WARMING UP
Innovatief Duurzaam Warmtecollectief

Formation, lithology and region-specific minimum horizontal stress field in the Netherlands

Implications for fault stability in geothermal doublets

Final report by
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1 Executive summary

The Dutch subsurface plays an important role in the energy transition, e.g. in the production of geothermal energy. So far few to no noticeable and undesirable effects have been observed at the surface related to geothermal doublet operations. However, potentially, geothermal operations in the subsurface may lead to observable and undesired effects. One of these effects is the occurrence of seismic events that are large enough to be felt at the surface and may cause damage. Induced seismicity is the result of the reactivation of pre-existing faults in the subsurface by stress changes that occur due to pressure and temperature changes around e.g. a geothermal doublet. One of the key factors that affects the potential for fault reactivation and the occurrence of seismicity is the in-situ, tectonic stress that is acting on these pre-existing faults. This in-situ, tectonic stress gives information about how close to failure the faults are before the operations are started. Since the subsurface of the Netherlands is associated with a normal faulting regime, a lower minimum horizontal stress gradient means a higher criticality.
The aim of this study is to improve the characterization of the initial, in-situ, tectonic stress field, particularly the minimum horizontal stress S_{hmin}, specified for different lithologies, litho-stratigraphic groups and tectonic regions in the subsurface of the Netherlands. The characterization of the in-situ tectonic stress field is of large importance, since the in-situ stress ratio S_{hmin}/S_v is a key parameter controlling fault reactivation and the occurrence of induced seismicity in geothermal doublet operations, as shown by stochastic modelling performed in WarmingUp 4B1 (Buijze et al., 2021), with lower stress ratio's promoting fault reactivation. Therefore a good quantification of the minimum principal horizontal stress S_{hmin} is of great value. In order to accomplish this aim, a new dataset of excellent quality, containing leak-off test (LOT) data and minifrac data of the NAM (Nederlandse Aardolie Maatschappij B.V.), is used and complemented with the leak-off test data of the already existing Pressure Southern North Sea (PSNS) database (Verweij et al., 2015). Since LOT measurements tend to overestimate the minimum horizontal stress due to multiple factors causing uncertainty, e.g. the perturbed stress field around the well, the lower bound gradients of the LOT data were taken as representative for the minimum horizontal stress gradient S_{hmin}.
Results show a strong dependence of the minimum horizontal stress gradient S_{hmin} on the lithology. The lithologies claystone, anhydrite and rock salt have higher minimum horizontal stress gradients and thus give high in-situ stress ratios, particularly at depths larger than 2 km for claystone. Therefore, fault reactivation and induced seismicity within these lithologies is less likely. Minimum horizontal stress gradients also vary with stratigraphic group (e.g. Chalk, Rijnland, Rotliegend, Zechstein etc). This is most likely related to the dominant lithology type occurring in the stratigraphic groups. Moreover, a spatial relation can be established for the minimum horizontal stress gradients. The stress gradients are the highest in the Northeastern part of the Netherlands and they are decreasing towards to Southwestern part of the Netherlands. This may be a result of the presence and thickness of the Zechstein rock salt deposits, the occurrence of overpressures and the differences in tectonic loading in the subsurface of the Netherlands. Additionally, the minimum horizontal stress gradient does not only vary with lithology, stratigraphic formation and tectonic region, but also with depth. From a depth of ~2 km, the stress gradient becomes higher than at shallower depths. This is most clearly visible for clay containing lithologies and may be lithology dependent. Moreover, the lithostatic pressure also increases with depth (dS_v/dy increases with depth) due to the increase in density with depth. This might partly explain the increase of the minimum horizontal stress (dS_{hmin}/dy) with depth. In addition, overpressures are found in the northern regions and some of the deeper lithologies (Verweij et al., 2012); these can also result in

higher S_{hmin} (Engelder & Fischer, 1994). Therefore, it is important to look at the in-situ stress ratio S_{hmin}/S_v and in particular the effective stress ratio (S_{hmin} – P) / (S_v – P) in further research.

When comparing the newly available NAM data of high quality with the PSNS data, which contains more but partially also less reliable data, which has not been computed from the pressure-volume curve such as the NAM data, it can be concluded that in the majority of the lithology groups, stratigraphic groups and tectonic regions the NAM data has (slightly) lower minimum horizontal stress gradients. Exceptions are the creeping lithologies such as rock salt and anhydrite. This may be related with either the quality of the data or with the limited number of measurements; a more careful analysis of the data will likely result in LOT values closer to the actual in-situ stress.

The results of this study imply that the potential for fault reactivation and induced seismicity may be the lowest in rock salt, anhydrite and clay containing formations. These types of formations typically form the base- and cap-rocks of the geothermal target formation, preventing eventual seismic events from growing beyond the depth extent of the geothermal reservoir. Furthermore, lower minimum horizontal stress gradients do not have to lead to induced seismic events, which is visible in the Southwestern part of the Netherlands. This statement is based on the lack of measured induced seismic events in the oil and gas fields in the Southwest versus the occurred induced seismic events in the North and West of the Netherlands. Other factors might thus be influencing the formation of induced seismic events.

Recommendations for further research include improvements on the quantity of the data, the integration of vertical stress, the execution of extended leak-off tests (XLOT) and more minifrac tests, and the further investigation of the mechanisms related to the spatial variation in minimum horizontal stress gradients.

2 Introduction

The Dutch subsurface plays an important role in the energy transition, e.g. in the production of geothermal energy. The number of geothermal doublets in the Netherlands, and abroad, is planned to increase significantly over the coming decades (PBL 2020, 2021; EBN&DAGO, 2018). However, geothermal operations in the subsurface may lead to noticeable and undesirable effects at the surface. One of these effects is the occurrence of seismic events that are large enough to be felt at the surface and may cause damage. Such seismic events are potentially a show-stopper for geothermal projects, in particular in the Netherlands, which is densely populated and where the population is sensitive to induced seismic events because of their history with induced events related to gas production. Mitigation of seismic events resulting from geothermal doublet operations is key in facilitating the increasing contribution of geothermal energy to the national energy budget. The mitigation of seismic events is one of the key research topics in the project WarmingUp, Theme 4B1. The WarmingUp collective is a consortium of 38 Dutch research institutes, operators, utility companies, and government organizations, which aims to accelerate geothermal energy in the Netherlands. In Theme 4 the aims are to reduce subsurface risks to enhance the development of geothermal energy, by 4A) better characterization of geological formations, 4B) quantification and mitigation of risks related to induced seismicity, and 4C) increasing the effectiveness of the geothermal doublet through production optimization.
Induced seismicity is the result of the reactivation of pre-existing faults in the subsurface by stress changes that occur due to pressure and temperature changes around e.g. a doublet. One of the key factors that affects the potential for fault reactivation and the occurrence of seismicity is the in-situ, tectonic stress that is acting on these pre-existing faults. This in-situ, tectonic stress gives information about how close to failure the faults are before the operations are started.
Stochastic modelling performed in WarmingUp 4B1 showed that the in-situ stress ratio S_{hmin}/S_v is one of dominant parameters governing fault reactivation and seismic events magnitudes (Buijze et al. 2021). A good constraint on the in-situ stress in the upper crustal formations targeted by geothermal operations is thus crucial for future seismic hazard assessment studies. In this work we investigate the magnitude of the minimum horizontal stress S_{hmin}, as a function of lithology and tectonic region.

2.1 The tectonic stress field in the Netherlands

Since the in-situ tectonic stress field, in particular the minimum principal horizontal stress S_{hmin}, is of large importance for the characterization of the seismic potential, it is essential to investigate the magnitudes and directions of the in-situ stresses.
A dominantly normal faulting stress regime is present in the subsurface of the Netherlands, where the minimum stress is lower than the vertical stress S_v derived from integrated density logs (Verweij, 2015; Muntendam-Bos, 2021; Heidbach et al., 2016; Van Balen et al., 2005). Since the Cenozoic, natural seismic activity has occurred predominantly in the Southeastern part of the Netherlands. This implies that the tectonic stress field in the largest part of the Netherlands, except for the Southeastern part, could be non-critical (Muntendam-Bos, 2021; Verweij, 2016; Verweij et al., 2016). This criticality depends on the following conditions: the exceedance of the Coulomb failure criterion and the dynamic slip properties of the fault plane.
Different studies have shown that the direction of the maximum principal horizontal stress S_{hmax} in the Netherlands and in Western Europe is generally NW-SE, as shown in Figure 1 (Heidbach et al., 2016; Mechelse, 2017; Müller et al., 1992; Van Eijs and Dalfsen, 2004; WSM). The amount of

anisotropy between the different horizontal stresses is relatively low (Osinga & Buik, 2019), e.g. 2-3% in Groningen (Van Eijs, 2015). The world stress map (WSM) displays the orientations of the maximum principal horizontal stresses S_{hmax}. However, the information on the world stress map is limited due to a number of constraints: i) the spatial resolution of the world stress map is not sufficient for the regional/local scale and ii) there are only one or two measurements of the S_{hmax} per well, therefore the variation of the S_{hmax} with depth cannot be established (Müller et al., 1992; Van Eijs and Dalfsen, 2004). The information on the magnitudes of the S_{hmax} is also limited, since there is a lack of reliable methodologies measuring the S_{hmax}. It can be inferred from interpretation using linear-elastic theorgy with a number of assumptions on the material and strength properties. However, the uncertainties in the methodology lead to a poor estimation of S_{hmax} magnitudes.

Verweij (2015) investigated the vertical stress (S_v) field in the subsurface of the Netherlands determined by density logs and basin modelling. Due to the low density of the rock salt layer in the Zechstein formation, the vertical stress gradient is lowered, with respect to a non-rock salt overburden, in the Zechstein and underlying formations (Rotliegend and Carboniferous). The thicker the rock salt layer, the lower the vertical stress is. A vertical stress gradient of 21 MPa/km is fitted to these formations. Above the Zechstein, the vertical stress is very close to lithostatic stress. A vertical stress gradient of 23 MPa/km is taken for the Triassic formations. Moreover, the Cenozoic sediments have a relatively low density as well, this leads to below lithostatic vertical stresses in the Vlieland Lower Cretaceous sandstones, with a vertical stress gradient of 20 MPa/km (Verweij et al., 2015; Muntendam-Bos, 2021).

A few studies were done on the minimum horizontal in-situ stress S_{hmin} in the subsurface of the Netherlands, e.g. Verweij et al. (2015) and Muntendam-Bos (2021). Those studies were based on leak-off test data contained in the Pressure Southern North Sea (PSNS) database, which is publicly available on nlog.nl (Verweij et al., 2015). Muntendam-Bos (2021) states that the in-situ stresses in the subsurface of the Netherlands are far from critical and very high effective stress ratios are present. In particular in the Zechstein formation and the formations below, the minimum horizontal stresses are relatively high. The presence of the thick, viscous Zechstein rock salt deposits may have a large effect on the in-situ stresses. According to Verweij (2015), the average lower bound of the leak-off pressures in the subsurface in the Netherlands corresponds to the standard S_{hmin} gradient of approximately 14 MPa/km. However, Verweij (2015) states that the lower bound of the leak-off pressures starts to deviate at depths larger than ~3500 meters. Verweij (2015) relates the lower bound of the leak-off pressures to stratigraphic group and tectonic region. In the majority of their stratigraphic groups, the lower bound of the leak-off test data follows corresponds to a gradient of 14 MPa/km. Exceptions form the North Sea Supergroup, which has a lower bound of leak-off pressures below the standard S_{hmin} gradient and the Upper/Lower Germanic Trias Groups, which have a lower bound of the leak-off pressures which deviates from the standard S_{hmin} gradient at larger depth (Verweij, 2015). Moreover, Verweij (2015) states that overpressures in the Zechstein rock salt and the formations below in the Northeastern offshore, Northern onshore and Eastern onshore parts of the Netherlands, result in a higher average lower bound of the leak-off pressures with respect to the Northwestern and the Southern part of the Netherlands.

However, the in-situ stress magnitudes and their variation in the subsurface of the Netherlands remain subject to large uncertainties. The aim of this project, which is part of the WarmingUp Theme 4B, is to improve the estimates of S_{hmin}, and relate S_{hmin} to different lithologies, stratigraphic groups and tectonic regions in the Netherlands. To this end, new LOT and minifrac data, made available by NAM (Nederlandse Aardolie Maatschappij B.V.), are combined with the existing PSNS database of Verweij (2015) (LOT data). Implications of the S_{hmin} gradients on fault stability and induced seismicity in Dutch geothermal target formations are discussed. Therefore, the research question of this study is: What are the S_{hmin} stress magnitudes and their variation in different tectonic regions, stratigraphic groups and lithologies in the Netherlands, and what does this mean for fault stability and induced seismicity in Dutch geothermal target formations?

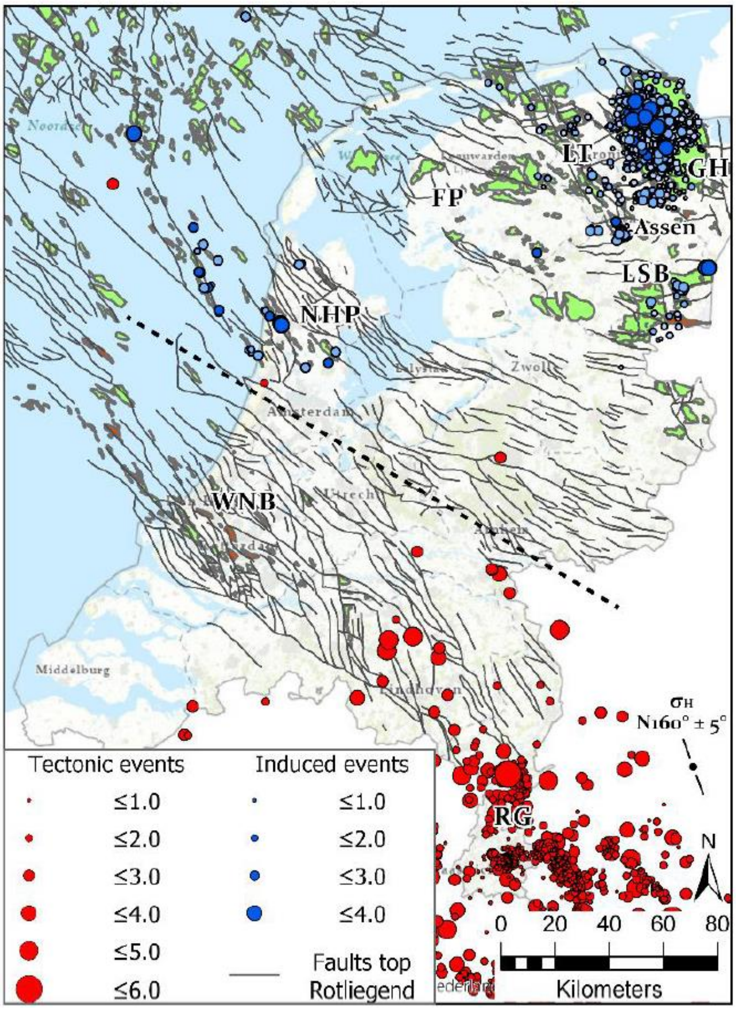

Figure 1: Overview of the faulting, seismicity (tectonic and induced events) and hydrocarbon reservoirs in the Netherlands (Muntendam-Bos, 2021). Gas reservoirs have green indications and oil reservoirs have red indications. Tectonic seismic events are indicated by red dots and induced seismic events are marked by blue dots. Tectonic regions on the map are: WNB: West Netherlands Basin, NHP: Noord-Holland Platform, FP: Friesland Platform, LT: Lauwerszee Trough, GH: Groningen High, LSB: Lower Saxony Basin, RG: Rhine Graben.

2.2 Leak-off tests (LOT) and minifrac tests

The original function of a leak-off test (LOT) is to determine the facture pressure of the open formation below a casing or linear shoe and this technique was developed in the oil industry. Where the properties of the formation are still unknown, a leak-off test is performed. A leak-off test is done at the shoe of a casing in a borehole, in order to assess the upper limit of the mud weight (safe mud weight window) for the next drilling section (Addis et al., 1998). A LOT is typically performed in the formations with a more stable state of stress, such as claystone and top Zechstein, to prevent a possible external blow-out and there are typically multiple LOT's done in one well. During a leak-off test, a fluid is pumped into the borehole, increasing the pressure. When the pressure-volume line is

deviating from linear, the leak-off pressure (LOP) is reached and the leak-off test is finished. At this point, the fluid starts diffusing into the formation via existing fractures.
Moreover, (extended) leak-off tests are used to estimate the in-situ stress magnitudes in formations, particularly to estimate the minimum horizontal in-situ stress magnitude. However, due to the testing procedure and the inaccurate instructions applied for interpreting leak-off tests, the leak-off pressures are not a perfect representation of the minimum horizontal stress (Li et al., 2009). There is quite some uncertainty on the interpretation of a leak-off test as a stress test, since the leak-off point depends on operational parameters (such as the fluid type, mud additives, temperature, pumping rate, well deviation) and rock parameters (such as failure type, presence of natural flaws, fluid penetration). Furthermore, the minimum horizontal in-situ stress (S_{hmin}) must be overcome in order to open fractures in the formation to get leak-off during a LOT, since the S_{hmin} is oriented perpendicular to the facture. However, the leak-off pressure (LOP) is an overestimation of the S_{hmin}, as this is the result of a combination of the in-situ tectonic stress and the stress around the well bore (the hoop stress) (Alberty and McLean, 2004; Breckels and Van Eekelen, 1982; Voegeli et al., 2021). The LOT data typically fall in the range S_{hmin} to $2S_{hmin} - P_c$, where P_c is the pore pressure. This is the tensile failure limit for a vertical well when $S_{hmin} = S_{hmax}$. Due to the uncertainties considering leak-off tests as stress tests, the lower bound of the leak-off pressures should be taken when deriving the minimum horizontal stress of a formation (Breckels and Van Eekelen, 1982; Verweij et al., 2012; Verweij, 2015).
An extended leak-off test (XLOT) has a more complex pressurizing procedure where pumping continues after the LOP until the formation breakdown pressure (FBP), when a new fracture is formed. After this point, the pressure reaches a constant level at the fracture propagation pressure (FPP). The point where the pressure rapidly decreases, is known as the instantaneous shut-in pressure (ISIP). Finally, the fracture is closing at the fracture closure pressure (FCP) and this value represents the minimum horizontal in-situ stress. Therefore, an extended leak-off test gives a more reliable estimation of the minimum horizontal stress magnitude of the formation, since the FCP (and ISIP) give a better approximation of the minimum horizontal stress than the LOP (Lin et al., 2008).

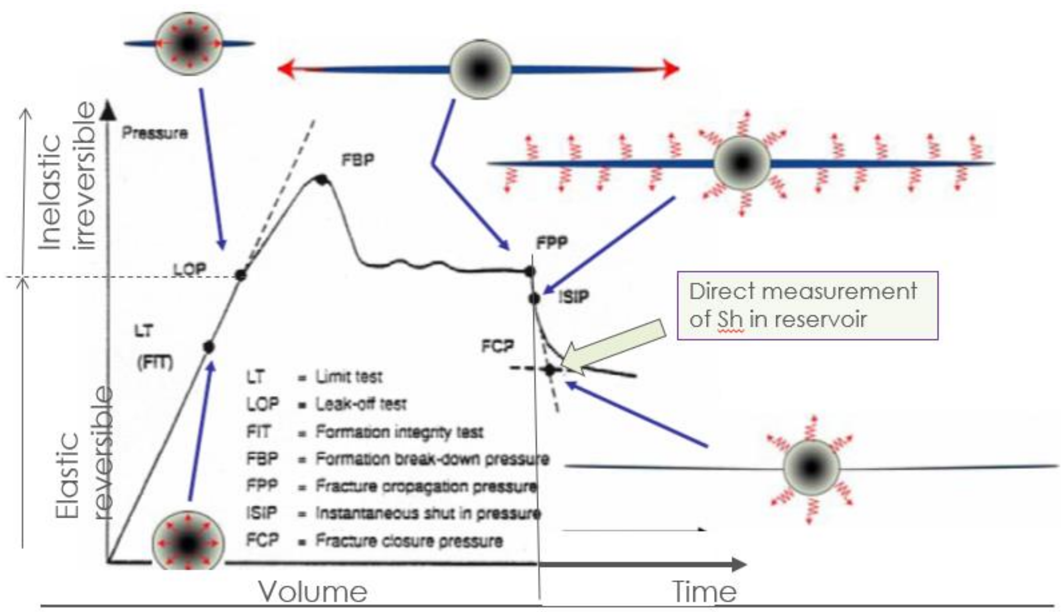

Figure 2: Schematic pressure-time graphic for an XLOT. Modified from GMI.

Minifrac tests are also more reliable for the determination of the minimum horizontal stress than LOT's, since they are a direct representation of the minimum horizontal in-situ stress. Minifrac test

procedures include a similar procedure as an extended leak-off test and both methods have the same purpose. The fracture closure pressure (FCP) in the minifrac test is a direct measure of the minimum horizontal in-situ stress in the reservoir (De Bree et al., 1989). However, an XLOT is performed under the shoe of a casing and a minifrac test is done through casing perforations, in the reservoir formation. Hence, an XLOT is usually performed in the overburden and a minifrac test is done in the reservoir. Other differences are that the fluid type used during the test may be different, there is more control on the pumping of the fluid, and a downhole pressure gauge is often used in a minifrac test. Therefore, the conditions of a minifrac test are better constrained and hence the estimation of the minimum horizontal in-situ stress is more reliable, in particular when interested in the state of stress in the reservoir.
In this study the used database does consist of leak-off test (LOT) data and minifrac data, but does not contain extended leak-off tests (XLOT).

3 Methods & Data

3.1 Method and data description

This study has been done using new LOT and minifrac databases made available by the NAM (Nederlandse Aardolie Maatschappij B.V.) within the WarmingUp program, and the previously published, third version of the Pressure Southern North Sea (PSNS) database (Verweij et al., 2015; see Appendix for the link to the file). For more information about this PSNS database, the reader is referred to the corresponding report (Verweij, 2015; see Appendix). The number of wells and side-tracks in the different databases includes 1274 for the NAM LOT database, 60 for the NAM minifrac database, and 1405 for the PSNS LOT database.

For the NAM LOT database, the data only consist of excellent quality measurements, where the LOP is determined on the basis of a pressure-volume graph. The LOT data from the PSNS database have a lower reliability than the NAM data, since for these data the pressure-volume graph have not been checked. The quality of the data is indicated with a quality qualifier (A-F). The LOT data of the NAM database has an excellent quality with only quality qualifier A. The PSNS database has a lower quality, with quality qualifiers ranging from B to F. The majority of the PSNS data have either a quality qualifier D or F. However, the qualifiers in the both databases cannot be compared, since the quality qualifiers are not the same.

Since the NAM LOT, NAM minifrac and PSNS databases have different content in the excel files, a number of adjustments were carried out in MATLAB R2021b before these databases could be merged. The databases have been processed in order to make units, naming, and depth conventions consistent. Moreover, the LOT database of the NAM consists of two data types: LOT and FIT data (see Figure 2). For the determination of the minimum principal horizontal stress (S_{hmin}), the FIT data is not useful, therefore these data have also been removed for the purpose of this study. Furthermore, the PSNS database consists of multiple test types, such as LOT, FIT, FST, FLT, PLT, LT, LFIT, LLOT and FSG. All previously named test types, except for the data in which a LOT occurred and the undefined test types, have been removed for the purpose of this study, since they are not useful for the determination of the minimum principal horizontal stress (S_{hmin}). Besides, in the case of overlap between the NAM LOT and the PSNS databases, the newer and more reliable data from the NAM database are taken. After the processing of the databases, the database consists of respectively 381 data points for the NAM LOT database, 59 data points for the NAM minifrac database and 836 data points for the PSNS database (see Figure 3). Via MATLAB scripts, all these relevant LOT and minifrac data are put into the same format and units, in order to combine the separate databases to one major database. This database contains measured formation leak-off pressure data from 678 different wells and side-tracks with corresponding field name, coordinates, test type, depth (true vertical depth subsea TVDSS), stratigraphic supergroup, stratigraphic group, stratigraphic subgroup, stratigraphic formation, stratigraphic member, stratigraphic code, lithology, quality of the data, (original) reservoir pressure, depletion if present and data source (NAM/PSNS).

In some cases, in the minifrac database of the NAM, the original reservoir pressure and the current reservoir pressure are not the same and therefore reservoir depletion has taken place. In those cases, the in-situ stress is no longer representable for the virgin principal horizontal stress (S_{hmin}) and thus these values are not incorporated into this study.

When plotting the data, a standard vertical stress gradient (lithostatic pressure gradient) of 22.6 MPa/km is plotted for comparison. Moreover, 14 MPa/km, 16 MPa/km and 18 MPa/km stress gradients and the standard hydrostatic gradient ($P = \rho * g * z$ with ρ of seawater = 1020 kg/m^3) are

plotted as well. In reality, the density of the water in the hydrostatic gradient is determined by the salinity of the formation water in the specific formation at depth.
Datapoints which are below the 12 MPa/km gradient or above the 24 MPa/km gradient (n = 8) are removed from the dataset because of their unrealistic nature, i.e. 12 MPa/km would fall below the frictional equilibrium (Zoback, 2010).

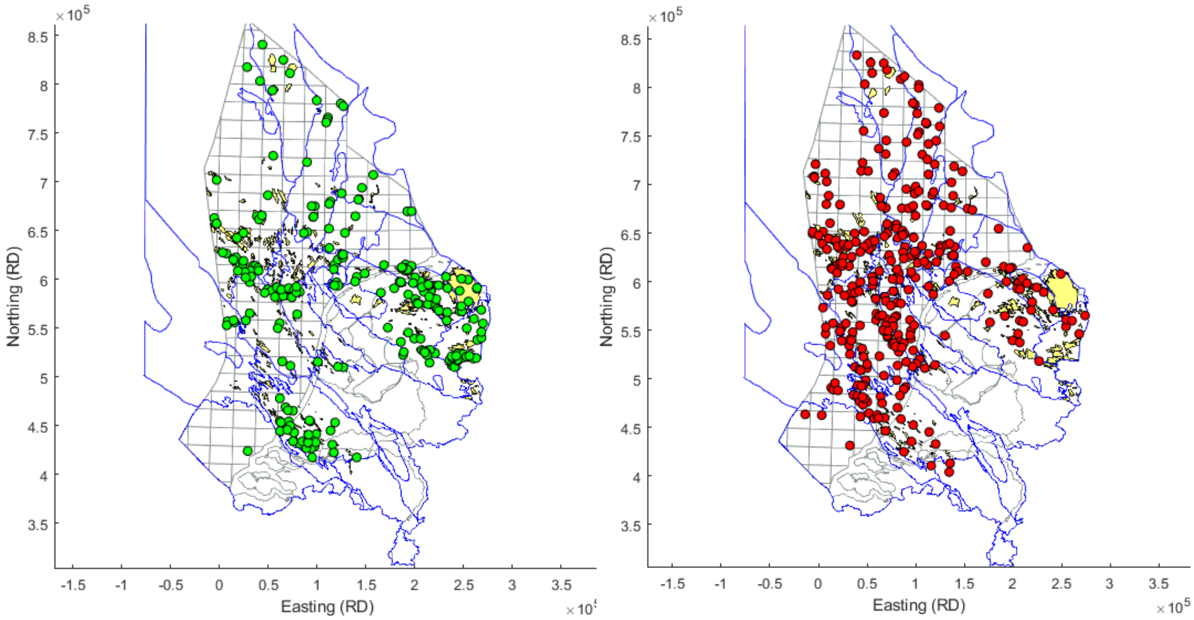

Figure 3: Maps with the spatial distribution of the NAM data (left in green) and the PSNS data (right in red). RD = Rijksdriehoek coordinates. The yellow fields are oil and gas fields.

3.2 Data subdivision in stratigraphy, lithology and tectonic region

Stratigraphic groups are assigned to each data point in the database via the corresponding well name and depth (TVDSS). For linking the stratigraphy to the data points, the NLOG stratigraphy file 'stratstelsel.xlsx' is used (see Appendix). This file contains stratigraphic information, e.g. stratigraphic group codes, per borehole and depth. This file is frequently updated by the DINO database; note however that inconsistencies in the lithostratigraphy may still be present in this database due to e.g. evolving definition of litho-stratigraphic boundaries. The NAM and PSNS data are divided in their stratigraphic groups (Upper Rotliegend, Zechstein, Lower Triassic etcetera) by stratigraphic group code (RO, ZE, RB etcetera) (Van Adrichem Boogaert and Kouwe, 1993; TNO-GDN, 2022). Measurements are available from the youngest unit the North Sea Supergroup up to the oldest unit the Carboniferous Limestone Group. Since the number of stratigraphic groups is relatively large, i.e. ~20 stratigraphic groups, the following stratigraphic groups were merged. The younger stratigraphic groups of the North Sea group (NL, NM, NU) are put together, as well as the Scruff and the Schieland Groups (SG, SL), due to the very limited amount of data in these groups. Identical merges of stratigraphic groups can be found in Verweij (2015). See Table 1 for the stratigraphic groups and the number of measurements per group.

Table 1: The number of measurements per stratigraphic group. The 74 measurements which have an undefined stratigraphic group are not taken into account.

Stratigraphic group code	Stratigraphic group name	Number of measurements
N (NL, NM, NU)	North Sea Super Group	370
CK	Chalk Group	262
KN	Rijnland Group	161
SG/SL	Scruff Group / Schieland Group	24
AT	Altena Group	24
RN	Upper Germanic Trias Group	77
RB	Lower Germanic Trias Group	52
ZE	Zechstein Group	152
RO	Upper Rotliegend Group	66
DC	Limburg Group	13
CL	Carboniferous Limestone Group	1

The NAM database mostly contains associated lithological information for each data point. For data points where the NAM and PSNS databases lack lithological information, the lithology is assigned via the corresponding formation using a stratigraphic main lithology file 'strat_main_lithology.xlsx' from Dinoloket (see Appendix). In this file, all stratigraphic codes are linked to specific lithologies. In general, the NAM and PSNS data is subdivided into 7 categories of lithologies: sandstone, claystone, carbonate, chalk, rock salt, anhydrite and the North Sea Group. The North Sea Group is taken as one group due to its unconsolidated character, young age and shallow occurrence. The lithology group 'claystone' contains lithologies in which the major components are clay(stone), shale, tuffite (silty clay with few layers of tuff), silt, marl and mud(stone) respectively, as classified by the NAM. The lithology group 'carbonate' consists of lithologies in which the largest component contains limestone or dolomite. The lithology group 'chalk' contains chalk-rich lithologies. The lithology group 'sandstone' is made up by lithologies in which the main constituent is sandstone and/or conglomerate. The 'rock salt' and 'anhydrite' groups are mainly consisting of lithologies in which respectively rock salt or anhydrite makes up the largest portion. North Sea Group is assigned to the shallowest lithologies which consist mainly of sands, clays, and marls (dinoloket.nl). See Table 2 for the number of measurements per lithology group.

Table 2: The number of measurements per lithology group. The 33 measurements which have an undefined lithology are not taken into account.

Lithology group	Number of measurements
Claystone (clay(stone), shale, silt, marl, mud(stone))	522
Carbonates (limestones, dolomites)	35
Chalk	255
Sandstone (sandstones, conglomerates)	89
Rock salt	106
Anhydrite	30
North Sea Group	206

Moreover, the data points are, based on their coordinates (Rijksdriekhoek RD), subdivided in tectonic regions, such as West Netherlands Basin, Central Netherlands Basin, Friesland Platform (De Jager, 2003; Kombrink et al., 2012). These tectonic regions are structural elements with different deformation history regarding subsidence, faulting, uplift and erosion (Krombrink et al., 2012). Since the burial history and sediments (age, type) differ are varying in basins, platforms and highs, this may have an effect on properties such as density and overpressures, which then may result in differences in in-situ stresses between the structural elements. Therefore it is important to look not only at the variation in horizontal stress gradients for different lithologies and stratigraphic groups, but also at regional differences.

Since the LOT and minifrac data of this study are located in ~20 tectonic regions, the tectonic regions are merged into larger tectonic super regions (See Table 3). The merge of the tectonic regions to these 5 larger super regions, is based on a number of parameters: the location of the tectonic regions (e.g. surrounding regions, onshore/offshore), the presence/absence of thick Zechstein rock salt deposits and on the division of Verweij et al. (2015).

Table 3: The merge of tectonic regions into larger areas. SG = Step Graben, DCG = Dutch Central Graben, TB = Terschelling Basin, SGP = Schill Grund Platform, AP = Ameland Platform, CBP = Cleaver Bank Platform, COP = Central Offshore Platform, BF = Broad Fourteens Basin, NHP = North Holland Platform, VB = Vlieland Basin, FP = Friesland Platform, LT = Lauwerszee Trough, GH = Groningen High, LSB = Lower Saxony Basin, RVG = Ruhr Valley Graben, CNB = Central Netherlands Basin, , WNB = West Netherlands Basin, IP = Indefatigable Platform, LBM = London Brabant Massif.

Tectonic super region	Tectonic regions
Northern-Northeastern offshore	SG, DCG, TB, SGP, AP
Northwestern offshore	CBP, COP, BF, NHP
Northern onshore	VB, FP, LT, GH
Eastern onshore	LSB
Southwestern onshore and offshore	CNB, WNB, RVG, LBM, IP

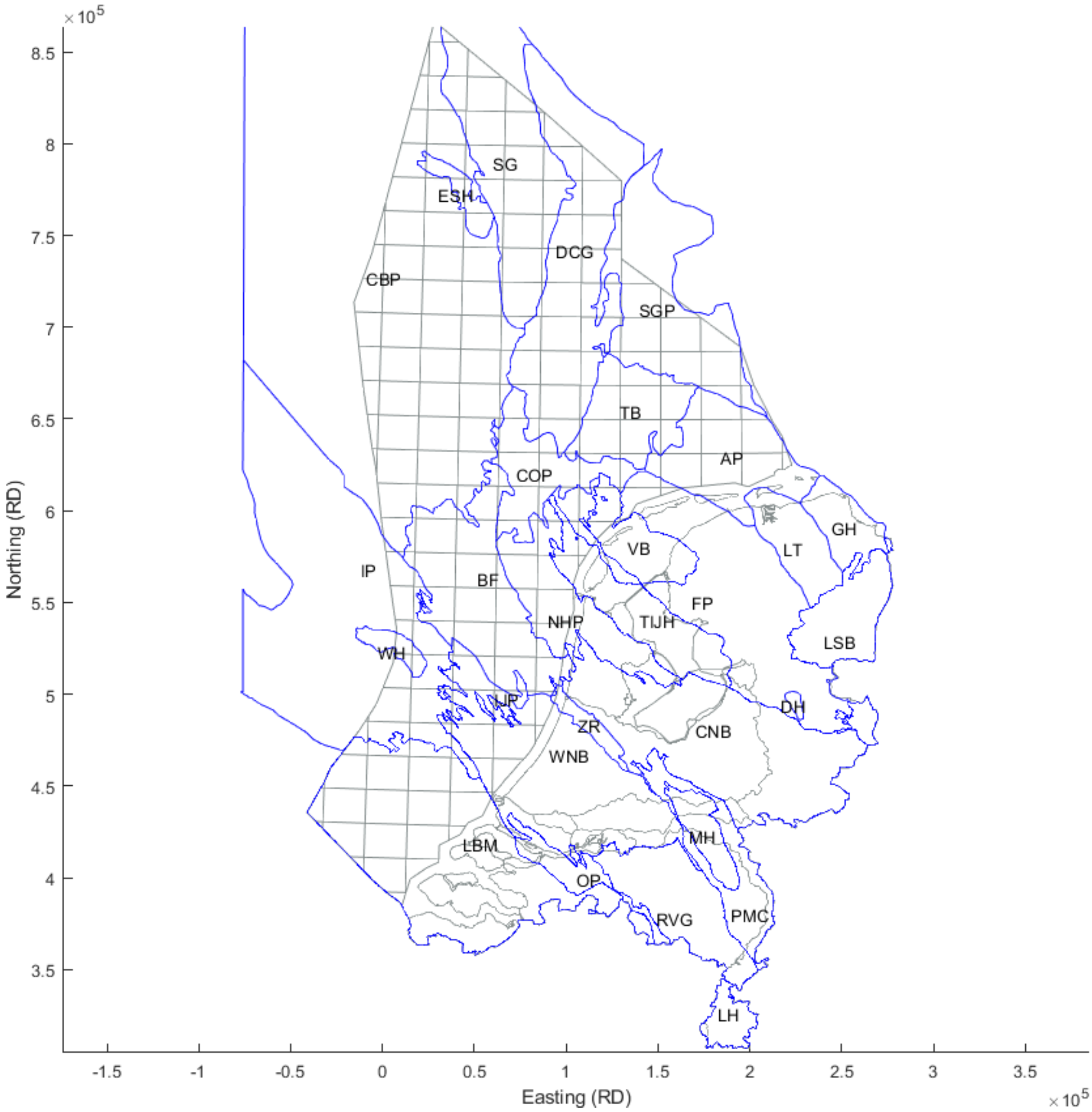

Figure 4: Overview of the tectonic regions in the Netherlands. MH = Maasbommel High, RVG = Ruhr Valley Graben, LBM = London Brabant Massif, LSB = Lower Saxony Basin, TIJH = Texel-Ijsselmeer High, LH = Limburg High, VB = Vlieland Basin, PMC = Peel Maasbommel Complex, CNB = Central Netherlands Basin, NHP = North Holland Platform, ZR = Zandfoort Ridge, WNB = West Netherlands Basin, IP = Indefatigable Platform, BF = Broad Fourteens Basin, WH = Winterton High, DH = Dalfsen High, COP = Central Offshore Platform, FP = Friesland Platform, LT = Lauwerszee Trough, SG = Step Graben, DCG = Dutch Central Graben, , TB = Terschelling Basin, SGP = Schill Grund Platform, AP = Ameland Platform, CBP = Cleaver Bank Platform, GH = Groningen High, LBM = London Brabant Massif. Along the axes, RD = Rijksdriehoek coordinates.

Subplots have been made for the different stratigraphic groups, lithologies and tectonic regions. The LOT data typically fall in the range S_{hmin} to $2S_{hmin} – P_c$, therefore, the lower bound of the leak-off pressures should be taken when deriving the minimum horizontal stress of a formation (Breckels and Van Eekelen, 1982; Verweij et al., 2012; Verweij, 2015). Using quantile regression (Grinsted, 2008), linear lower bound fits are made on the LOT data in each of the subplots, based on the 90th percentile. Here, 90% of the data are above the lower bound fit. When the LOT data shows a deviating trend of the lower bound with depth (>2000 m) and the data at those deeper levels consist of more than 50 measurements, different linear lower bound fits are made for the depth interval 0 – 2000 m and >2000 m, such as for the claystone consisting lithologies (see Results section).

Besides a linear fit, also a power law fit is made on the lower bound of the LOT data using quantile regression, based on the 90th percentile. In order to accomplish this, the code of Grinsted (2008) is adapted for a power law and upper and lower boundary constraints for the fit coefficients are added. For the minifrac data, quantile regression (Grinsted, 2008) is done using the 50th percentile (median). For this type of data the median should be taken instead of the lower bound, since the minifrac data gives a direct representation of the minimum horizontal stress.

The different stratigraphic groups, lithologies or tectonic regions require at least 3 LOT data points for a linear lower bound fit and 5 data points for a power law fit on the lower bound, otherwise they are deleted when making subplots, as well as data which have an undefined stratigraphic group, lithology or tectonic region.

4 Results

4.1 The selected LOT and minifrac data

The selected PSNS and NAM data containing leak-off test (LOT) data and minifrac data (MF) are shown in Figure 5, together with the standard hydrostatic (10.2 MPa/km for seawater) and lithostatic (vertical stress) gradients (22.6 MPa/km) and gradients of 14 MPa/km, 16 MPa/km and 18 MPa/km as a reference. A gradient of 14 MPa/km approaches the standard minimum horizontal stress gradient, S_{hmin} = 0.6 x vertical stress gradient (Verweij et al., 2015), i.e. indicative of the frictional limit of the upper crustal formations (Zoback et al., 2003). Note that we assume a constant lithostatic gradient; in reality the lithostatic gradient will increase with depth to the increase of density with depth.

The standard horizontal stress gradient plots at the lower bound of the LOT data in Figure 5, but deviates from it at depths larger than ~2000 meters, this might be due to the increase in the S_V gradient with depth as a consequence of the increasing density with depth, and/or the occurrence of overpressures in the Northern regions of the Netherlands at depth (Verweij et al., 2012), which can also lead to larger S_{hmin} values (e.g. Engelder & Fischer, 1994). Figure 5 displays that the minifrac data is more or less located on the lower bound of the LOT data.

To determine the S_{hmin} gradients in this study, linear and power law lower bound fits on the LOT data are determined by quantile regression using the 90th percentile and the fits on the minifrac data using the 50th percentile (median) (Grinsted, 2008).

The minifrac data from depleted reservoirs (red triangles in Figure 5) approach more or less the 14 MPa/km gradient or even below and are not taken into account in this study, since they do not represent the original state of stress in the reservoir.

Large variations can be seen in the leak-off pressures at same depth levels, therefore the detailed results are subdivided into stratigraphic groups, lithology groups and tectonic regions.

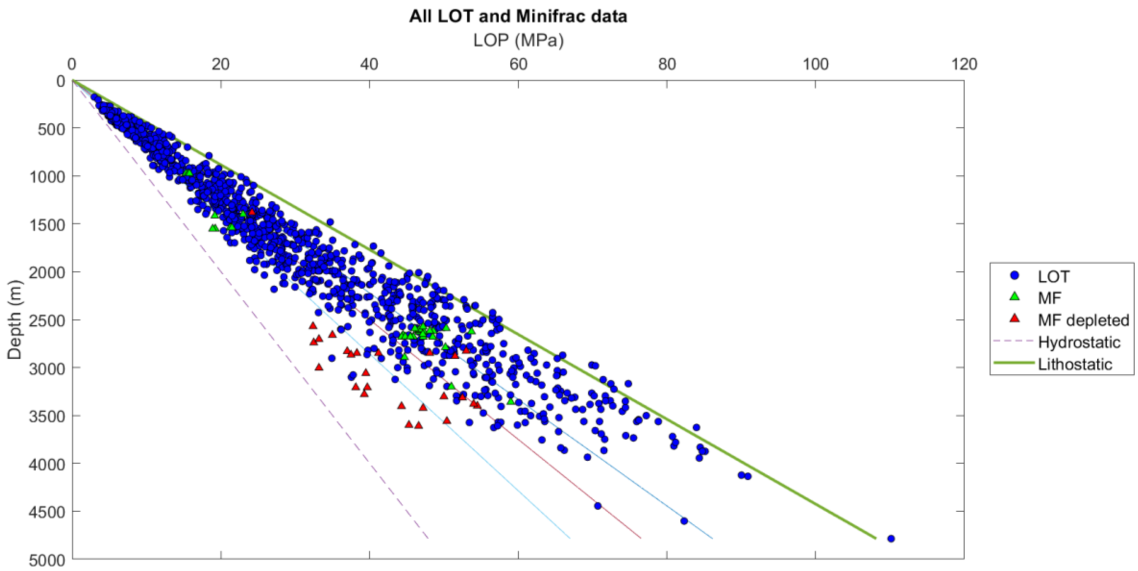

Figure 5: Overview of the PSNS and NAM LOT and minifrac data plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient (22.6 MPa/km). LOT stands for leak-off test data, MF for minifrac data and MF depleted for the minifrac data taken in depleted reservoirs.

4.2 Stratigraphic groups

The data are divided into the different stratigraphic groups (e.g. Zechstein, Rotliegend etc). Some of these stratigraphic groups are merged, in order to reduce the number of groups (see Table 1). Figure 6 shows the distribution of leak-off pressures with depth as a function of stratigraphic group and Figure 7 displays the leak-off pressures with depth per stratigraphic group with (lower bound) fits, also shown in Table 4. The leak-off pressure data generally range from the 14 MPa/km gradient to the average lithostatic pressure gradient. With larger depth, the data show a deviating trend towards higher values. In the majority of the stratigraphic groups, some of the leak-off pressures exceed lithostatic pressures. In principle, pressure magnitudes cannot exceed the lithostatic pressure, since fracturing would occur. However, an average lithostatic gradient is assumed here, whereas at depth it may be higher due to increasing density with depth.

A relatively low linear lower bound gradient on the LOT data is displayed for the shallow North Sea group, the Chalk group, the Rijnland group, the Altena group and the Limburg group. There is some uncertainty to the gradients of the Altena group and the Scruff/Schieland group since the number of measurements is limited (n = 24). A relatively higher linear lower bound gradient on the LOT data is present for the Scruff/Schieland group, the Upper and Lower Germanic Trias groups, the Zechstein group and the Upper Rotliegend group. The LOT data for the Rijnland group and Upper Germanic Trias group shows a deviating trend with depth. The linear lower bound gradients for the Rijnland group and the Upper Germanic Trias group are higher at depths larger than 2000 meters. The minifrac data confirms the relatively low lower bound gradient of the Rijnland group. In the case of the Upper Rotliegend group, the minifrac fit is significantly higher than the lower bound fit. For the Limburg group, there is a large difference between the lower bound fit and the fit on the minifrac data. This may be caused by the limited amount of data in the Limburg group (n = 13), particularly for the minifrac data which consists of only one minifrac measurement in the Limburg group.

The lower bound power law fits on the LOT data present similar trends as previously described, showing that the Altena group, the Limburg group, the Rijnland group and the Chalk group have relatively low power law fits on the lower bound of the LOT data. The North Sea group, Scruff/Schieland group and Lower Germanic Trias group show slightly higher fits, and the Upper Rotliegend, Upper Germanic Trias and Zechstein groups show the highest power law fits.

Table 4: The (lower bound) gradients (MPa/km) derived for the different stratigraphic groups.

Stratigraphic group	Lower bound gradient (MPa/km)	Lower bound gradient >2 km (MPa/km)	Minifrac fit (MPa/km)	Lower bound power law fit (MPa/km^n)	Depth range (m)	Number of measurements
North Sea group (N)	13.7			14.31 $D^{1.06}$	~200-1760	370
Chalk group (CK)	14.0			13.84 $D^{1.05}$	~200-3075	262
Rijnland group (KN)	14.3	18.1 ± 5.1	13.9	14.24 $D^{1.01}$	~500-3350	161
Scruff/Schieland group (SG/SL)	15.2			15.01 $D^{1.03}$	~1075-3300	24
Altena group (AT)	13.9			13.73 $D^{1.01}$	~975-3050	24
Upper Germanic Trias group (RN)	15.6	20.2 ± 1.7		14.61 $D^{1.08}$	~1300-4120	77
Lower Germanic Trias group (RB)	14.8			10.50 $D^{1.39}$	~1400-3875	52
Zechstein group (ZE)	16.0			16.03 $D^{1.00}$	~690-3880	152
Upper Rotliegend group (RO)	15.9		17.6	14.83 $D^{1.05}$	~2120-4445	66
Limburg group (DC)	13.9		18.1	11.37 $D^{1.25}$	~1370-4700	13

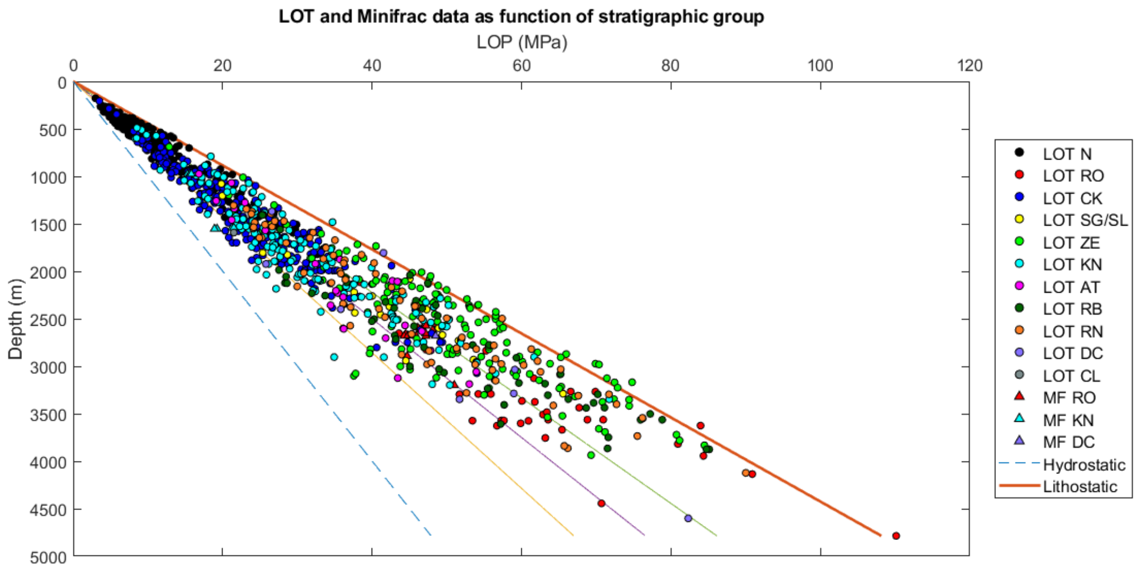

Figure 6: Overview of the PSNS and NAM LOT and minifrac data as function of stratigraphic group plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

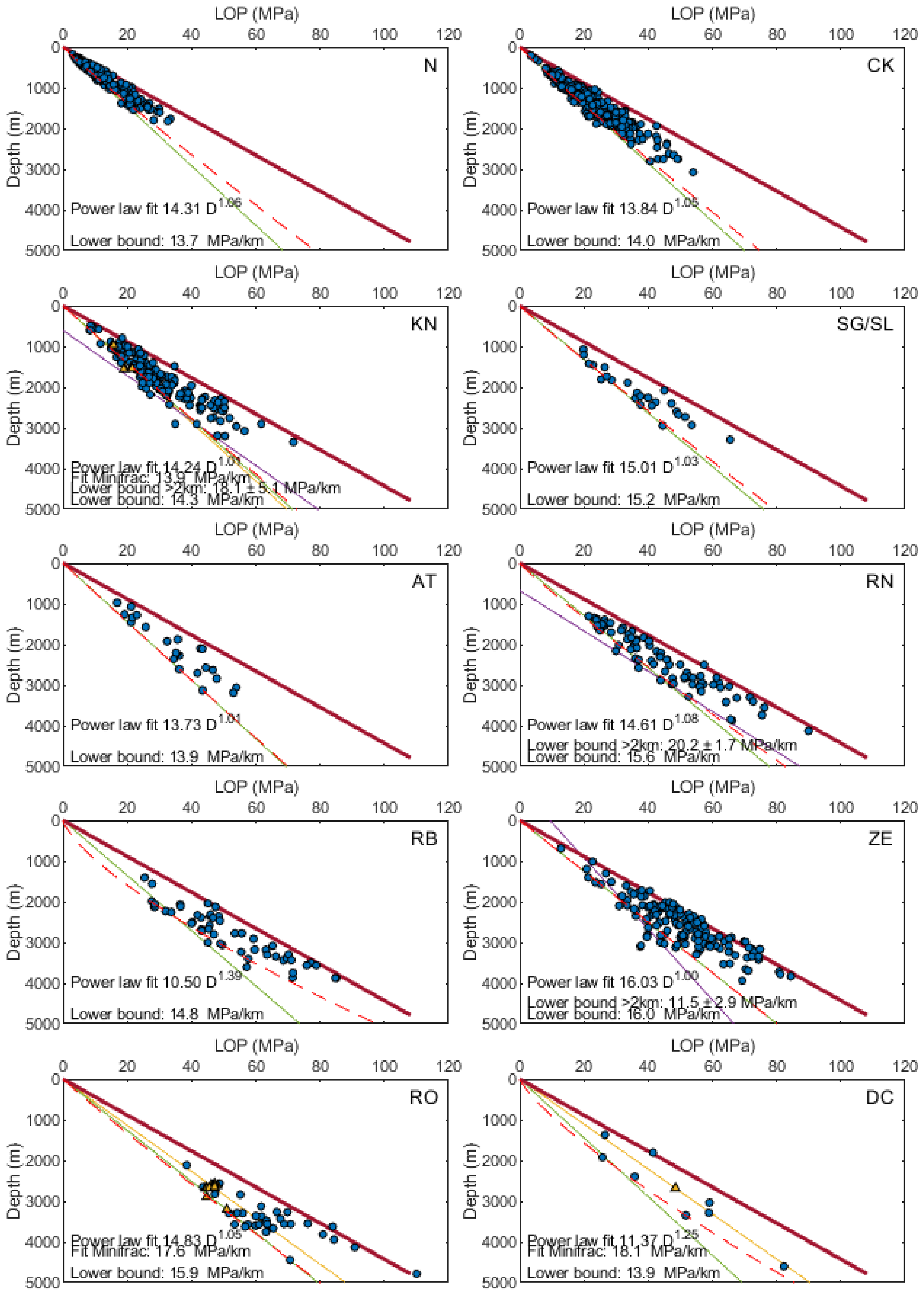

Figure 7: Overview of the data per stratigraphic group with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements (50th percentile), purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data.

4.3 Lithology

The data is divided into different lithologies (e.g. claystone, sandstone etcetera). Lithologies are merged, in order to reduce the number of groups (see Table 2). Figure 8 shows the distribution of leak-off pressures with depth as a function of lithology and Figure 9 displays the leak-off pressures with depth per lithology with (lower bound) fits, also shown in Table 5. The leak-off pressure data generally range from the 14 MPa/km gradient to the average lithostatic pressure gradient. In the majority of the lithology groups, some of the leak-off pressures exceed average lithostatic pressures.

Sandstone, chalk and the North Sea group have relatively low linear lower bound fits on the LOT data. Claystone, anhydrite and carbonate have intermediate linear lower bound gradients and rock salt has a relatively high linear lower bound fit on the LOT data. However, based on the minifrac data, sandstone and claystone have relatively higher gradients than for the lower bounds of the LOT data. Claystone has both higher minifrac and lower bound LOT gradients than sandstone. Moreover, at depths larger than 2000 meters, the linear lower bound gradient is also significantly higher in the case of claystone and rock salt. The lower bound power law fits on the LOT data show similar trends, with a relatively low lower bound power law fit for sandstone and chalk, an intermediate fit for anhydrite, clay, the North Sea group and carbonate, and a high fit for rock salt.

Table 5: The (lower bound) gradients (MPa/km) derived for the different lithology groups.

Lithology	Lower bound gradient (MPa/km)	Lower bound gradient >2km (MPa/km)	Minifrac fit (MPa/km)	Lower bound power law fit (MPa/km^n)	Depth range (m)	Number of measurements
Anhydrite	14.8			14.06 $D^{1.05}$	~1860-3935	30
Carbonate	15.2			13.47 $D^{1.15}$	~1050-3410	35
Chalk	14.1			13.85 $D^{1.05}$	~200-2830	255
Claystone	14.2	18.3 ± 1.1	18.4	14.15 $D^{1.05}$	~265-4785	522
North Sea Group	13.7			14.43 $D^{1.06}$	~150-1820	206
Rock salt	17.2	18.5 ± 4.3		17.03 $D^{1.01}$	~690-4120	106
Sandstone	13.4		16.9	13.75 $D^{1.04}$	~250-3550	89

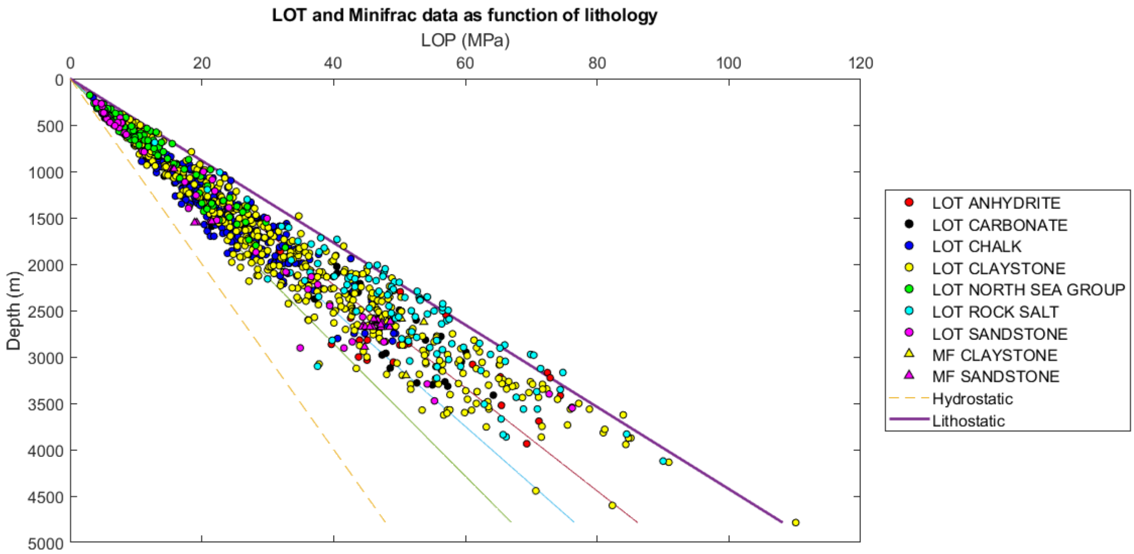

Figure 8: The PSNS and NAM LOT and minifrac data as function of lithology plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

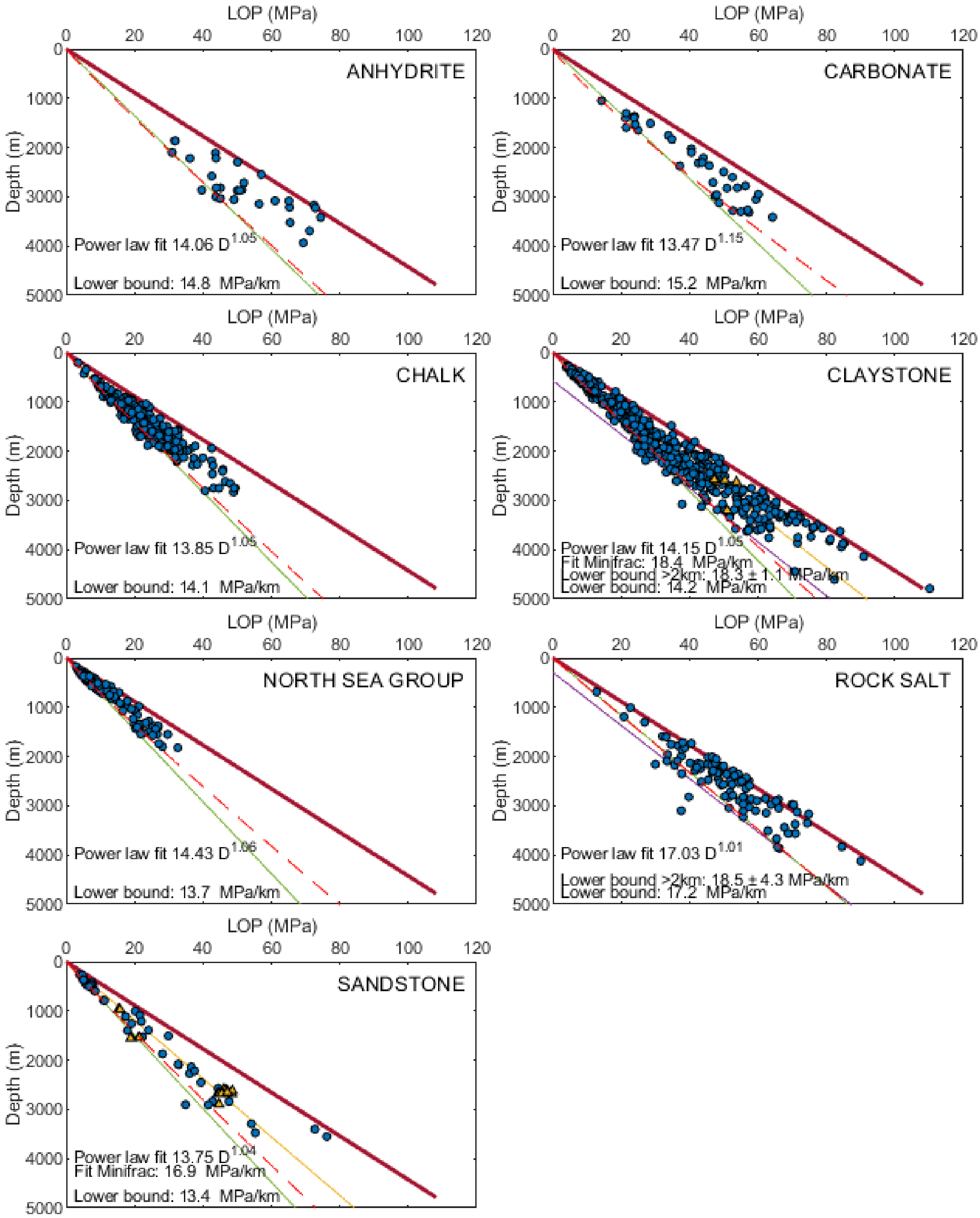

Figure 9: The PSNS and NAM LOT and minifrac data subdivided per lithology group with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data.

4.4 The lithology group Claystone

The lithology group Claystone has the largest depth range of measurements, i.e. from ~250 meters to ~4800 meters. Figure 9 shows that the relatively shallow measurements, < 2000 meters, have a lower gradient than the relatively deeper measurements. Therefore, the data is divided into two different depth ranges: from 0 – 2000 meters and larger than 2000 meters. This results in two different lower bound gradients: 13.9 MPa/km for the data in depth range 0 – 2000 meters and 18.3 ± 1.1 MPa/km for the measurements with depths larger than 2000 meters (Figure 10). Moreover, a power law fit on the lower bound of the LOT data is made, taking the depth dependence of the gradient into account.

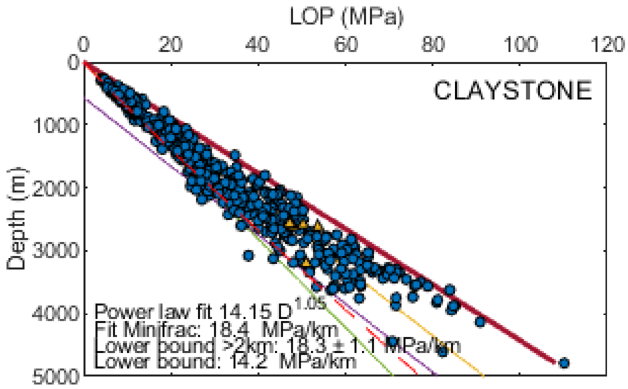

Figure 10: The data of the lithology group Claystone with associated lower bound gradients. Red line: average lithostatic gradient (22.6 MPa/km), green line: lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements (50th percentile), purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data.

4.5 Claystone versus sandstone minifrac data

The minifrac database of the NAM provides data in the sandstones and claystones. This is high quality data in the reservoir. The used data consists of ~30 measurements, since the other minifrac data originated from depleted reservoirs and are therefore not taken into account. A pronounced difference is visible between the sandstone and claystone minifrac data, showing that claystone has a significantly higher fit than sandstone, which is displayed in Figure 11. Moreover, Figure 12 shows that also within a specific gas field in the Friesland Platform, the fit on the minifrac data for the claystones (18.9 MPa/km) is significantly higher than for the sandstones (17.9 MPa/km) in the same field.

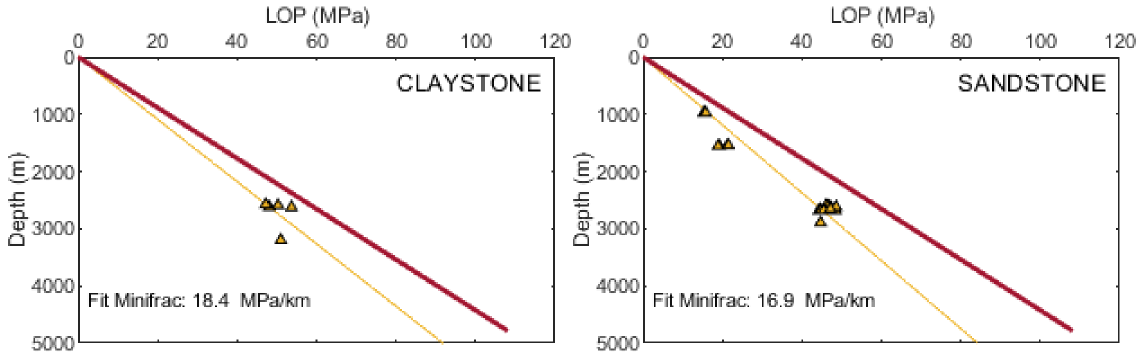

Figure 11: The minifrac data of the NAM which is measured in claystones and sandstones. The red line is the average lithostatic gradient of 22.6 MPa/km and the yellow line is the 50th percentile fit on the minifrac data.

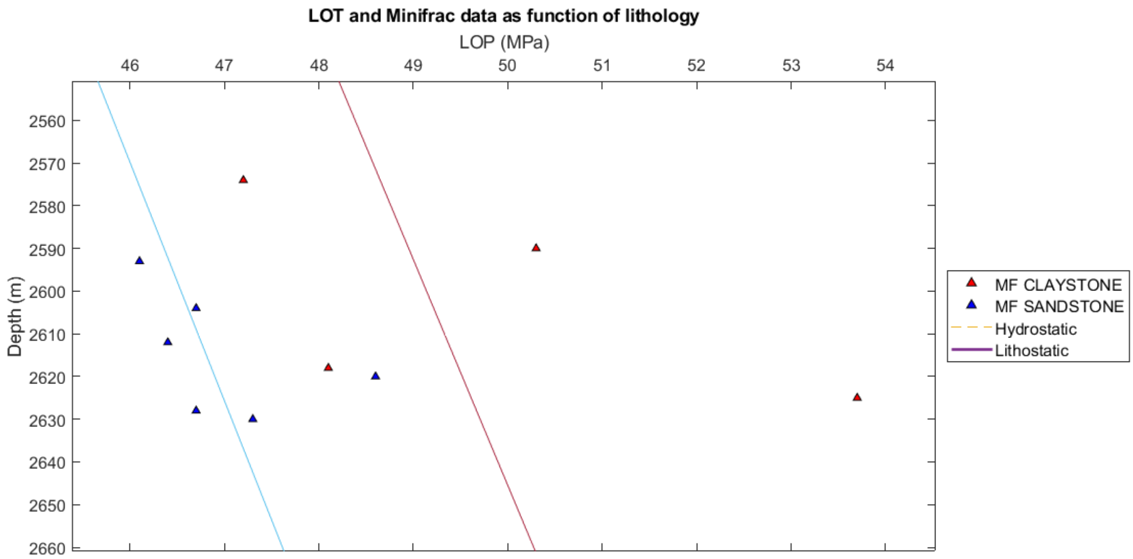

Figure 12: The minifrac data for claystones and sandstones in a specific field in the Friesland Platform. The fit on the claystones is shown in red (18.9 MPa/km) and the fit on the sandstones in blue (17.9 MPa/km)

4.6 Tectonic regions

The LOT and minifrac data of the NAM and PSNS databases can be spatially divided into the different tectonic regions/structural elements of Figure 4. In 22 of these tectonic regions, LOT and minifrac data can be found, see Figure 13-15 and Table 6-8. Since the large number of tectonic regions makes it hard to distinguish between trends in the data, the tectonic regions are merged into 5 larger tectonic super regions (Figure 16): Northern-Northeastern offshore, Northwestern offshore, Northern onshore, Eastern onshore and Southwestern onshore and offshore, based on their location (surrounding regions, onshore/offshore), the presence/absence of thick rock salt layers and the categories of Verweij (2015). The leak-off pressure data generally range from the 14 MPa/km gradient to the average lithostatic pressure gradient. In the majority of the tectonic regions, some of the leak-off pressures exceed standard lithostatic pressures. Those measurements exceeding lithostatic pressure can be found in the rock salt, anhydrite and claystone lithologies predominantly.

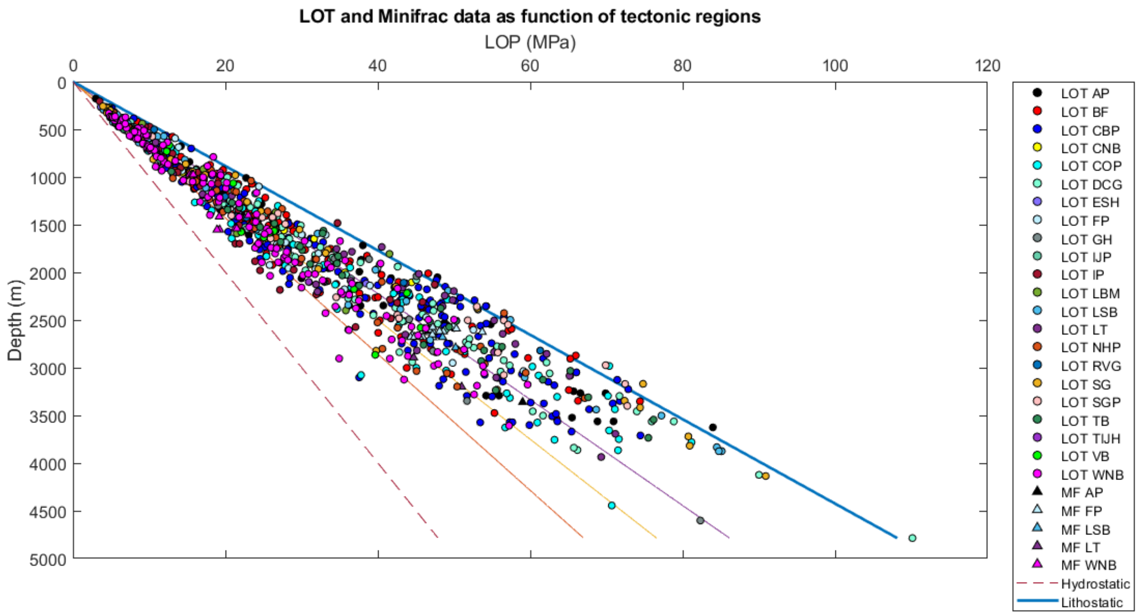

Figure 13: Overview of the PSNS and NAM LOT and minifrac data as function of tectonic region plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient..

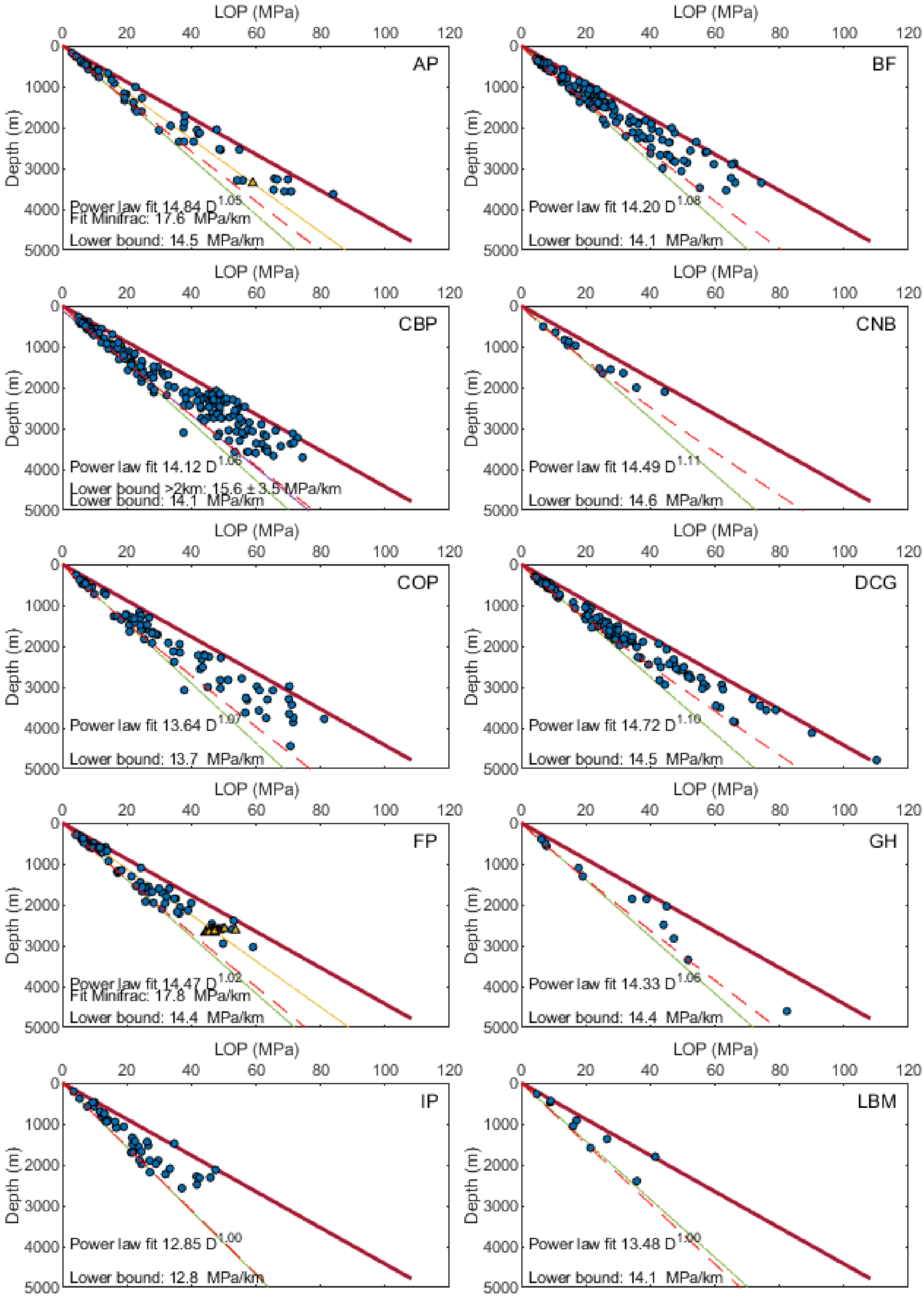

Figure 14: The PSNS and NAM LOT and minifrac data subdivided per tectonic region (part 1), with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data. DCG = Dutch Central Graben, AP = Ameland Platform, CBP = Cleaver Bank Platform, COP = Central Offshore Platform, BF = Broad Fourteens Basin, FP = Friesland Platform, GH = Groningen High, CNB = Central Netherlands Basin, IP = Indefatigable Platform, LBM = London Brabant Massif.

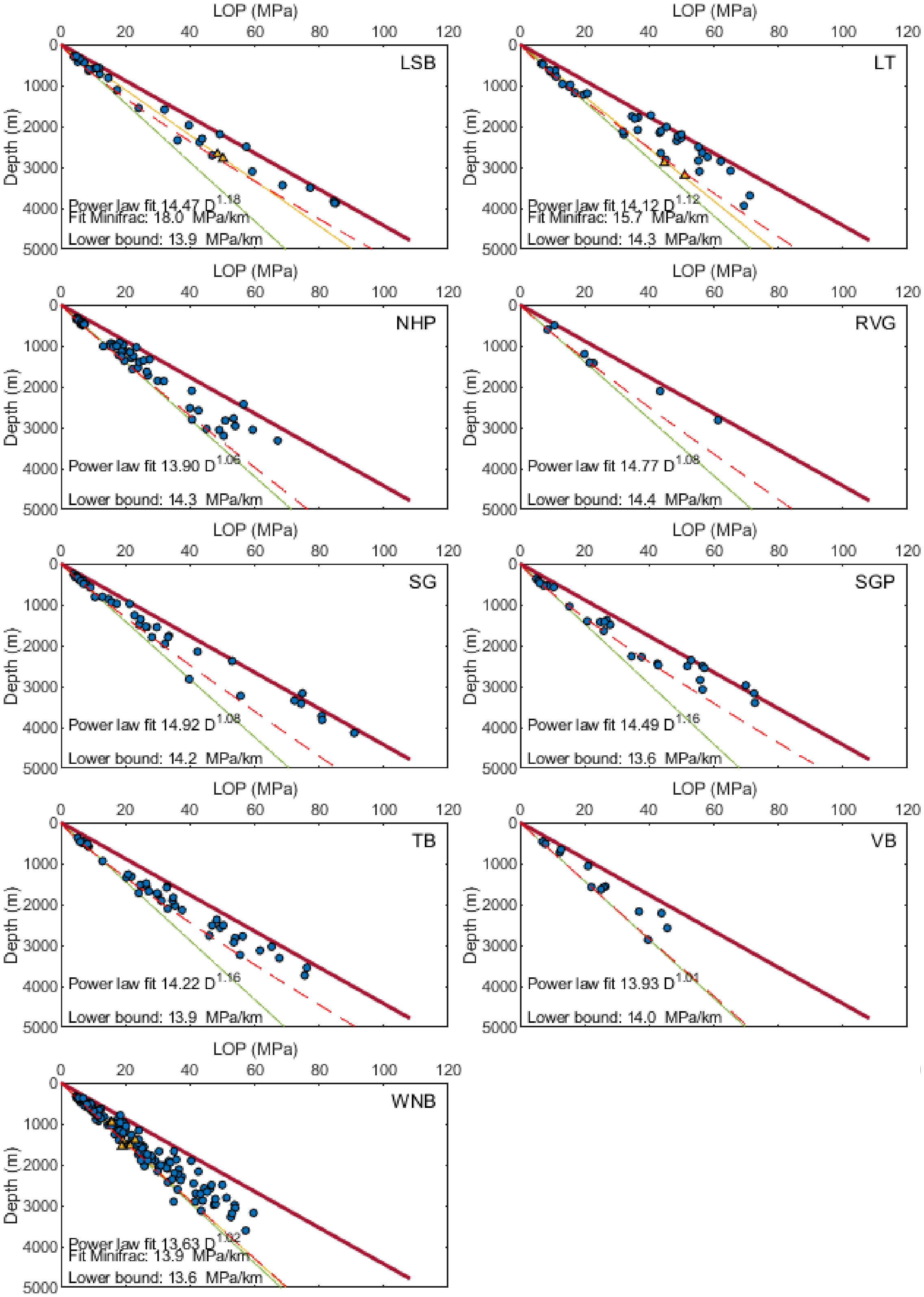

Figure 15: The PSNS and NAM LOT and minifrac data subdivided per tectonic region (part 2), with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, red dashed line: lower bound power law fit on the LOT data. SG = Step Graben, TB = Terschelling Basin, SGP = Schill Grund Platform, NHP = North Holland Platform, RVG = Ruhr Valley Graben, VB = Vlieland Basin, LT = Lauwerszee Trough, LSB = Lower Saxony Basin, WNB = West Netherlands Basin.

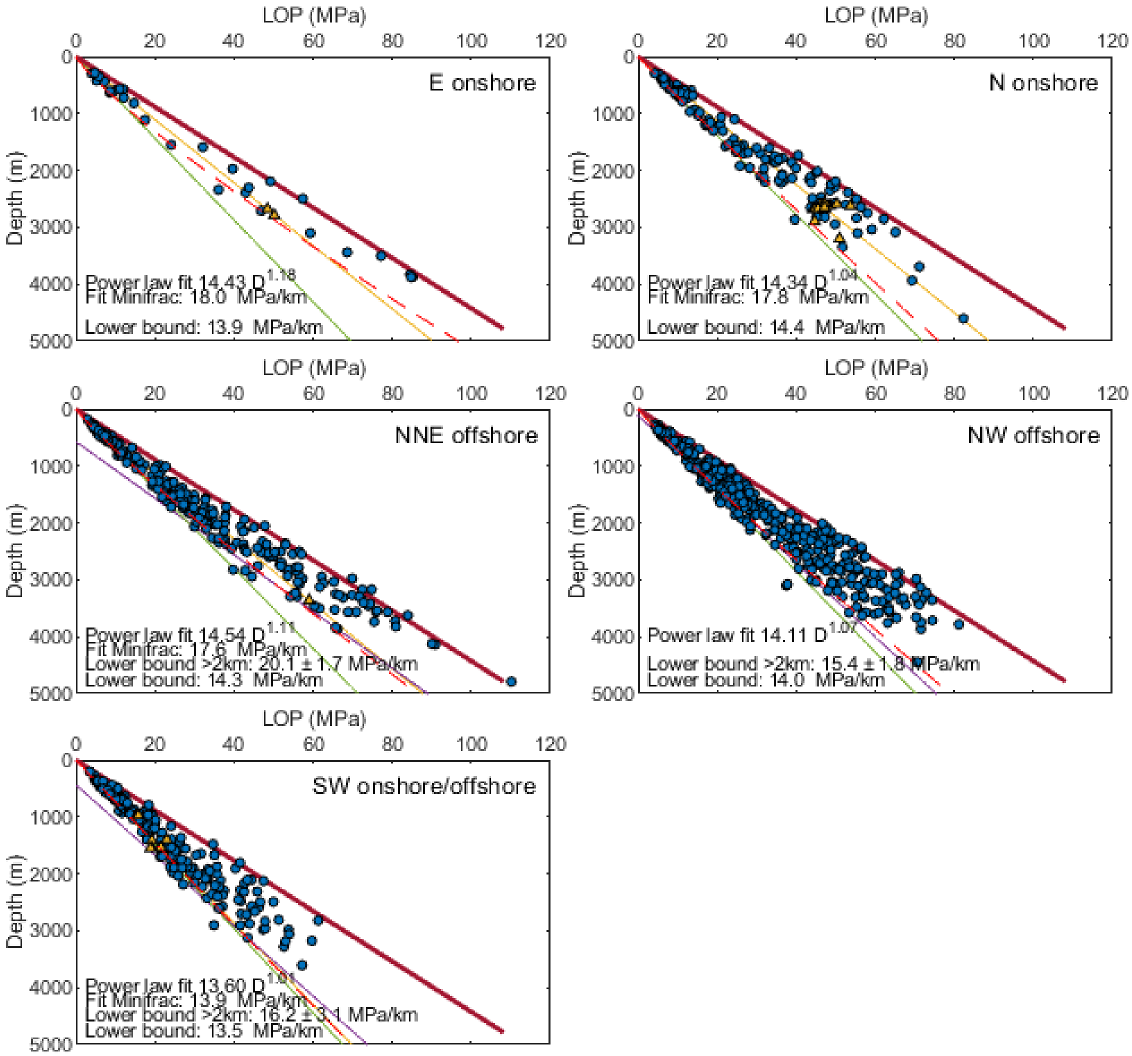

Figure 16: The PSNS and NAM LOT and minifrac data subdivided per tectonic super region, with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data.

4.6.1 Northern-Northeastern offshore (SG, DCG, TB, SGP, AP)

At shallower depths (<2000 meters), the linear lower bound of the LOT data for the tectonic regions in the Northern-Northeastern offshore area more or less fits the 14 MPa/km gradient. At depths larger than ~2000 meters, the linear lower bound of the LOT data starts to deviate and has a better fit with the 16 MPa/km gradient. From ~3500 meters, the lower bound more or less fits the 18 MPa/km gradient. The linear lower bound fit of the Schill Grund Platform (SGP) is relatively low in comparison to the other tectonic regions, especially when comparing to the Dutch Central Graben (DCG) and the Ameland Platform (AP). The power law fits on the lower bound of the LOT data of the tectonic regions in the NNE offshore are relatively high with respect to the other regions (Figure 14-16).

Minifrac data is found at a depth of 3360 meters in the Ameland Platform and plots more or less on the 18 MPa/km gradient (17.6 MPa/km), which is significantly higher than the LOT lower bound.

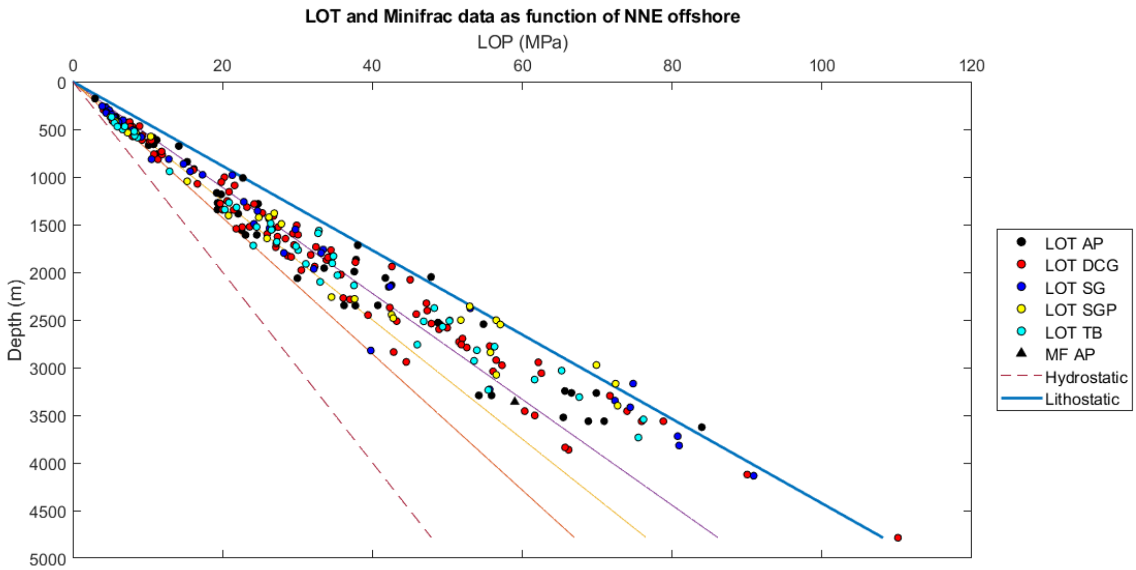

Figure 17: LOT and minifrac data of the Northern-Northeastern offshore tectonic regions (SG, DCG, TB, SGP, AP) plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

4.6.2 Northwestern offshore (CBP, COP, BF, NHP)

At depths to ~2000 meters, the linear lower bound of the LOT data in the Northwestern offshore tectonic regions is approximately 14 MPa/km. At depths larger than ~2000 meters, the lower bound starts to deviate towards the 16 MPa/km gradient. The deviation of the LOT data with larger depth is visible for the Cleaverbank Platform, which shows a linear lower bound of 15.6 ± 3.5 MPa/km for depths larger than 2 km. The Central Offshore Platform has a slightly lower linear gradient than the other tectonic regions. The power law fit on the LOT data of the tectonic regions is comparable to the Northern onshore regions, slightly lower than for the NNE offshore and Eastern onshore regions, but higher than the Southwestern regions (Figure 14-16).

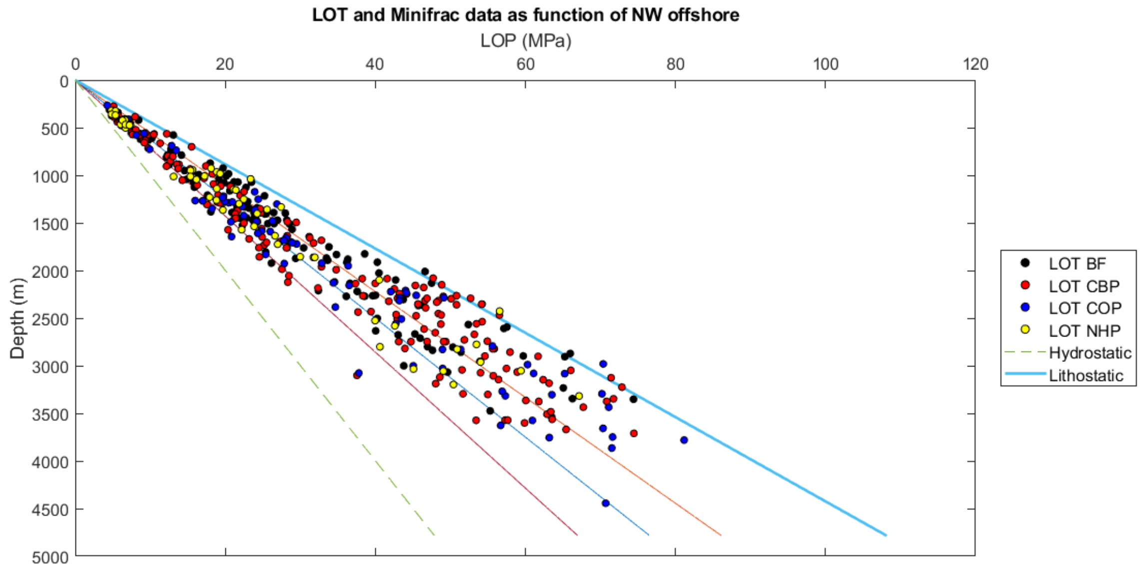

Figure 18: LOT data of the tectonic regions in the Northwestern offshore (CBP, COP, BF, NHP) plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

4.6.3 Northern onshore (VB, FP, LT, GH)

The linear lower bound on the LOT data follows the 14 MPa/km gradient up to ~2200 meters, but at greater depth the lower bound deviates from that towards the 16 MPa/km gradient. Minifrac data can be found in the Friesland Platform and the Lauwerszee Trough. In the Friesland Platform, the minifrac data is present at a depth of ~2600 meters and the leak-off pressure ranges from 16 MPa/km to approximately 20-21 MPa/km. The fit on the minifrac data in the Friesland Platform is 17.8 MPa/km, which is significantly higher than the linear lower bound fit of this region. In the Lauwerszee Trough, the minifrac data can be found at a depth range of 2900-3200 meters. The fit on the minifrac data in the Lauwerszee Trough is 15.7 MPa/km, which is higher than the lower bound fit (total depth range). The minifrac fit of the Lauwerszee Trough is lower than the Friesland Platform.
The power law fit on the LOT data of the tectonic regions is comparable to the NW offshore regions, slightly lower than for the NNE offshore and Eastern onshore regions, but higher than the Southwestern regions.

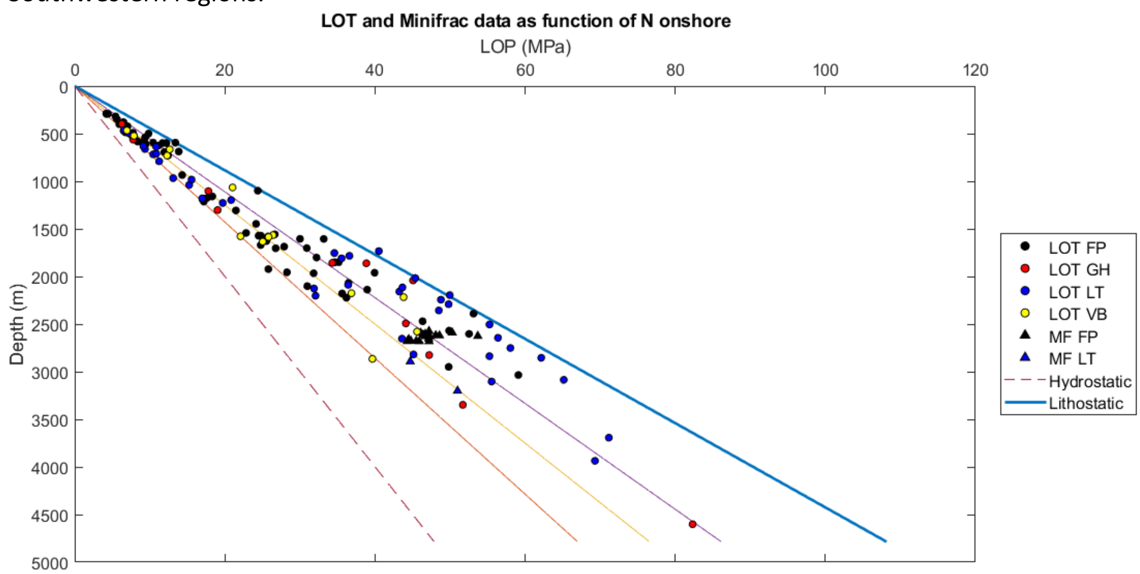

Figure 19: LOT and minifrac data of the Northern onshore tectonic regions (VB, FP, LT, GH) plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

4.6.4 Eastern onshore (LSB)

For this region, a clear deviation of the linear lower bound gradient is visible with depth. At shallow depth (<700 meters), the lower bound of the LOT data fits the 14 MPa/km gradient. In the depth range 700-2300 meters the lower bound is approximately 16 MPa/km. At depths larger than 2300 meters, the lower bound of the LOT data equals 18 MPa/km or higher. The latter corresponds to the minifrac data which is available at a depth of ~2700 meters, plotting on the 18 MPa/km gradient. The minifrac fit is significantly higher than the lower bound fit over the total depth range. The power law fit on the LOT data is the highest for the Eastern onshore with respect to the other tectonic regions, followed by the NNE offshore (Figure 14-16).

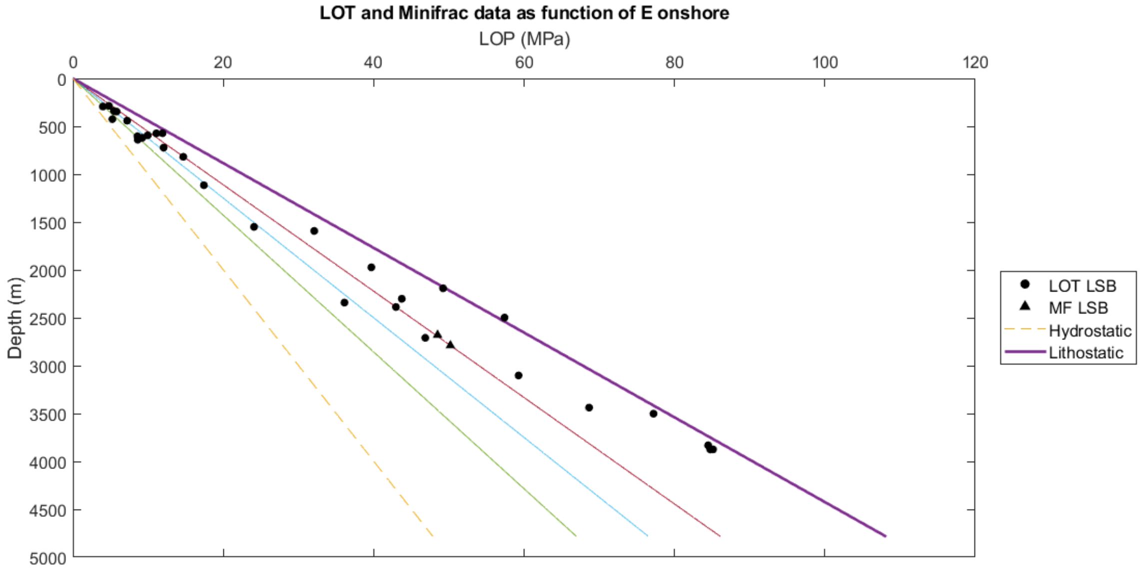

Figure 20: LOT and minifrac data of the Eastern onshore tectonic region (LSB) plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient..

4.6.5 Southwestern onshore and offshore (CNB, IP, WNB, RVG, LBM)

Leak-off pressure data in the southwestern onshore and offshore regions vary from below the 14 MPa/km gradient (~13 MPa/km) to the average lithostatic stress gradient as shown in Figure 21. There are some differences between the five different regions. LOP data in the West Netherlands Basin (WNB), Indefatigable Platform (IP) and the London Brabant Massif (LBM) range from below the 14 MPa/km gradient to the average lithostatic pressure gradient and the lower bound of the data is approximately 14 MPa/km or lower. Minifrac data can be found in the West Netherlands Basin at depths of ~1000 meters and ~1400 meters. The fit on the minifrac data in the West Netherlands Basin is relatively low and similar to the lower bound fit, i.e. 13.9 MPa/km.

The power law fits on the LOT data of the tectonic regions of the Southwestern onshore and offshore regions are relatively low with respect to the other regions. The LOP data in the Central Netherlands Basin (CNB) and Ruhr Valley Graben (RVG) have a slightly deviating linear and power law lower bound. It is, however, unclear whether these differences can be attributed to regional differences in leak-off pressures or to a limited amount of measurements in the London Brabant Massif (n = 9), Central Netherlands Basin (n = 12) and Ruhr Valley Graben (n = 7).

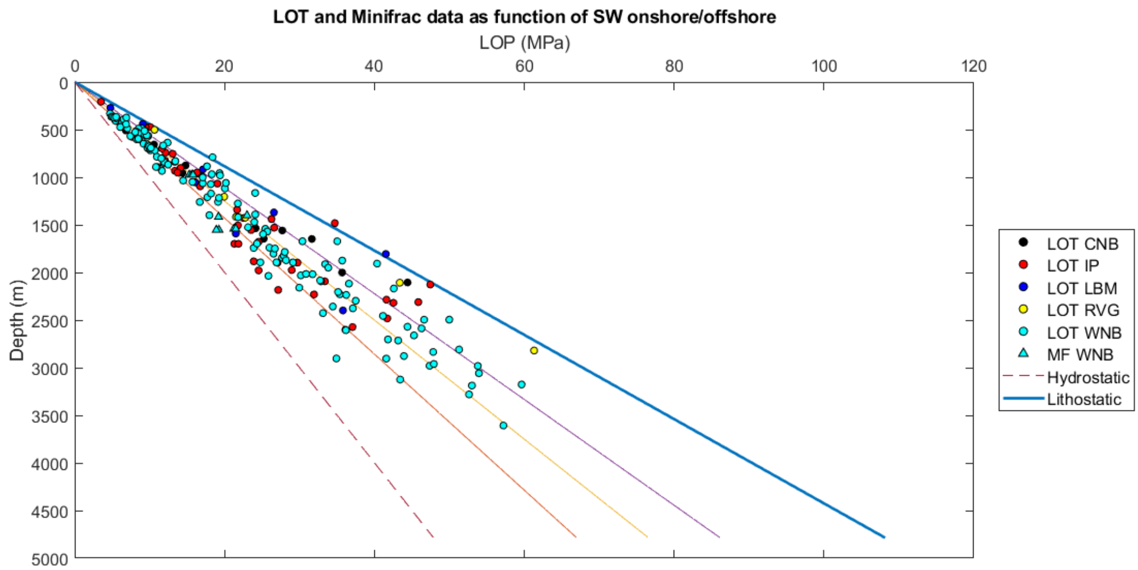

Figure 21: LOT and minifrac data of the Southwestern onshore and offshore tectonic regions (CNB, WNB, IP, RVG, LBM) plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

Table 6: The lower bound gradients (MPa/km) and minifrac fit (MPa/km) derived per tectonic region.

Tectonic region	Lower bound gradient (MPa/km)	Lower bound gradient > 2km (MPa/km)	Minifrac fit (MPa/km)	Lower bound power law fit (MPa/km^n)	Depth range (m)	Number of measurements
SG (Step Graben)	14.2			14.92 $D^{1.08}$	~260-4135	39
DCG (Dutch Central Graben)	14.5			14.72 $D^{1.10}$	~300-4785	109
TB (Terschelling Basin)	13.9			14.42 $D^{1.16}$	~370-3735	41
SGP (Schill Grund Platform)	13.6			14.49 $D^{1.16}$	~370-4000	28
AP (Ameland Platform)	14.5		17.6	14.84 $D^{1.05}$	~180-2635	60
CBP (Cleaver Bank Platform)	14.1	15.6 ± 3.5		14.12 $D^{1.06}$	~275-3710	185
COP (Central Offshore Platform)	13.7			13.64 $D^{1.07}$	~265-4445	81
BF (Broad Fourteens Basin)	14.1			14.20 $D^{1.08}$	~310-3350	140
NHP (North Holland Platform)	14.3			13.90 $D^{1.06}$	~320-3320	56
VB (Vlieland Basin)	14.0			13.93 $D^{1.01}$	~465-2865	14
FP (Friesland Platform)	14.4		17.8	14.47 $D^{1.02}$	~290-3030	86
LT (Lauwerszee Trough)	14.3		15.7	14.12 $D^{1.12}$	~460-3935	50
GH (Groningen High)	14.4			14.33 $D^{1.06}$	~400-4600	16
LSB (Lower Saxony Basin)	13.9		18.0	14.47 $D^{1.18}$	~285-3875	39
CNB (Central Netherlands Basin)	14.6			14.49 $D^{1.11}$	~510-2105	12
WNB (West Netherlands Basin)	13.6		13.9	13.63 $D^{1.02}$	~330-3600	152
RVG (Ruhr Valley Graben)	14.4			14.77 $D^{1.08}$	~500-2820	7

LBM (London Brabant Massif)	14.1			13.48 $D^{1.00}$	~270-2400	9
IP (Indefatigable Platform)	12.8			12.85 $D^{1.00}$	~200-2575	42

Table 7: The lower bound gradients (MPa/km) and minifrac fit (MPa/km) derived per tectonic super region.

Tectonic super region	Lower bound gradient (MPa/km)	Lower bound gradient >2 km (MPa/km)	Minifrac fit (MPa/km)	Lower bound power law fit (MPa/km^n)
NNE offshore	14.3	20.1 ± 1.7	17.6	14.54 $D^{1.11}$
NW offshore	14.0	15.4 ± 1.8		14.11 $D^{1.07}$
N onshore	14.4		17.8	14.34 $D^{1.04}$
E onshore	13.9		18.0	14.43 $D^{1.18}$
SW onshore/offshore	13.5	16.2 ± 3.1	13.9	13.60 $D^{1.01}$

Table 6 and 7 show an overview of the lower bound gradients, minifrac fit, amount of data and depth range of the measurements per tectonic region and per tectonic super region. Strikingly, the lower bound gradients and the minifrac fits are generally decreasing from the north/northeast to the west/southwest of the Netherlands. For the minifrac data the depth range of the measurements is different, with shallower measurements in the Southwest and deeper measurements in the North. Table 8 shows the tectonic regions classified per structural element type, i.e. basin, platform, high. Although there is variation between the different tectonic regions, a clear relation between the lower bound gradient and the structural element type and its burial history (basin, platform, high) is not present.

Table 8: The lower bound gradients (MPa/km) and minifrac fit (MPa/km) derived per tectonic region. Basin type I = strongly inverted basin, Basin type II = mildly or not inverted basin, Platform type I = Cretaceous or Paleogene on top of Zechstein, Platform type II = Cretaceous or Paleogene on top of Triassic. Structural element types based on Krombrink et al. (2012).

Tectonic region	Lower bound gradient (MPa/km)	Lower bound gradient > 2km (MPa/km)	Minifrac fit (MPa/km)	Lower bound power law fit (MPa/km^n)	Structural element type
					Basins
CNB (Central Netherlands Basin)	14.6			14.49 $D^{1.11}$	Basin type I
SG (Step Graben)	14.2			14.92 $D^{1.08}$	Basin type II
TB (Terschelling Basin)	13.9			14.22 $D^{1.16}$	Basin type II
VB (Vlieland Basin)	14.0			13.93 $D^{1.01}$	Basin type II
LSB (Lower Saxony Basin)	13.9		18.0	14.47 $D^{1.18}$	Basin type II
RVG (Ruhr Valley Graben)	14.4			14.77 $D^{1.08}$	Basin type II
DCG (Dutch Central Graben)	14.5			14.72 $D^{1.10}$	Basin type I and II
BF (Broad Fourteens Basin)	14.1			14.20 $D^{1.08}$	Basin type I mostly (and basin type II)
WNB (West Netherlands Basin)	13.6		13.9	13.63 $D^{1.02}$	Basin type I (East) and basin type II (West)
					Platforms
AP (Ameland Platform)	14.5		17.6	14.84 $D^{1.05}$	Platform type II
LT (Lauwerszee Trough)	14.3		15.7	14.12 $D^{1.12}$	Platform type II
GH (Groningen High)	14.4			14.33 $D^{1.06}$	Platform type II

IP (Indefatigable Platform)	12.8			12.85 $D^{1.00}$	Platform type II
SGP (Schill Grund Platform)	13.6			14.49 $D^{1.16}$	Platform type I and II
CBP (Cleaver Bank Platform)	14.1	15.6 ± 3.5		14.12 $D^{1.06}$	Platform type I and II
COP (Central Offshore Platform)	13.7			13.64 $D^{1.07}$	Platform type I and II
NHP (North Holland Platform)	14.3			13.90 $D^{1.06}$	Platform type I and II
FP (Friesland Platform)	14.4		17.8	14.47 $D^{1.02}$	Platform type I and II
					Highs
LBM (London Brabant Massif)	14.1			13.84 $D^{1.00}$	High

4.7 Sandstone formations in different tectonic regions

The lithology group Sandstone (Figure 22) in the Broad Fourteens Basin (BF) has a limited amount of data. Lower bound fits are established on the basis of this limited amount of LOT data and are therefore subject to substantial uncertainty. The sandstones in the Dutch Central Graben (DCG) and Friesland Platform (FP) have a lower bound on the LOT data of ~16 MPa/km, thus significantly higher than in the Broad Fourteens Basin. Minifrac data is found in the Friesland Platform at a depth of approximately 2600 meters and is located between the 16.5 MPa/km and ~18 MPa/km gradients.
The majority of the LOT data in the West Netherlands Basin (WNB) scatters between 14 MPa/km and 18 MPa/km. A few measurements plot below the 14 MPa/km gradient at approximately 13 MPa/km. Minifrac data can be found at a depth of ~1000-1500 meters and plot on the ~14 MPa/km gradient. The earlier observed trend with higher gradients in the Northern regions and lower gradients in the Southern regions, is also visible for the sandstones.

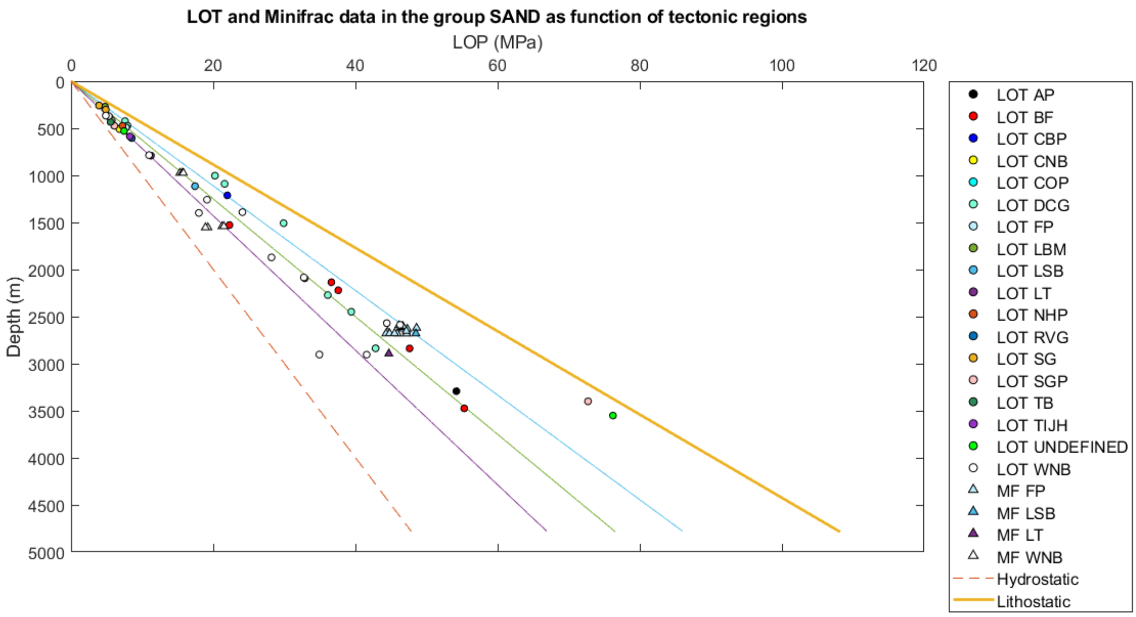

Figure 22: The LOT and minifrac data in the lithology group sandstone in the different tectonic regions plotted together with the hydrostatic gradient, 14 MPa/km, 16 MPa/km and 18 MPa/km gradients and the average lithostatic gradient.

5 Discussion and conclusions

5.1 Minimum principal horizontal stress S_{hmin} in the Netherlands

The difference between standard lithostatic pressure magnitudes and minimum principal horizontal stress magnitudes increases with depth. This is the result of the increase in differences between the three principal stresses with depth in the earth, since rocks increase in frictional strength and density with increasing depth, when considering hydrostatic fluid pressure conditions (Zoback, 2010).
The minimum principal horizontal stress S_{hmin} gradient also varies with depth within studied lithologies, stratigraphic groups or tectonic regions. At depths greater than ~2000 meters, the gradient becomes higher than at shallow depths in the groups. This is in particular clearly visible for the claystone consisting lithologies (Figure 10). The lithostatic pressure also increases with depth (dS_v/dy increases with depth) due to the general increase in density of rocks with depth. This might partly explain the increase of the minimum horizontal stress gradient (dS_{hmin}/dy) with depth. In addition, overpressures are found in the Northern regions and some of the deeper lithologies in the Dutch subsurface (Verweij et al., 2012); these can also result in higher S_{hmin} (Engelder & Fischer, 1994). Therefore, it is important to look at the in-situ stress ratio S_{hmin}/S_v and in particular the effective stress ratio $(S_{hmin} – P) / (S_v – P)$ in further research.
The lower bound of the leak-off pressures varies at similar depths (see Figure 5). This can be attributed to the different lithologies, stratigraphic groups or tectonic regions, which will be discussed in more detail below.

Formation lithology is related to the most pronounced differences in minimum horizontal stress gradients (Table 5). Rock salt, and to a lesser extent anhydrite and claystone (the latter particularly deeper than 2 km) have relatively high minimum horizontal stress gradients and a very large range of leak-off pressures with depth, which occasionally exceed the average lithostatic pressure gradient. The minimum horizontal stress gradients of rock salt and claystone are even higher at larger depth, e.g. for rock salt 18.5 ± 4.3 MPa/km for >2 km, with respect to 17.2 MPa/km over the total depth range. The high minimum horizontal stresses are caused by the flowing or creeping nature of rock salt, anhydrite and claystone, which tends to relax differential stresses $S_v – S_{hmin}$ by increasing S_{hmin} (S_v remains constant as the overburden weight remains unchanged). The fact that rock salt and anhydrite have relatively high minimum horizontal stress gradients was previously recognized by other studies, such as Verweij et al. (2015) and Muntendam-Bos (2021). Additionally, the results of this study show that claystone-containing lithologies also have a relatively high minimum horizontal stress gradient, particularly at depths larger than 2 km, i.e. for the linear fit >2 km on the LOT data 18.3 ± 1.1 MPa/km applies. This 2 km boundary is characteristic for the claystone consisting lithologies, since it is hardly present in other lithologies, such as sandstone. This may be a result of the compaction behaviour of claystones and could have important implications on the seal integrity of claystones. However, this absence of the 2 km boundary in other non-creeping lithologies could also be a result of limited data at larger depths for those lithologies. The minifrac data of the claystones confirm the high gradient for claystones, indicating a minifrac gradient of 18.4 MPa/km (Figure 11). The minifrac data also show that claystones have a higher gradient than the surrounding sandstones even within the same reservoir formation, where tectonic setting, depth etc. are the same. This data is of high quality and measured in the reservoir and thus considered as valuable data, supporting the hypothesis of the creeping behaviour of the claystones and the corresponding high minimum horizontal stress gradient. The other lithologies sandstone, chalk and the North Sea group have a relatively low lower bound fit on the LOT data (13.4 – 14.1 MPa/km for the linear fit). For the latter two lithologies, this may be related to their relatively shallow occurrence. For the sandstones, such a relation cannot be established. Anhydrite and carbonate have an intermediate lower bound gradient (14.8 – 15.2 MPa/km for the linear fit).

The results of this study show that clay-rich formations have a significantly higher minimum horizontal in-situ stress gradient, particularly at larger depth, compared to the other lithologies e.g. sandstones, except for the evaporites (rock salt and anhydrite) which have also high minimum horizontal stress gradients. This higher minimum horizontal stress gradient of clay-rich lithologies is also found in other studies. Warpinski and Teufel (1989) state that clay-rich rocks in the Piceance basin in Colorado generally have a larger minimum horizontal in-situ stress gradient than sandstones adjacent to the clay-rich rocks. The minimum horizontal stress gradient of clay-rich rocks is generally very close to the lithostatic stress gradient in the Piceance basin (Warpinski and Teufel, 1989). An explanation for this can be found in the behaviour of the clay-rich rocks. Clay-rich rocks exhibit relaxation behaviour at relatively fast rates, forcing the horizontal stresses to be relatively close to the lithostatic stress (Warpinski and Teufel, 1989). Furthermore, Teufel (1989) also agrees with the relation between lithology and minimum horizontal stress magnitude, showing that sandstones have approximately 4 MPa lower minimum horizontal stress magnitudes than surrounding shales/clay-rich rocks at the same depth. The difference between the minimum horizontal stress gradients in the clay-rich rocks and sandstones in our study is also significant, i.e. 0.8 to 5.1 ± 1.1 MPa/km difference for the linear gradient. Zhang and Zhang (2017) also endorse the lithology dependence of the minimum horizontal stress. They agree with the fact that sandstones have a lower minimum horizontal stress compared to claystones/shales, stating it is caused by the smaller value of the Poisson's ratio in sandstones, which is lithology-dependent.

Breckels and Van Eekelen (1982) found out that for leak-off test data in the North Sea (Figure 23) there is a difference of 0 – 5 % between the shales and sandstones, depending on the depth. At a depth of ~2400 meters, the shales have ~2 MPa higher leak-off pressures than the sandstones. In the onshore Netherlands, this difference is larger, i.e. at a depth of ~2400 meters, the difference between shales and sandstones is ~2.8-7 MPa (Figure 23). This difference is of significance and might illustrate a difference in minimum horizontal stress between shales and sandstones (Breckels and Van Eekelen, 1982).

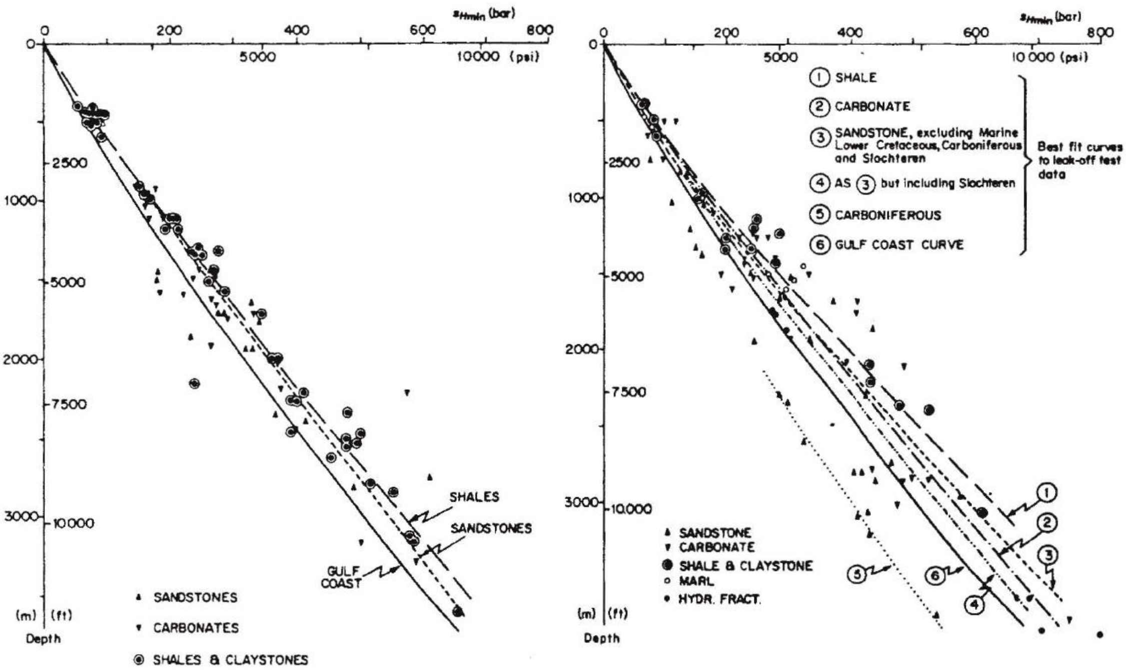

Figure 23: Relations between leak-off test data from the subsurface of the North Sea (left) and onshore Netherlands (right) and lithology type (Breckels and Van Eekelen, 1982).

Differences in minimum horizontal stress gradients in the stratigraphic groups could be also the result of varying lithology in different stratigraphic groups. The results of this study show that the Scruff/Schieland group, Upper Germanic Trias group, the Lower Germanic Trias group, the Zechstein group and the Upper Rotliegend group have a relatively high minimum horizontal stress gradient. The North Sea Group, the Chalk group, the Rijnland group, the Altena group and the Limburg group have relatively lower minimum horizontal stress gradients. Here, the strong imposed effect of lithology on the S_{hmin} is again clearly visible, with creeping lithologies such as rock salt resulting in a higher S_{hmin} gradient. E.g. the rock salt in the Zechstein group and in the Upper Germanic Trias Group (Keuper formation) leads to high S_{hmin} gradients. Groups where the creeping lithologies are less dominantly present have a lower S_{hmin} gradient. Although the Altena Group and North Sea group are (partly) composed of claystones/clays, they show lower values for the minimum horizontal stress gradients. This may be attributed to the shallow occurrence of these groups. A suggestion for further research would be to color the data according to the lithology type within the stratigraphic group figures, e.g. give rock salt and anhydrite a different color in the Zechstein (ZE) plot, similarly for sandstone and claystone in e.g. the Rotliegend (RO) plot. This could also be done for the lithology plots; coloring the stratigraphic groups.

Moreover, differences in minimum horizontal stress gradients can also be attributed to varying lithology or tectonic history associated with different tectonic regions/structural elements in the Netherlands. In order to analyse the spatial trends in minimum horizontal stress gradients, the tectonic regions are grouped in 5 larger tectonic super regions (Figure 16) and into structural element type (basin, platform, high as in Table 8), described in the method and results sections. The results of this study show that the minimum horizontal stress gradient is generally decreasing from the north(east) to the south(west) of the Netherlands. The North(east)ern offshore and onshore part of the Netherlands generally has higher minimum horizontal stress gradients than the offshore and onshore Southern part. A relation between burial history (regarding basins, platforms and highs) and minimum horizontal stress gradients can hardly be established on the basis of the results of this study (see Table 8). However, the horizontal stress data should be integrated with vertical stress data to see if there is a relation between the tectonic history and the stress ratio. This is a suggestion for further research. Possible explanations of the observed spatial trends may have a relation with the distribution and thickness of the Zechstein rock salt formation, the presence/absence of overpressures in formations with depth and differences in tectonic loading. These factors will be discussed in more detail below.
First of all, the spatial distribution of the thick Zechstein rock salt/anhydrite in the Netherlands could lead to higher minimum horizontal stress gradients in the North(east)ern part of the Netherlands, which is also noticed by Verweij (2015) and Muntendam-Bos (2021). The presence of such a thick rock salt layer may have an elevating influence on the minimum horizontal stress in the formation itself (Muntendam-Bos, 2021). The effect of rock salt creep tends to reduce the differential stress (S_v – S_h) and S_v remains constant, thus S_h is increased. In the Northeastern and Northern offshore and onshore parts of the Netherlands, the Zechstein is made up of thicker layers of evaporites and in these parts of the Netherlands, the minimum horizontal stress gradients are the highest. In the Northwestern offshore part of the Netherlands, the Zechstein contains a much thinner layer of rock salt, which may correspond to the observed slightly lower minimum horizontal stress gradients. In the Southern onshore and offshore part of the Netherlands, the rock salt in the Zechstein is absent and the Zechstein predominantly contains clastics (Peryt et al., 2010; Tolsma, 2015). Here, the minimum horizontal stress gradients are even lower. A map of the thickness of the Zechstein formation is shown in Figure 1 in the Appendix (Peryt et al., 2010). There may be a correlation between the thickness of the Zechstein and the minimum horizontal stress gradient. A suggestion for further research is to correlate the minimum horizontal stress data to a Zechstein rock salt

isopach and to visualize the possible relation between the thickness of the Zechstein rock salt layer and the minimum horizontal stress. The presence of thick rock salt deposits in the Northern part of the Netherlands thus may cause a high minimum horizontal stress, whereas the presence of clastics in the Southern part of the Netherlands may result in lower minimum horizontal stresses. The Lower Saxony Basin has a relatively high lower bound and minifrac fit in comparison with the surrounding tectonic regions, this may be attributed to the fact that it also has a thick Zechstein rock salt layer (Juez-Larré et al., 2019). The kink in the data of the Lower Saxony Basin in Figure 20 may be related to the presence of the Vlieland claystones at depths larger than 2000 meters.

Furthermore, the presence of overpressured formations could also contribute to the higher minimum horizontal stress gradients in the Northern part of the Netherlands as seen in the results of this study (Engelder & Fischer, 1994). Verweij et al. (2012) and Verweij (2015) state that overpressures are found in formations in the Northeastern offshore, Northern onshore and Eastern onshore parts of the Netherlands. Overpressured formations are present in the Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform, Lauwerszee Trough, Lower Saxony Basin and Friesland Platform (e.g. see Figure 2 and 3 in the appendix for the spatial distribution of overpressures in the Rotliegend and Chalk groups) (Verweij, 2012). Formations in the Southwestern part of the Netherlands (e.g. the Broad Fourteens Basin, the southern part of the Central Offshore Platform and the West Netherlands Basin) have close to normal fluid pressure conditions (Verweij, 2012). The fluid pressure conditions in the Cleaver Bank Platform and the Central Offshore Platform are transitional. The presence/absence of overpressures can be largely explained by the varying burial history of the different structural elements/tectonic regions and the geologic framework (Verweij et al., 2012). In the Northern part of the Netherlands, the relatively fast rates of Neogene sedimentary loading and the presence of relatively impermeable formations such as the Zechstein and Triassic rock salt formations and the more shallow mudstones in the Chalk and Rijnland Groups, creating horizontal and vertical fluid barriers, lead to the formation of overpressures. Whereas the Southern part of the Netherlands is associated with low rates of sedimentary loading and the occurrence of permeable formations, leading to the normal fluid pressure conditions (Verweij et al., 2012). Due to poroelastic behaviour, overpressures may result in a higher average lower bound of the leak-off pressures and thus result in higher S_{hmin} in the North, Northeast and East with respect to the Northwestern offshore and the Southern part of the Netherlands (Verweij et al., 2012; Verweij, 2015; Engelder & Fischer, 1994). Therefore, it is important to look at the in-situ stress ratio S_{hmin}/S_v and in particular the effective stress ratio $(S_{hmin} – P) / (S_v – P)$ in further research.

A third factor contributing to the differences in minimum horizontal stress gradient between the Northern and Southern part of the Netherlands may be the variation in tectonic loading in the Netherlands. The southern part of the Netherlands is associated with more effective tectonic loading. Since the Cenozoic, natural seismicity has occurred predominantly in the Southeastern part of the Netherlands, in the Ruhr Valley Graben (Muntendam-Bos, 2021). The lower minimum horizontal stress gradients in that part result in a more critical stress state (Muntendam-Bos, 2021).

Muntendam-Bos (2021) presented the magnitudes of the linear minimum horizontal stress gradients of six tectonic regions in the Netherlands (FP, LSB, GH & LT, NHP and WNB), based on the leak-off test data of Verweij et al. (2015) as shown in Table 9. When comparing the minimum horizontal stress gradients of Muntendam-Bos (2021) with the linear gradients of this study (see Table 10), the gradients of Muntendam-Bos (2021) tend to be remarkably higher than in this study. In this study we consider the lower bound of the LOT data to be representative of S_{hmin}, rather than the average of the LOT values, which may be the case in Muntendam-Bos (2021) (Breckels and Van Eekelen, 1982). However, the fit method in Muntendam-Bos (2021) is not explicitly stated. The leak-off pressure is an overestimation of the S_{hmin}, since this is the result of a combination of the in-situ tectonic stress and the stress around the well bore (the hoop stress), thus the lower bound of the LOT data should

be taken in order to be representative of the S_{hmin} (Alberty and McLean, 2004; Breckels and Van Eekelen, 1982; Voegeli et al., 2021, Verweij, 2015). The minimum horizontal stress gradient of Muntendam-Bos (2021) of the Friesland Platform with d < 1.5 km is lower than the gradient determined in our study (14.4 MPa/km with depth range ~300-3000 m). The minifrac fit of our study corresponds well to the gradient of Muntendam-Bos (2021) at d > 1.5 km. The minimum horizontal stress gradient of Muntendam-Bos (2021) of the Lower Saxony Basin does not show similarity with the result of our study (13.9 MPa/km). The fit of Muntendam-Bos (2021) is more similar to our fit on the minifrac data in the Lower Saxony Basin, but is still relatively high in comparison to the results of our study. Differences can also be seen for the Groningen High/Lauwerszee Trough. Our study has not merged the data of these tectonic regions such as in Muntendam-Bos (2021). Our minimum horizontal stress gradients for the Groningen High (14.4 MPa/km with depth range ~400-4600 m) and Lauwerszee Trough (14.3 MPa/km with depth range ~450-4000 m) are lower than the minimum horizontal stress gradient for the GH & LT with d < 1.5 km and d > 1.5 km in the case of Muntendam-Bos (2021). Moreover, if we look at the minimum horizontal stress gradient determined for the Northern onshore super region (14.3 MPa/km) in order to make a better comparison with the merged GH&LT region of Muntendam-Bos (2021), our study provides still lower LOT gradients than Muntendam-Bos (2021). The fit on the minifrac data of the Lauwerszee Trough (15.7 MPa/km) is closer to the shallow fit of Muntendam-Bos (2021). However, the number of measurements is limited in these tectonic regions, so the fits are relatively uncertain. The minimum horizontal stress gradient for the North Holland Platform of Muntendam-Bos (2021) is significantly higher than the minimum horizontal stress gradient determined in our study (14.3 MPa/km). The minimum horizontal stress gradient for the West Netherlands Basin of our study (13.4 MPa/km for a depth range of ~300-3600 m) is lower than for both depth intervals (0-2.5 km and >2.5 km) of Muntendam-Bos (2021). Minifrac data of our study also gives a lower fit (13.9 MPa/km) than Muntendam-Bos (2021).
It is hard to make further comparison between the minimum horizontal stress gradients obtained in our study and that of Muntendam-Bos (2021), since the fit method, the data selection from the PSNS database and number of measurements per tectonic region in Muntendam-Bos (2021) is unclear and may cause differences.

Table 9: Minimum horizontal stress gradients determined by Muntendam-Bos (2021).

Region	S_{hmin} gradient (MPa/km)
FP (d < 1.5 km)	13.4
FP (d > 1.5 km)	17.8
LSB	19.6
GH & LT (d < 1.5 km)	14.8
GH & LT (d > 1.5 km)	19.9
NHP	17.0
WNB (d < 2.5 km)	15.8
WNB (d > 2.5 km)	18.1

Table 10: Minimum horizontal stress gradients determined by our study.

Region	S_{hmin} gradient based on LOT data (MPa/km)	S_{hmin} gradient based on minifrac data (MPa/km)
FP (d = 290 – 3030 m)	14.4	17.8
LSB (d = 285 – 3875 m)	13.9	18.0
GH (d = 400 – 4600 m)	14.4	
LT (d = 460 – 3935 m)	14.3	15.7
NHP (d = 320 – 3320 m)	14.3	
WNB (d = 330 – 3600 m)	13.6	13.9

5.2 Reliability of the minimum horizontal stress gradients

The type of fit (lower bound fit versus average fit) used has large effects on the magnitudes of the minimum horizontal stress gradients. The choice for an average fit on the LOT data could lead to overestimation of the minimum horizontal stress gradients. Based on previous research, the lower bound gradient of the leak-off test data can be taken as a relatively good approximation of the minimum horizontal stress gradient, since the LOT data typically fall in the range S_{hmin} to $2S_{hmin} – P_c$ (Alberty and McLean, 2004; Breckels and Van Eekelen, 1982; Voegeli et al., 2021, Verweij, 2015). For the purpose of this study, the power law and linear lower bound gradients are determined by quantile regression, based on the 90th percentile (Grinsted, 2008). Here, 90% of the data are above the lower bound fit. The choice of the 90th percentile is associated with some uncertainty in the lower bound gradients, i.e. a different percentile would probably have a minor influence on the results. However, the 90th percentile shows a good fit on the lower bound of the data. When the LOT data shows a deviating trend of the lower bound with depth (>2000 m) and the data at those deeper levels consist of more than 50 measurements, different linear lower bound fits are made for the depth interval 0 – 2000 m and >2000 m in order to give reliable linear lower bound gradients. The power law fit on the lower bound takes these depth dependences already into account. For the minifrac data, quantile regression is done using the 50th percentile (median) (Grinsted, 2008), since this data is a direct representation for the minimum horizontal stress and thus for this type of data the median should be taken instead of the lower bound.

Moreover, in this study, the choice for a linear lower bound fit and a power law lower bound fit is made. The choice for a linear lower bound fit is motivated by the fact that the pressure in the earth increases approximately linearly with depth due to the weight of the overburden. Using linear minimum horizontal stress gradients, the results can be compared with other studies on this topic in the Netherlands, e.g. Muntendam-Bos (2021), which also uses linear trendlines. The other option for a lower bound fit is the power law, as also in e.g. Breckels and Van Eekelen (1982). A better fit on the data is observed using a power law fit, since a general increasing gradient trend in the data with depth is observed. Furthermore, the choice for a power law is motivated by the fact that the viscosity in the earth is non-linear, i.e. non-Newtonian power law creep (e.g. Karato, 2010). Moreover, when an exponential compaction curve to describe porosity reduction with depth for the overburden density gradient is assumed and this is integrated with the horizontal stress gradient, the choice for a power law fit has also a physical basis.

Another factor of uncertainty in the gradients is the amount of data. The fits are less reliable when there is a relatively small amount of measurements in the subgroup, such as in some tectonic regions, or if the measurements are limited to a narrow depth interval.

Moreover, the quality and the type of used data may also influence the minimum horizontal stress gradients. As previously stated, minifrac data are a direct representation of the minimum horizontal stress and is therefore a reliable type of data. LOT data are less reliable than minifrac data but more abundant. The quality of the LOT data also has an influence on the reliability of the derived minimum horizontal stress gradients. The NAM LOT data have a higher quality than the PSNS data, since the NAM LOT data were checked on the basis of the pressure-volume curve.

The minifrac gradients are generally (slightly) higher than the lower bound gradients of the LOT data. This could be related with the limited number of data, higher reliability of the minifrac data being closer to the actual values of the S_{hmin}, the location of the data (North of the Netherlands predominantly) in relation with the corresponding overpressures in the reservoir formations and/or occurrence of thick Zechstein rock salt layers and/or less effective tectonic loading, and the limited amount of minifrac data. Therefore, the stress ratio should be taken in order to analyze the differences between the gradients associated with the different test types (LOT and minifrac) in a better constrained way.

5.3 The NAM leak-off test and minifrac data

The described data in the results is composed of LOT and minifrac data of the NAM and LOT data of the PSNS database. Since the NAM LOT values have a high reliability, as they were checked on the basis of the pressure-volume curve, and are a new dataset, the NAM data will be highlighted here.
When comparing the stratigraphic groups of the NAM data (Figure 24) to the total dataset in the results, most of the stratigraphic groups of the NAM have (slightly) lower minimum horizontal stress gradients (both linear and power law). However, strikingly, the Zechstein group is the only exception on this, showing higher minimum horizontal stress gradients for the NAM data (e.g. for the linear fit: 17.4 MPa/km for the NAM data, compared to 16.0 MPa/km for the total dataset in the results). The Altena and Upper Rotliegend groups for the linear fit and the Lower Germanic Trias group for both linear and power law fits also show higher minimum horizontal stress gradients for the NAM data. However, this can be attributed to a very limited amount of measurements in the NAM data for these groups.
A possible reason for these differences in minimum horizontal stress gradients is that due to the higher quality of the data in the NAM database, the NAM data might be closer to the actual values for the minimum horizontal stress gradients. For example, for creep-prone lithologies such as rock salt, the d_{Shmin}/dy is expected to be closer to the lithostatic gradient. Another explanation could be that the amount of data is less for the NAM data and this could have an influence on the lower bound gradient and its reliability. A statistical test could be eventually executed in order to check whether the differences are significant.
When looking at lithology groups, the majority of the lithologies of the NAM data have lower minimum horizontal stress gradients (Figure 25) than the total database, except for the anhydrite and rock salt lithology groups, which have higher minimum horizontal stress gradients in the case of the NAM data (for linear fit respectively 18.2 MPa/km and 17.7 MPa/km) compared to the total dataset in the results (for linear fit respectively 14.8 MPa/km and 17.2 MPa/km). The power law fits show the same differences for the NAM data. Additionally, sandstone and the North Sea group also show a higher fit for the power law fits on the NAM data. This may be attributed to the limited amount of data in these groups for the NAM data. Since we assume the NAM data is more reliable, due to its extensive quality check, it may tell us something on the effects of the leak-off test analysis. Apparently, the NAM data points to a state of stress closer to lithostatic for creeping lithologies, such as rock salt and anhydrite, and lower S_{hmin} gradients for other lithologies. If this difference is significant, it may be that less reliable values (determined without the use of pressure-volume curves) tend to overestimate values in non-creeping lithologies. This emphasizes the need for a careful analysis of the leak-off tests.
Comparing the tectonic regions of the total database with the NAM data shows that the majority of the minimum horizontal stress gradients is (slightly) lower for the NAM data (Figure 26 and 27). Exceptions on this are the tectonic regions Cleaver Bank Platform (CBP) for both linear and power law fits, Central Netherlands Basin (CNB) for the linear fit, Indefatigable Platform (IP) for both fits, Lauwerszee Trough (LT) for the power law fit and Vlieland Basin (VB) for the linear fit, which have slightly higher minimum horizontal stress gradients for the NAM data. In the case of the Central Netherlands Basin, Indefatigable Platform and Vlieland Basin this higher gradients can be attributed to the limited amount of data in general. The Cleaver Bank Platform contains sufficient data, but the difference in minimum horizontal stress gradient is relatively small (0.2 MPa/km for the linear fit).

The quality of the used data thus may have effects on the magnitudes of the minimum horizontal stress gradients. High quality data, where the leak-off test data is checked with the pressure-volume graph, leads to values of the minimum horizontal stress gradients which may be closer to the actual values. Therefore, a good check on the LOT data is associated with lower S_{hmin} gradients for non-creeping lithologies and S_{hmin} gradients which are closer to lithostatic pressure for creeping lithologies.

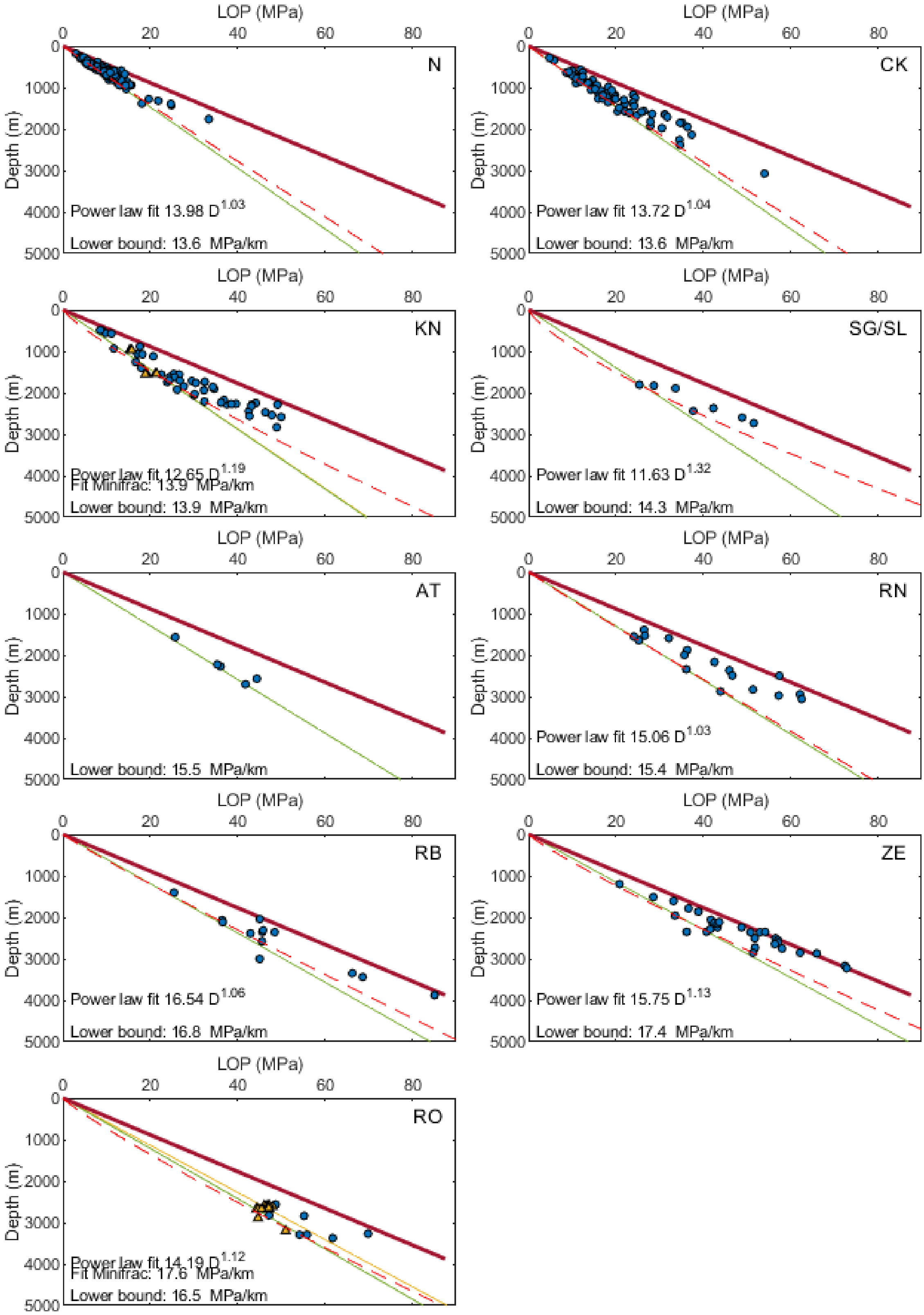

Figure 24: The NAM data as function of stratigraphic groups with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) on the LOT data, yellow line: fit through minifrac measurements, red dashed line: lower bound power law fit on the LOT data.

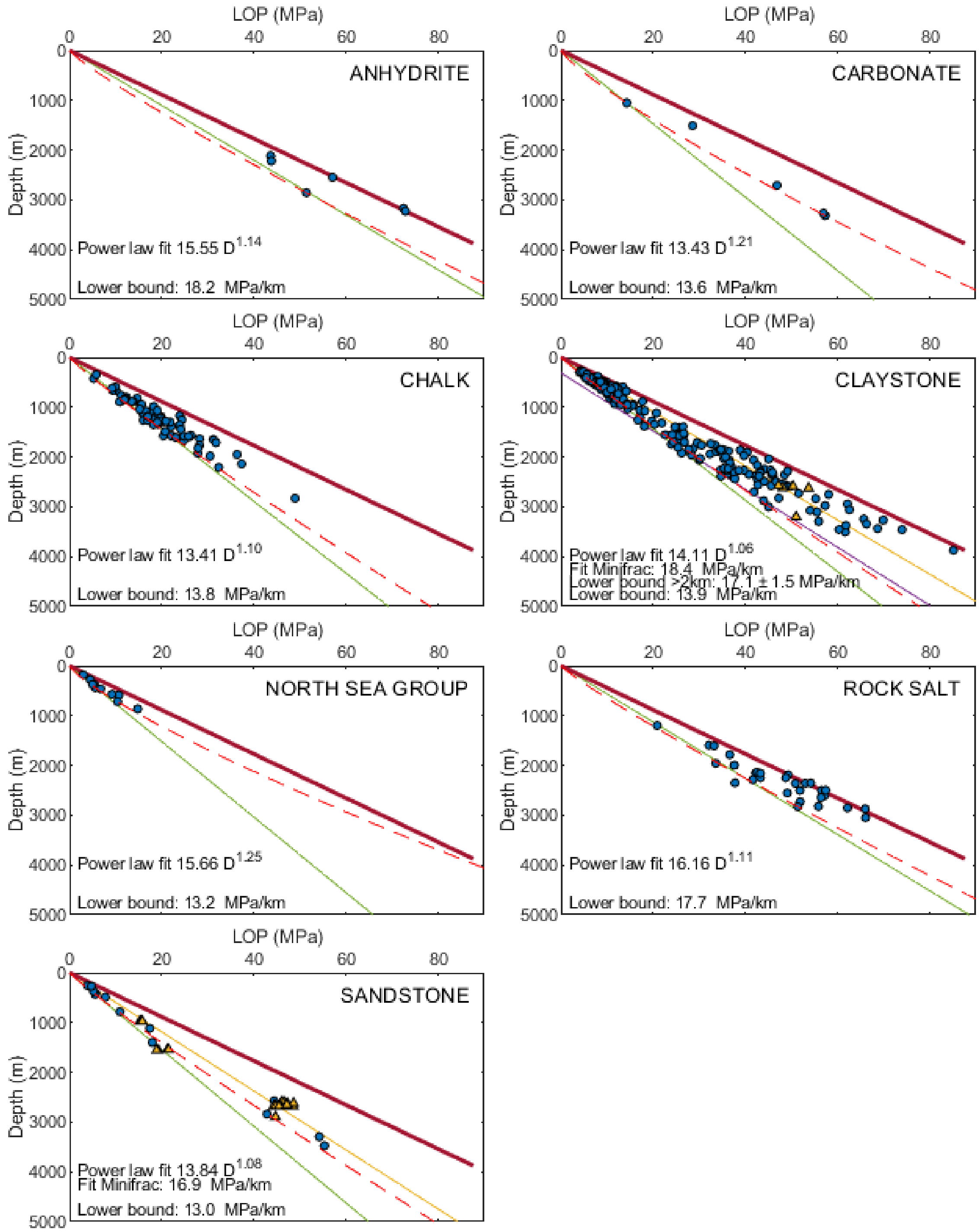

Figure 25: The NAM data as function of lithology with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, purple line: lower bound to the LOT data > 2000 m, red dashed line: lower bound power law fit on the LOT data.

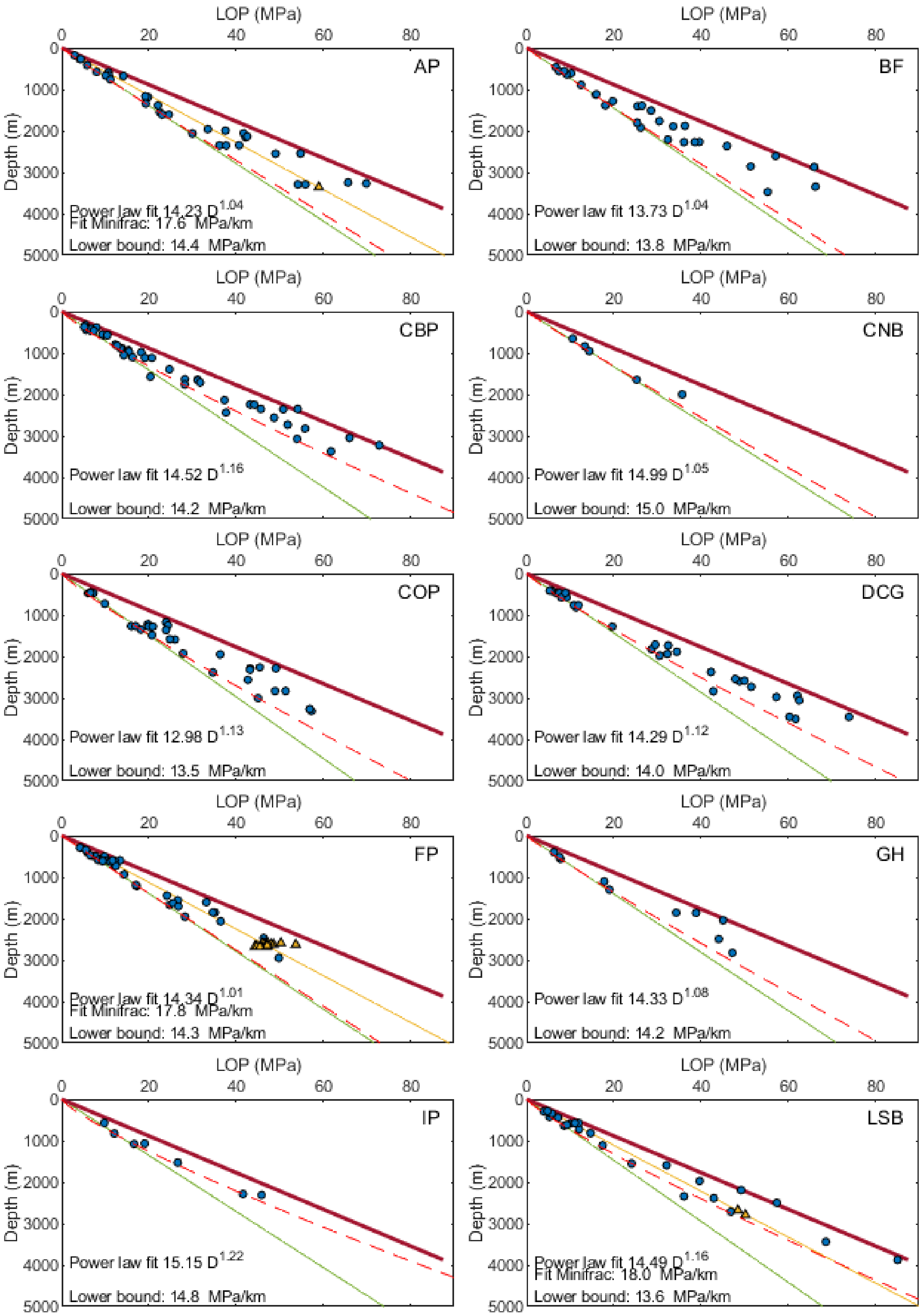

Figure 26: The NAM data as function of tectonic region (part 1), with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, red dashed line: lower bound power law fit on the LOT data.

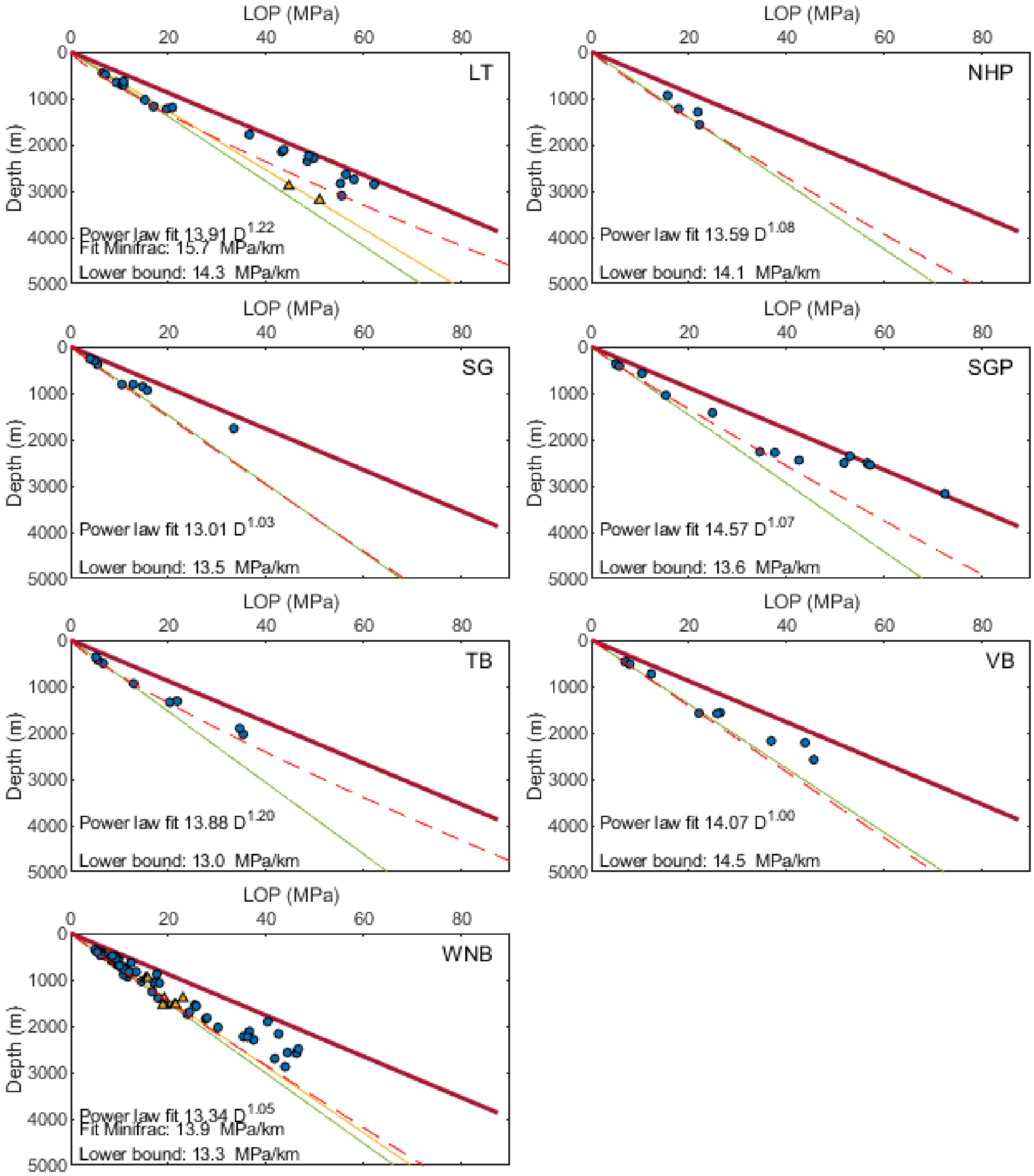

Figure 27: The NAM data as function of tectonic region (part 2), with lower bound fits (linear (MPa/km) and power law (MPa/km^n)) and fits on the minifrac data. Red line: average lithostatic gradient (22.6 MPa/km), green line: linear lower bound (90th percentile) to the LOT data, yellow line: fit through minifrac measurements, red dashed line: lower bound power law fit on the LOT data.

5.4 Implications

The state of stress on a fault is determined by the effective stress ratio K' = S_{hmin}'/S_v', where S_{hmin}' = S_{hmin} – P. This ratio gives a measure of the criticality of pre-existing faults in a normal faulting regime (Zoback, 2010). Steep, favourably oriented faults in a normal faulting regime are more or less critical for an effective stress ratio K' of 0.32, assuming a typical coefficient of friction, i.e. μ = 0.6 (Byerlee, 1978).

Although the differences in lithology-, stratigraphic group- and tectonic region-specific minimum horizontal stress gradients are in the order of a few MPa's, the influence of these differences on the in-situ stress ratio S_{hmin}/S_v and σ'_{hmin}/σ'_v can be significant. Stochastic modelling performed in WarmingUp 4B1 showed that the in-situ stress ratio S_{hmin}/S_v is one of dominant parameters governing fault reactivation and seismic events magnitudes (Buijze et al. 2021). Since the subsurface of the Netherlands is associated with a normal faulting regime, a lower minimum horizontal stress gradient means a higher criticality, as a larger difference between the smallest (S_{hmin}) and largest (S_v) principal stresses leads to a more critical state of stress (see Figure 28). Figure 28 illustrates the large effect of the minimum horizontal stress gradient on the criticality of the state of stress, showing that lower minimum horizontal stress gradients (i.e. 14 MPa/km) are significantly more critical than higher minimum horizontal stress gradients (i.e. 18 MPa/km) for the same amount of cooling (10 degrees).

The results of this study show that rock salt, and to a lesser extent anhydrite and claystone (the latter particularly at depths >2 km), have high minimum horizontal stress gradients and thus give high in-situ stress ratios. This implies that these lithology types have a relatively stable stress state in which it requires large stress changes to reactivate pre-existing faults. Therefore, the potential for seismicity in these lithologies is relatively low. Rock salt, anhydrite and clay containing layers underlying and/or overlying the geothermal reservoir formations, would prevent seismic events from growing large. Clay-rich formations typically form the base and cap rocks of the geothermal sandstone reservoirs in the Netherlands. During geothermal operations, cold injection fluids flow from the injection through the production well, heating up as the fluid flows through the pores of the sandstone. This results in substantial cooling of the rock volume around the injection well. Previous studies have shown that this cooling is the primary cause for stress changes and fault reactivation (e.g. Buijze et al., 2012). Part of the formation above and below the sandstone reservoir also cools down because of vertical conduction of heat. However, a more stable state of stress in these formations implies a smaller likelihood of fault reactivation and fracturing compared to the reservoir itself.

Additionally, there is a possible spatial relation between high minimum horizontal stresses and the occurrence of a thick Zechstein rock salt layer and/or overpressures in the subsurface. The presence of thick rock salt deposits and/or overpressures in the Northern part of the Netherlands may be related with a high, stable stress, whereas the presence of clastics and normal fluid pressure conditions in the Southern part of the Netherlands may result in more critical stresses.

Based on the results of this study, it can be stated that the high minimum horizontal stresses derived from the leak-off test and minifrac data in the Northern part of the Netherlands are relatively far from critical. This may explain the long timespan between the production start of the gas fields and the start of seismicity observed in the gas fields. However, the Southern part of the Netherlands is associated with more effective tectonic loading (Muntendam-Bos, 2021). Since the Cenozoic, natural seismic activity has predominantly occurred in this part of the Netherlands. This is validated by the results from this study, showing a lower S_{hmin} for the Southern part, resulting in a more critical state of stress.

Although the minimum horizontal stress gradients in the Southern part of the Netherlands are lower, induced seismicity has not been recorded in oil and gas fields in the South(western) part of the Netherlands. On the other hand, induced seismicity has occurred in the Northern and Western part of the Netherland, despite the presence of higher minimum horizontal stress gradients. The induced seismic events in the Northern and Western part of the Netherlands cannot be explained solely by the high in-situ stress ratios in those regions. This implies that lower minimum horizontal stress gradients do not have to lead to induced seismic events and that other factors may also contribute to the generation of induced seismic events. Induced seismicity results from both the initial, tectonic stress and the induced stress changes due to e.g. gas production. If the induced stress change is large enough, many fault orientations can be reactivated. Moreover, varying velocity weakening or strengthening behaviour of lithologies could also play an important role in the possibility of slip acceleration and seismogenic potential (Hunfeld et al., 2017). Faults consisting of Basal Zechstein anhydrite-carbonate gouge are related to the highest seismogenic potential. A different explanation for the non-occurrence of seismic events in the Southern part of the Netherlands could be that fault reactivation has taken place, but aseismic slip occurred and therefore no seismic events have been measured. This conundrum is a motivation for further study into the fundamental of induced seismic and the impact of geological, lithological, and mineralogical variation on the stress changes and faulting behavior.

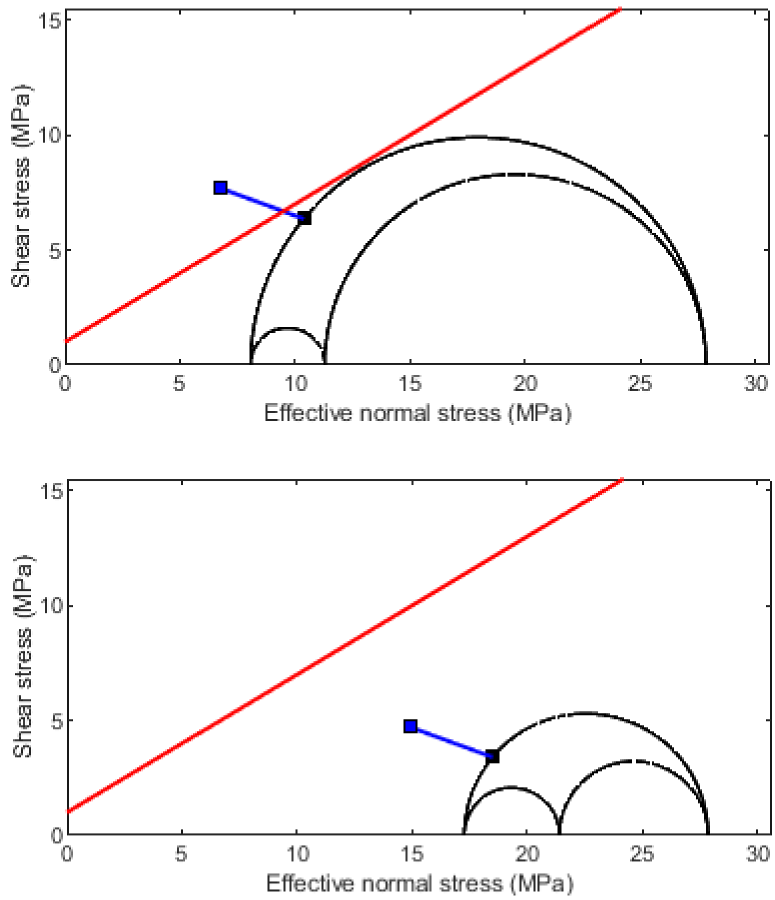

Figure 28: The Mohr-Coulomb failure criterion, for two different minimum horizontal stress gradients: the upper case is for 14 MPa/km and the lower case is for 18 MPa/km, both with a dT = -10. The vertical stress (22.6 MPa/km) and the depth (2300 meters) are the same in both cases. The Mohr circle is defined by the magnitudes of the smallest and largest principal stress. When the Mohr circle touches or exceeds the failure envelope, failure will occur. The upper case (14 MPa/km) is critical, whereas the lower case (18 MPa/km) is significantly less critical. Cooling induced stress is computed assuming a lateraly extensive cooled reservoir volume (Buijze et al., 2021; Soltanzadeh (2009)).

5.5 Conclusions and recommendations

The main goal of this study is to improve the characterization of the initial (in-situ, tectonic) minimum horizontal stress, in particular considering its variability in different lithologies, stratigraphic groups and tectonic regions in the subsurface of the Netherlands. This characterization of the in-situ tectonic stress field is of large importance, since the in-situ stress ratio S_{hmin} / S_v is one of the key parameters which has a large influence on fault reactivation and the occurrence of induced seismicity in geothermal doublet operations. Therefore a good quantification of the minimum principal horizontal stress S_{hmin} (and S_v) at depth ranges targeted by geothermal operations in the Netherlands (<4 km) is of great value.
In order to accomplish this goal, a new dataset of leak-off test data and minifrac data provided by NAM within the WarmingUp project is used and complemented with the leak-off test data of the already existing Pressure Southern North Sea (PSNS) database (Verweij et al., 2015).

The main conclusions of this study are summarized below:

- There is a strong dependence of the minimum horizontal stress gradient S_{hmin} on lithology.
- Creeping lithologies such as rock salt, anhydrite and clay containing formations have higher minimum horizontal stress gradients and are less likely to produce fault reactivation and induced seismicity.
- Minimum horizontal stress gradients also show dependence on litho-stratigraphic group (e.g. Chalk, Rijnland, Rotliegend, Zechstein etc). This is related to the dominant lithology type occurring in the stratigraphic groups.
- A spatial relation can be established between the minimum horizontal stress gradient and the tectonic regions in the Netherlands, including highest stress gradients in the Northeastern part of the Netherlands, which are decreasing towards to Southwestern part of the Netherlands. This may have a relation with the occurrence and thickness of the Zechstein evaporite deposits, the fact that formations are mostly overpressurized in the Northern part of the Netherlands and differences in tectonic loading.
- The minimum horizontal stress gradient does not only vary with lithology, stratigraphic formation and tectonic region, but also with depth. From a depth of ~2000 meters, the stress gradient becomes higher than at shallower depths. This is most clearly visible within the claystone lithologies. Note that also the vertical stress gradient increases with depth (not considered in this study) and the fact that overpressures could play a role.
- When comparing the newly available NAM data of higher quality with the PSNS data, it can be concluded that in the majority of the lithology groups, stratigraphic groups and tectonic regions the NAM data has (slightly) lower minimum horizontal stress gradients. Exceptions include the creeping lithologies such as rock salt and anhydrite, which show a higher minimum horizontal stress gradient for the NAM data. This may either have to do with the quality of the data (with the NAM data being closer to the actual stress values) or with the reliability of the lower bound gradient due to less measurements.
- Implications of the results of this study include that the potential for fault reactivation and induced seismicity is presumably the lowest in rock salt, anhydrite and clay containing formations. Clay-rich formations typically form the base and cap rocks of the geothermal target formation. Our findings suggest the reactivation potential in these formations would be lower than within the sandstone reservoir itself.
- The way of determining the S_{hmin} gradient (lower bound fit versus average fit), the fit type (power law versus linear fit), the type of data (LOT versus minifrac), the amount of data and the quality of the data have effects on the magnitude of the S_{hmin} gradient and its reliability. A robust and applicable fit function is essential to quantify the gradients.

Recommendations

- In order to have an improved characterization of the in-situ tectonic stress field in the subsurface of the Netherlands, minimum horizontal stress data should be integrated with vertical stress data, based on e.g. density logging, as well a pressure data. The vertical stress gradient is also influenced by local factors such as lithology, overpressures and burial history.
- More leak-off test and minifrac data are needed in the stratigraphic groups, lithology groups and tectonic regions with few data, to get more reliable minimum horizontal stress gradients. This holds in particular for sandstone reservoirs.
- Extended leak-off tests (XLOT) and more minifrac tests could be executed in order to get more reliable data.
- A publicly available database could be made with the data stored in such a way that it can be efficiently used by the geothermal operators in the onshore Netherlands.
- Investigate overlapping effects of litho-stratigraphic groups versus the dominant lithology in these groups on the in-situ stress.
- Further investigate the possible relation between the in-situ stress ratio and the tectonic history, regional overpressures and occurrence and thickness of the Zechstein rock salt layer.
- Investigate whether the Zechstein rock salt acts as a decoupling mechanism for the in-situ stresses by e.g. coloring the data above/below the top Zechstein in the tectonic region plots. More data, particularly at larger depth, is needed to get a reliable relation.
- Incorporate lithology-dependent and location-specific in-situ minimum horizontal stress gradient in future numerical models. When basing the input on LOT measurements, use the lower bound values rather than the average as representative for the in-situ stress.

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8 Appendix

Links to files

Pressure Southern North Sea (PSNS) database
https://www.nlog.nl/pressure-southern-north-sea-psns-database/PressureSNS-123_database_V3_Sep2014_publiek_correctie_feb2021

Pressure Southern North Sea (PSNS) report
https://www.nlog.nl/sites/default/files/2020-05/TNO-Report-2015-R10065-final-public2020.pdf

NLOG stratstelsel.xlsx
https://www.nlog.nl/sites/default/files/thematische_data/nlog_stratstelsel.xlsx

Dinoloket strat_main_lithology.xlsx
strat_main_lithology.xlsx is a file made by Hans Veldkamp corresponding stratigraphic formations, groups etcetera to lithology types using https://www.dinoloket.nl/stratigrafische-nomenclator.

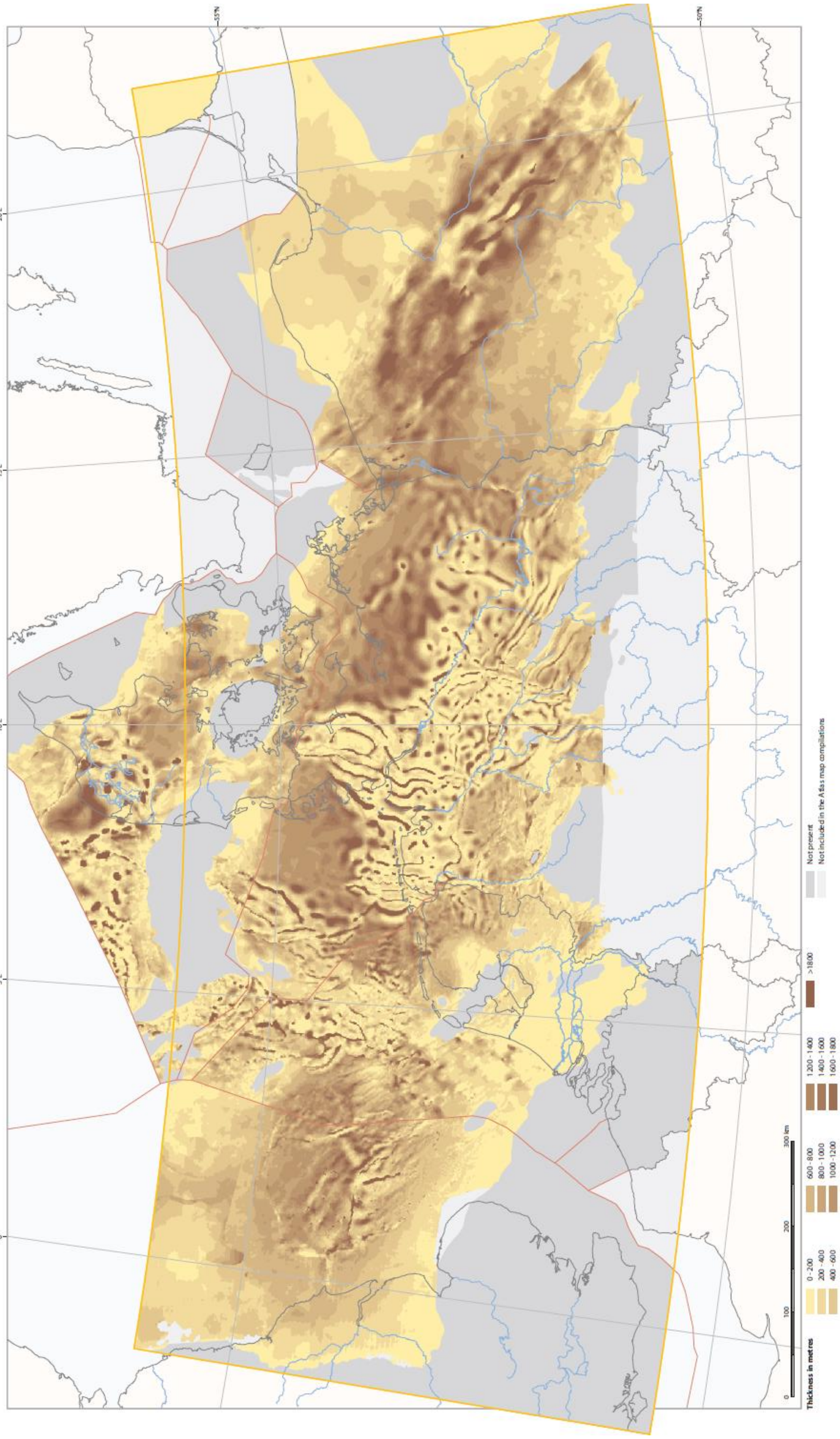

Figure 1: Thickness and distribution map of the Zechstein (Peryt et al., 2010).

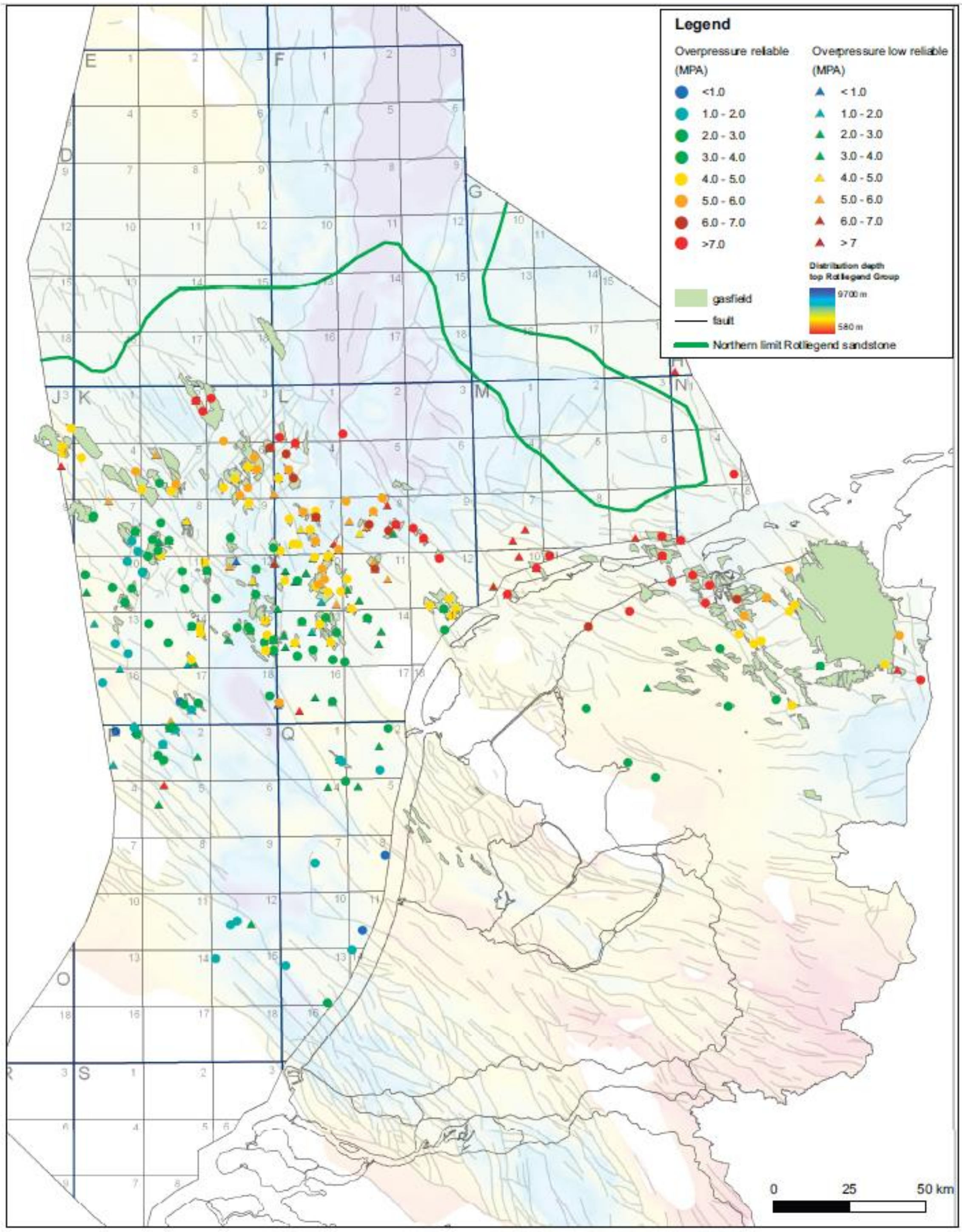

Figure 2: An overview of the distribution of the overpressures in the Rotliegend reservoirs in the Netherlands (Verweij et al., 2011).

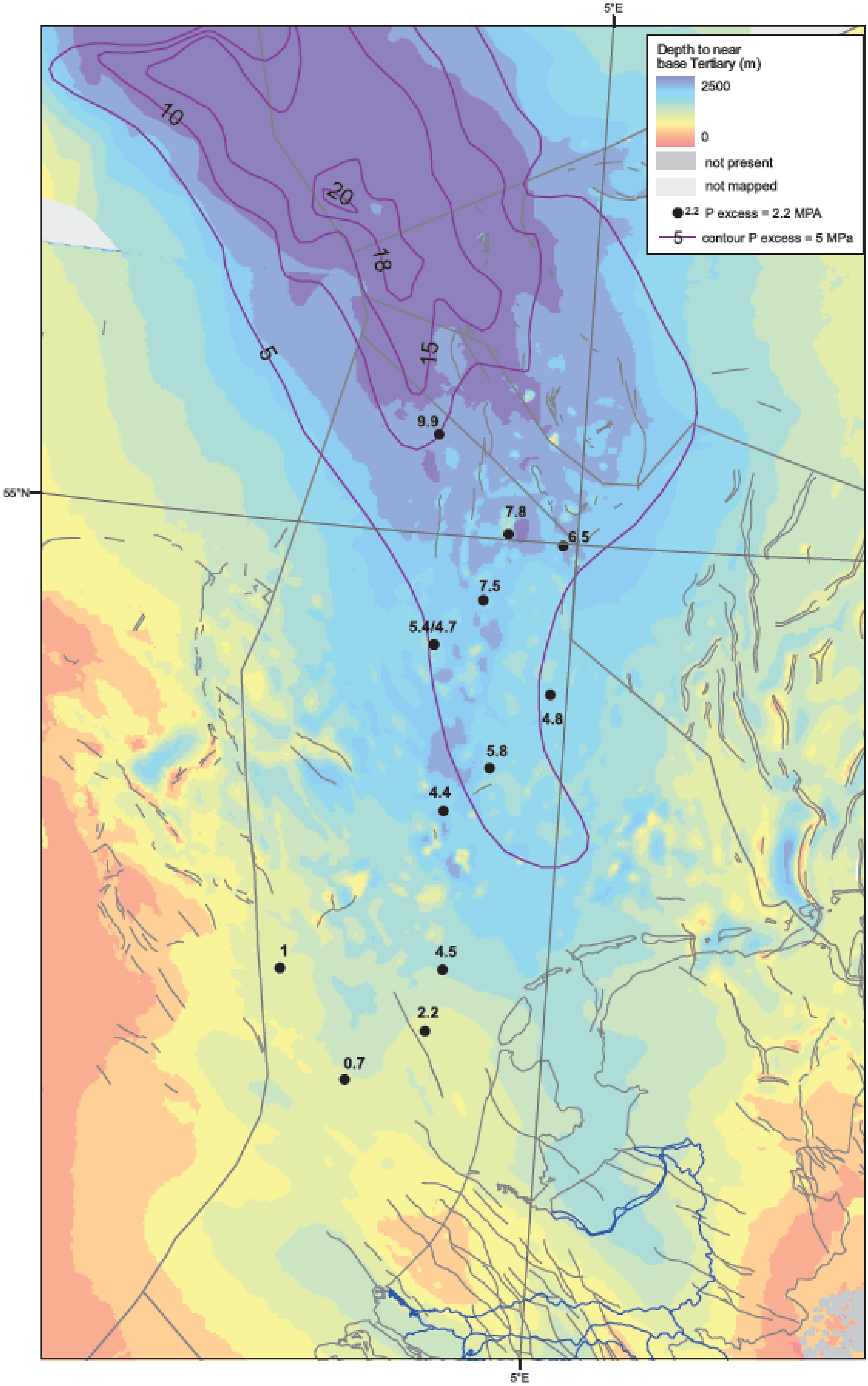

Figure 3: An overview of the distribution of the overpressures in the Chalk group in the Netherlands (Verweij et al., 2012).

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