flanks of folded top Zechstein. Accordingly, the main improvement of preventive risk measures is to improve the identification, imaging and mapping of stringers and surrounding salt boundaries. Innovative seismic and imaging techniques such as curvature techniques and attribute mapping may better identify stringers from seismic data (Figure 19).

Mitigation Measures		Typical examples
Preventive Measures		
1	Regulations, contingency plans & internal procedures	Well planning, monitoring & mitigation protocols, regulations & best practices for drilling stringers
2	Geological characterization	Prediction of rock types, overpressures & pore fluid content of stringers
3	Seismic imaging	Analysis of location, geometry, spatial extent and distribution of stringers
Control Measures		
1	Modification of drilling fluids (mud weights)	Increase mud weight to handle brine or gas kicks
2	Flowback	Flowback of drilling fluids to reduce fluid exchange between formation and well
3	Well shut-in & sidetracking	Shut-in & cementation of (parts of) well, potentially side-track around stringer

Table 1 Examples of preventive and control measures for mitigating risks associated with incidents while drilling stringers in salt.

For most stringer-related drilling events in the Zechstein, control measures include modification of mud weights, in some cases, in combination with flowback. Only 4-5 cases these control measures were insufficient to maintain or regain well control and drilling of stringers have led to failed operations (e.g., shut-in, plugging and abandonment, and side-tracking of wells). Improvements of control measures could be in best practices for handling pressure kicks, locations of casing shoes and timing of casing cementation. Other possible improvements related to well engineering and drilling equipment is beyond the scope of the current study (see for example expert meeting presentation by Van der Woude on Wintershall drilling practices, Appendix B Expert Meeting Results).

In the expert meeting (Appendix B), most operators indicated that the main approach to reducing stringer-related drilling risks is to avoid stringers if identified. As it may not always be possible to identify stringers (due to absence of seismics or limited seismic resolution), the general notion was that stringer-related drilling risks should always be taken into account when drilling the Zechstein salt. There seems to be some ambiguity whether to avoid or target areas with high stringer curvature.

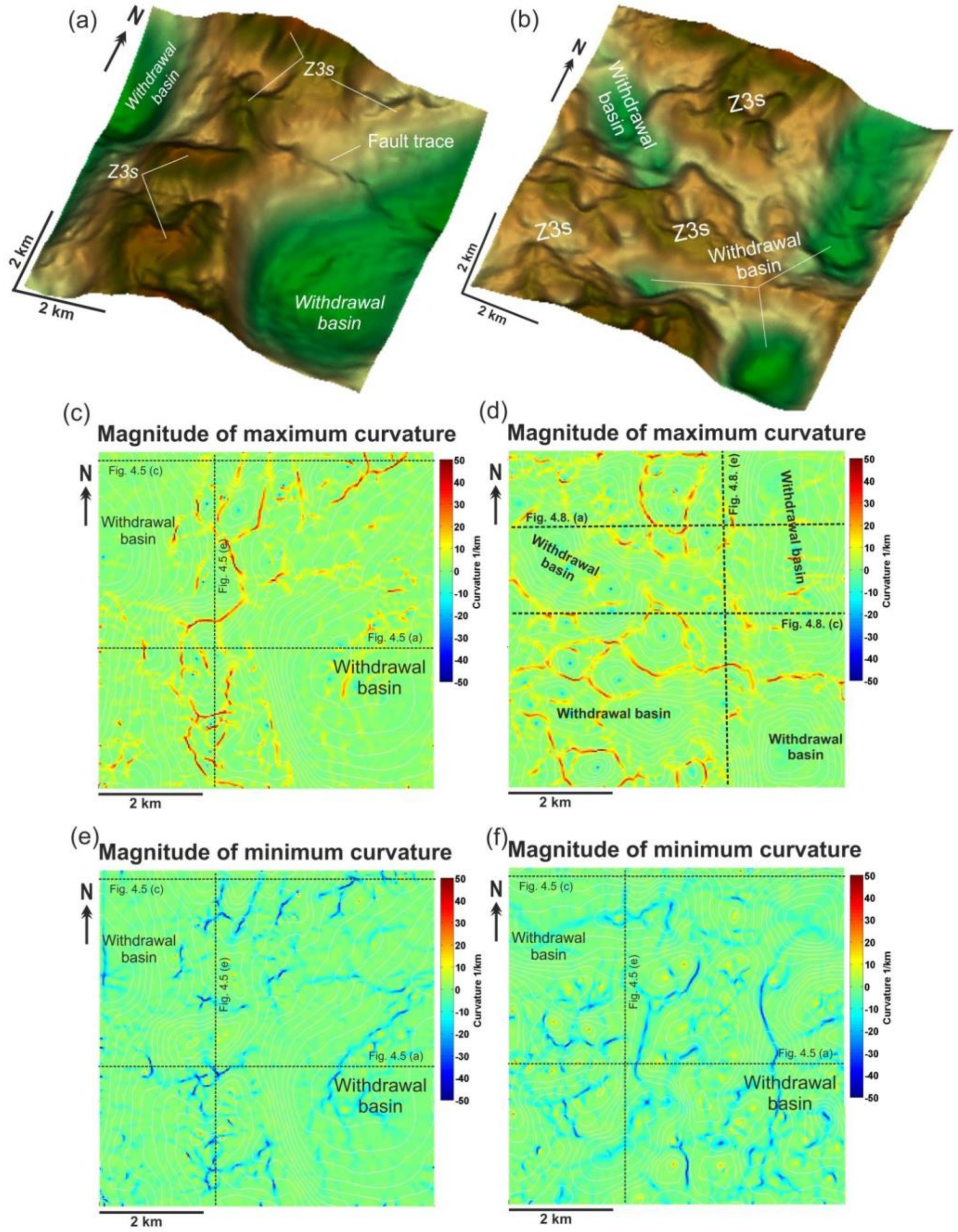

Figure 19 Topographic relief map using different surface and area constraint parameter, the eight from gradient reconstruction performed on a seismic time slice (a, b). Magnitude of maximum curvature (c, d). Magnitude of minimum curvature (e, f). From Masiero, 2015 (unpublished TNO report).

7 Recommendations for future research

- *On the data inventory of stringer-related drilling issues.* The occurrence of drilling events has been analyzed for a total of 921 unique wells out of 2575 wells that drilled the Zechstein formation in the Netherlands (section 5.3). The analysis could be extended by screening all 2575 wells for drilling events. 3D seismics could be more thoroughly studied to find more stringers. This could be aided by going through all end of wells report of wells that drill through one of the carbonate or anhydrite layers of the Zechstein Formation. It would improve statistics on the probability of encountering issues when drilling the Zechstein and better constrain drilling risks. The analysis could be extended to include other drilling issues, for example related to brine pockets or squeezing salts.
- *On the identification and imaging of stringers.* The location and structure of stringers have been identified based on available seismics (section 3). New techniques for the interpretation of seismic surveys such as curvature analyses can be applied to better map stringers and surrounding structures in the Zechstein salt. It would help finding better indicators for the occurrence of overpressures in stringers and identify preferred drilling trajectories.
- *On predictions of pore pressures in stringers*. Bounds on possible overpressures in stringers have been defined on the basis of the lithostatic pressure gradient (section 4.3, 5.3). Tighter constraints on stringer overpressures and pore fluid compositions can be obtained if predictive models are developed that combine (1) basin modelling to determine the burial history of Zechstein and stringers, (2) models for the generation of fluids or gas in stringers based on the kinetics of hydrocarbon generation, gypsum-anhydrite transformation, or other transformations, (3) models for diagenetic changes in porosity and permeability (e.g., pressure solution), and (4) models for the development of fracture networks due to stringer deformation. The integrated models can better constrain pore pressure in the stringers, predict expected volume of brine or gas influx, and map out areas in the Zechstein with high probabilities for the presence of stringers with overpressures.
- *On mitigation measures for drilling risks associated with stringers in salt.* The focus of this study has been on preventive measures (section 6.4). Control measures could be improved by compiling guidelines with best practices for handling pressure kicks, drilling trajectories, locations of casing shoes and timing of casing cementation.

8 Conclusions

In this study drilling risks associated with stringers in Zechstein salt were investigated. Research focused on (1) the formation of the stringers, (2) preferred locations and geological setting of stringers in the Dutch subsurface (on- and offshore), (3) the causes and effects of overpressures and pore fluid content of the stringers, and (4) drilling risks and possible risk mitigation measures associated with overpressures and pore fluid content of the stringers.

Based on this study it can be concluded that:

- Key problems associated with drilling through salt and stringers include (1) reduced well control due to abrupt variation in formation fluid pressures associated with stringers or brine/gas pockets, (2) borehole closure and stuck drill strings due to salt creep after drilling, (3) washouts, stuck or buckled casings, and problematic cementation due to the presence of squeezing salts, (4) changes in the rate of penetration during drilling and borehole deviation in preferred directions due to variations in salt lithology.
- Overpressures in stringers can develop by (1) rapid compaction during burial leading to non-hydrostatic pore pressures, (2) sealing and compartmentalization of carbonates by overlying anhydrite, (3) changes in pore fluid composition (e.g., generation of hydrocarbons), (4) mineral transformations (e.g., dewatering of gypsum to anhydrite), (5) pressure- an temperature-induced changes in the density of pore fluids, (6) stress-induced porosity reduction due to poroelastic effects or pressure solution.
- Stringers in the Zechstein mainly originate from Z2 and Z3 lithologies. Most of the stringers identified within the Zechstein of the Dutch subsurface are Z3 anhydrite-carbonate (Z3AC) stringers. Overpressures have been mainly associated with the Z2 Salt (ZEZ2H), Carbonate (ZEZ2C) and Basal (ZEZ2A) and Roof (ZEZ2T) Anhydrite Members, and with the ZEZ3 Salt (ZEZ3H) and Main Anhydrite (ZEZ3A) Members. The anhydrite and carbonate lithologies are prone to hard overpressures (i.e. formation pressures that are close to the lithostatic pressure).
- Stringers in the Zechstein can usually be identified in both well and seismic data due to the large contrast in acoustic impedance between the stacked carbonate and anhydrite with the surrounding rock salt that produces high-amplitude reflections. Stringers may become seismically invisible inside larger salt pillows and diapirs where the signal-to-noise-ratio is generally low and very complex intra-salt structures are to be expected, or if stringers have reduced thickness, size or very steep dips (highly tilted stringers). ~80% of stringers associated with drilling events are visible on seismics, and most stringers that caused drilling events could have been spotted on seismic before drilling commenced. The quality of seismics is an important factor in identifying stringers and predict potential drilling issues prior to drilling.
- A total of 2575 wells have been drilled through the Zechstein formation in the Netherlands. The occurrence of drilling events has been analyzed for a total of 921 unique wells. 62 wells with reported drilling events have been identified and investigated. 32 formation pressures were collected for the 62 wells indicating that (1) overpressures can be up to the maximum overpressure constrained by the lithostatic pressure, (2) all Zechstein lithologies (ZEZ1-ZEZ3) can develop overpressures, but most overpressures occur in ZEZ2 and ZEZ3, (3)

overpressures in carbonate and anhydrite formations tend to be close to the upper bound for formation pressure given by the lithostatic pressure, (3) most kicks are from influx of brine or unknown fluids, gas kicks are observed in 3 carbonate and anhydrite formations, (4) maximum possible overpressure is increasing with depth, (5) there is no clear trend of maximum possible overpressure with relative position within the local Zechstein formation. If the (structural) characteristics of the stringer and base/top Zechstein is used as an indicator for the occurrence of drilling events associated with stringer, the best option for planning a well trajectory is to avoid folded, tilted stringers, and to avoid areas where the base Zechstein is faulted or areas below the flanks of folded top Zechstein.

- Measures to mitigate stringer-related drilling risks may be improved by (1) new techniques for the interpretation of seismic surveys to improve the identification, imaging and mapping of stringers and surrounding salt boundaries, (2) better constraints on pore pressure in the stringers and expected volume of brine or gas influx using predictive models to map out areas in the Zechstein with high probabilities for the presence of stringers with overpressures, (3) compiling guidelines with best practices for handling pressure kicks, drilling trajectories, locations of casing shoes and timing of casing cementation.

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Appendix A List of wells and events

Well name	**Spud date**	**Depth event (MD)**	**Strati-graphy**	**Incident type**	**Reported Overpressure**
AME-203	1991	3495	ZEZ2C	Pressure kick	n/a
AME-205	2007	2910	ZESA	Brine influx	n/a
B17-04	1989	4081	ZEZ2A	Brine	high
BUMA-01	1996	3371	ZEZ3A	H2S	n/a
COV-29	1982	2345	ZEZ3C	Pressure kick	n/a
COV-48-S2	1987	3058	ZEZ3C	Pressure kick	n/a
COV-58	2007	3170	ZEZ3C	Brine	n/a
D15-04	1994	2886	ZEZ3C	Pressure kick	n/a
E09-01	1980	2764	ZEZ1C	Gas	middle
E13-01-S02	1984	2550	ZEZ3	Pressure kick	middle
E17-02	1996	2916	ZEZ2A	Brine	high
E18-02	1983	3140	ZESAL	Brine	n/a
ENA-02	1980	3532	ZEZ3C	Pressure kick	n/a
F04-03	1992	3432	ZEZ3H	Brine and losses	high
F07-02	1992	2434	ZESA	Pressure kick	middle
F10-02	1985	2185	ZESAL	Pressure kick	n/a
F16-A-03	2005	4039	ZE	Losses	n/a
F16-A-06-S1	2006	3241	ZE	Pressure kick	n/a
G18-01	1983	2473	ZEZ3C	Pressure kick	n/a
GGT-103	2002	2778	ZEZ2C	Pressure kick	n/a
GRO-01	2005	3445	ZEZ3C	Losses	n/a
GRO-01-S1	2012	3445	ZE	Brine	n/a
J06-A-05	1995	3126	ZESAL	Pressure kick	low
K02-A-01	2005	3550	ZE	Pressure kick	n/a
K05-ENC-02	1994	3130	ZEZ2H	Pressure kick	middle
K07-07	1979	2985	ZE	Pressure kick	n/a
K07-07-S2	1980	2933	ZE	Pressure kick	n/a
K07-07-S3	1980	3111	ZE	Losses	n/a
K07-08	1980	2486	ZEZ1C	Pressure kick	n/a
K08-02	1972	3239	ZEZ2H	Pressure kick	middle
K08-FA-308	2011	3950	ZEZ3C	Pressure kick	n/a
K08-FA-308-S1	2012	3812	ZEZ3C	Pressure kick	n/a
K08-FA-308-S2	2012	3946	ZEZ3C	Pressure kick	n/a
K09AB-B-03	1999	3862	ZE	Brine	n/a
K10-01-S	1972	2437	ZEZ1	Pressure kick	middle
K10-17	2001	2863	ZE	Pressure kick	n/a
K11-03	1972	1788	ZEZ2H	Pressure kick	middle

K11-04	1975	3157	ZEZ1C	Gas x2	high
K11-10	1986	2303	ZEZ3A	Pressure kick	middle
K12-15	2001	3435	ZE	Pressure kick	n/a
K12-15-S1	2001	3373	ZE	Pressure kick	n/a
K12-15-S2	2001	3378	ZE	Brine influx	n/a
K12-C5-S1	2014	4000	ZE	Gas and brine	n/a
K14-05	1975	2977	ZEZ3A	Pressure kick	high
K15-13-S1	1992	2852	ZEZ2H	Pressure kick	high
K15-FG-104	2002	3882	ZESA	Pressure kick	n/a
K15-FG-104-S1	2002	4168	ZEZ3	Pressure kick	n/a
KOL-02	1991	1620	Z3Z3H	Pressure kick	n/a
L04-06	1994	2934	ZEZ3H	Pressure kick	middle
L04-PN-04	2000	3652	ZE	Brine	n/a
L06-07	2008	4282	ZE	Pressure kick	n/a
L16-12	1991	3206	ZECP	Pressure kick	low
LNS-02	2005	3344	ZE	Brine	n/a
LWZ-03-S1	2007	3889	ZEZ2H	Pressure kick	n/a
M03-01	1991	3395	ZEZ2A	Pressure kick	n/a
MKZ-06	2010	3869	ZEZ3H	Pressure kick	n/a
N05-01-S2	2017	3219	ZEZ3C	Brine	n/a
TVN-01	2009	3455	ZEZ2H	Pressure kick	n/a
URE-202	1993	2122	ZEZ3C	Pressure kick	n/a
VRS-401	1985	2670	ZEZ2H	Pressure kick	n/a
WIT-03	2009	3395	ZEZ2C	Losses	n/a
WYK-06	1952	1587	ZEZ3C	Pressure kick	n/a

Appendix B Expert Meeting Results

On February 6th an Expert Meeting was held at TNO. A number of oil and gas operators, AkzoNobel and TNO gave a presentation to inform each other on their experiences with salt stringers and how to tackle the possible problems occurring with them. 40 people attended.

The following presentations were held (see https://www.nlog.nl/presentaties):

- Janos Urai (Aachen University), ‘Stringers in Salt a Drilling Hazard? Everything you always wanted to know but were afraid to ask’

- Berend Vrouwe (Oranje Nassau Energie), ‘Stringers in Zechstein salt as a drilling risk - case study Ruby exploration well’

- Guido Hoetz (EBN), ‘Stringers hit by the bit; Geo Drilling Events Database helping to understand drilling hazards’

- Pieter Gerritsen (ENGIE) ‘Floaters in the Zechstein: (un)predictable & (un)safe to drill?’

- Sebastiaan van der Woude (Wintershall), ‘Wintershall Drillings Practices of Salt Stringers’

- Alice Post (NAM), ‘Planning a well through a Zechstein Stringer - Best practices used in NAM’

- Marinus den Hartogh (AkzoNobel), ‘Using salt knowledge to reduce drilling risk’

- Jan ter Heege (TNO), ‘Hazards associated with drilling through “stringers” in salt formations’

Next to the presentations there were cores on display from wells BAS-01, D15-02, E16-03, E17-01, LEW-01, PNB-01, SLO-04, ZWD-01.

Appendix C Wells with investigated stringers on seismic sections

Offshore

B17-04
D15-04
E09-01
E13-01-S02
E17-02
E18-02
F04-03
F07-02
F10-02
F16-A-03
F16-A-06-S1
G18-01
J06-A-05
K02-A-01
K05-ENC-02
K07-07
K07-08
K08-02
K08-FA-308
K09-AB-B-03
K10-01-S1
K10-17
K11-03
K11-04
K11-10
K12-15
K12-C05-S1
K14-05
K15-13-S1
K15-FG-104
L04-06
L04-PN-04
L06-07
L16-12

Onshore

AME-203
AME-205
BUMA-01
COV-29
COV-48-S2
COV-58
ENA-02
GGT-103
GRO-01
GRO-01-S1
KOL-02
LNS-02
LWZ-03-S1
MKZ-06
TVN-01
URE-202
VRS-401
WIT-03
WYK-06