Stress field characterization in the Dinantian carbonates in the Dutch subsurface

Report by SCAN

October 2019

Ministerie van Economische Zaken en Klimaat
ebn
TNO
Interreg North-West Europe DGE-ROLLOUT

Stress field characterization in the Dinantian carbonates in the Dutch subsurface

Report written by Sander Osinga[1] and Nick Buik[2]

1. TNO, Princetonlaan 6, 3584 CB Utrecht, the Netherlands
2. IF Technology, Velperweg 37, 6824 BE Arnhem, the Netherlands

October 2019

Dit rapport is een product van het SCAN-programma en wordt mogelijk gemaakt door het Ministerie van Economische Zaken en Klimaat

Table of Contents

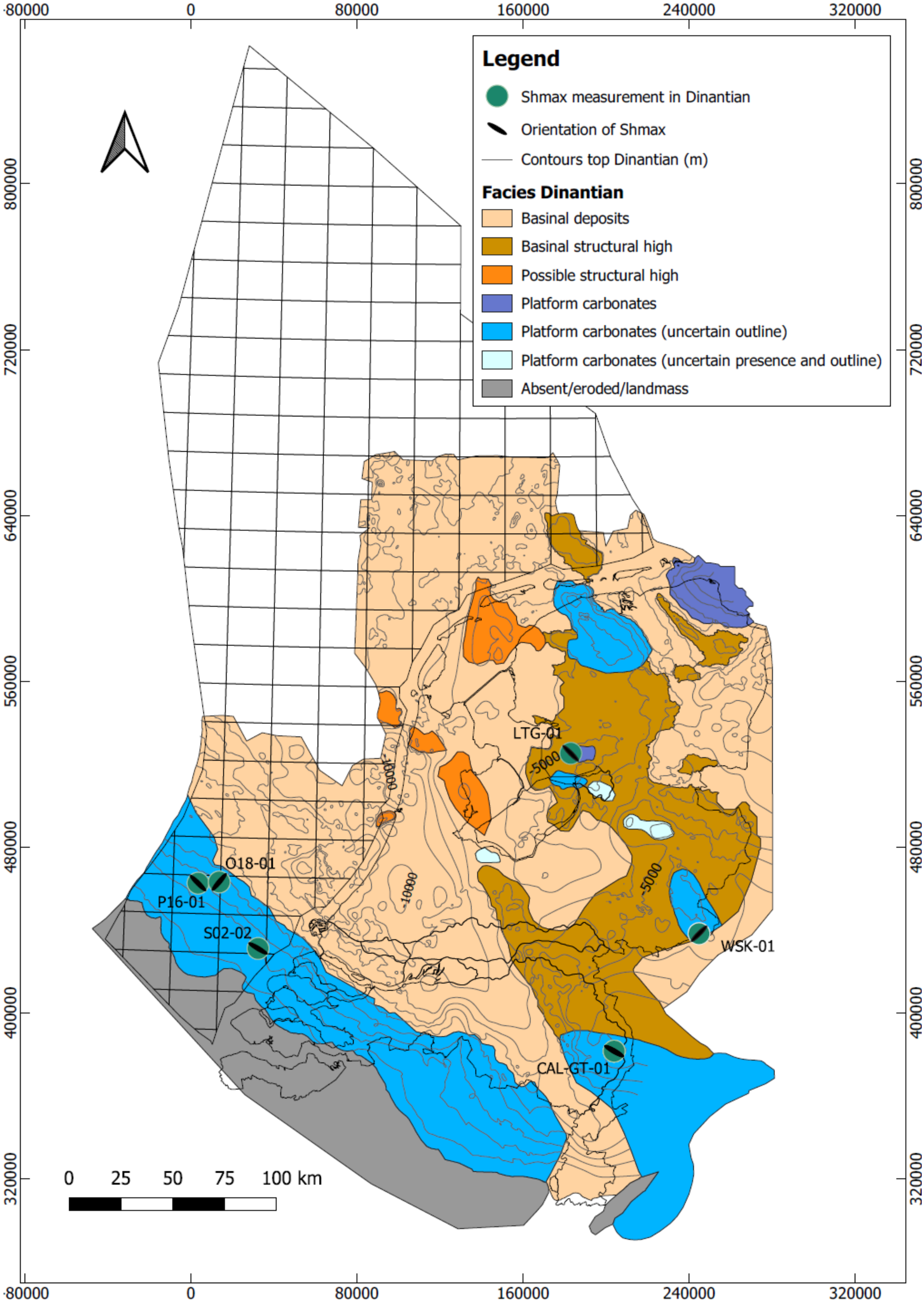


Figure 1: Orientation of SHmax, as determined in this work. Dinantian facies map (Seq 2 & 3) from Mozafari et al, 2019

Samenvatting en conclusies

Er is een geomechanische studie uitgevoerd, gebruikmakend van alle publiek beschikbare putdata in kalksteen van Dinantien ouderdom. Deze studie richt zich op het karakteriseren van het spanningsveld in deze formatie. Kennis van het spanningsveld is van belang bij het inschatten van doorlaatbaarheid en seismiciteit in de Dinantian kalksteen. Putdata op deze diepte is zeldzaam en bevat vaak geen data die bruikbaar is voor analyse van het spanningsveld. In deze studie zijn 60 putten bestudeerd, waarvan 6 informatie over het spanningsveld bevatten. Data met betrekking tot de grootte/magnitude van de horizontale spanning in de Dinantien kalksteen formaties in niet beschikbaar.
In dit rapport worden alle putten die bestudeerd zijn benoemd. Er wordt aangegeven of de put informatie bevat die gebruikt kan worden voor analyse van het spanningsveld en welke informatie ze bevatten. Appendix 3 geeft een volledig overzicht van deze ruwe en geïnterpreteerde data per put.

Naast het de verzameling en interpretatie van data wordt in dit rapport ook aandacht besteed aan generieke en breed toepasbare principes die gebruikt kunnen worden bij het bestuderen en inschatten van het lokale spanningsveld voor een specifiek aardwarmteproject. Bovendien bevat dit rapport een beschrijving van data-acquisitie technieken die toegepast kunnen worden in nieuw te boren putten om nieuwe data met betrekking tot het spanningsveld te verkrijgen.

De conclusies van dit rapport zijn als volgt:

- Het beperkte aantal putten dat doordringt tot de Dinantien formatie geven een beeld van het spanningsveld dat qua richting van SHmax consistent is met spanningsveldmetingen in ondiepere formaties. Dit suggereert dat de richting van SHmax van ondiepere formaties indicatief kan zijn voor de Dinantien kalksteen formaties.
- Er is geen informatie over de magnitude van de minimale horizontale stress in de publiek beschikbare informatie.
- Nieuwe data over het spanningsveld op Dinantien niveau, zowel voor de magnitude als de richting zou extreem waardevol zijn, gezien de zeer beperkte hoeveel momenteel beschikbare data.
- FMI logs van de CAL-GT-01 en LTG-01 putten laten zien dat de strekking van scheuren en diaklazen overeenkomen met de huidige oriëntatie van de maximale horizontale spanning.

Aanbevelingen

De volgende aanbevelingen worden gedaan, gebaseerd op het hier uitgevoerde onderzoek:

- Verzamel zoveel mogelijk data van nieuwe en bestaande putten die doordringen tot de Dinantien kalksteen formaties om een betere karakterisatie van het spanningsveld te kunnen uitvoeren.
- Haardmechanismen van natuurlijke aardbevingen kunnen in sommige gevallen gebruikt worden om informatie over het spanningsveld op diepte te achterhalen. Analyses van dit type zijn niet uitgevoerd in dit werk en zouden van toegevoegde waarde kunnen zijn.
- Analyses waarin het lokale spanningsveld een rol spelen, zoals doorlatenheidsbepalingen of breuk- of putstabiliteitsanalyses moeten rekening houden met de grote onzekerheid die gepaard gaat met de huidige data. Het wordt aanbevolen

om de gevoeligheid van de resultaten voor zowel de richting als de magnitudes van de spanningscomponenten te verkennen.

Summary and conclusions

A geomechanical study has been performed on all publicly available well data of the Dinantian carbonates in the Dutch subsurface pertaining to the stress field indicators. Knowledge of the stress field is important for assessing permeability and seismicity potential in the Dinantian carbonates. Well data at these depths is rare and often does not contain data that is suitable for stress field analysis. In this study, approximately 60 wells have been studied, 6 of which contain information about the direction of the horizontal stress field at the level of the Dinantian. Horizontal stress magnitude data in the Dinantian carbonates is not available.

In this report all studied wells are listed, indicating whether they contain stress field information, and what information they contain. Appendix 3 gives a complete overview of this interpreted data, as well as the uninterpreted well logs.

Besides the data collection and interpretation effort contained in this work, the final chapter of this report contains a description of general principles which can be used when assessing the local stress state for a specific geothermal project, as well as a description of data acquisition techniques that can be employed to obtain data from new wells in such projects.

The conclusions from the study are as follows:

- The limited number of wells penetrating the Dinantian, give a stress field orientation that is consistent with stress field orientations obtained in shallower formations. This suggests that shallower stress field information can be indicative of the stress field in the Dinantian carbonates.
- There is no information in the publicly available data on the magnitude of the minimum horizontal stress
- New stress field data on both direction and magnitude from geothermal (exploration) wells would be extremely valuable, considering the current lack of data
- FMI image log data from both the CAL-GT-01 well and the LTG-01 well indicate that the main strike of fractures aligns with the current orientation of SHmax.

Recommendations

Based on the findings of the geomechanical study of the Dinantian the following recommendations result:

- Gather as much data as possible from new and existing Dinantian wells and evaluate them to provide a better assessment of the stress field
- Focal mechanism analysis of natural earthquakes can in some cases by analyses to obtain information about the stress field at depth. Such analyses have not been carried out in this work and could be of additional value.
- Analyses that depend on the local stress field, such as permeability assessments and fault/well stability analyses should consider the large amount of uncertainty that is associated with the current data. It is recommended to explore the sensitivity to the modelling results to both changes in orientation and magnitude.

Acknowledgements

We would like to thank Rob van Eijs (NAM) for his scientific input and provoking insights as well as his thorough review of this manuscript. We gratefully acknowledge Bastiaan Jaarsma (EBN), Marc Hettema (EBN), and Jan the Heege (TNO) for their helpful suggestions and constructive reviews that allowed us to improve this report. Lonneke van Bijsterveldt and Marianne van Unen are gratefully acknowledged for their work on the maps in this report.

Introduction

Geothermal energy systems have been considered as a potential alternative for the fossil fuel heating. Currently, there are geothermal projects already functioning in the Netherlands. However, the application of geothermal energy in existing projects is not adequate for the provision of high-temperature heat for, as an example, the process industry. It is anticipated that Ultra Deep Geothermal (UDG) energy could potentially make a substantial contribution to the transition towards a sustainable heat supply. To reach sufficiently high temperatures in the Netherlands, geothermal reservoirs at depths over 4 km are required. The Dutch subsurface at these depths has not been explored extensively until now and is therefore relatively unknown. Based on the limited amount of subsurface data, the Lower Carboniferous Dinantian Carbonates were identified by Boxem et al., 2016 as the most promising target matching the initial requirements for UDG.

The study reported in this document is a result of SCAN, a government funded, program to scope out the potential of geothermal energy, including from the Dinantian Carbonates. This program includes a range of subsurface studies of the Dinantian Carbonates. The results of the SCAN studies will be released and become available via www.nlog.nl.

The direction and magnitude of the stress field components in the subsurface are important unknowns for many aspects of geothermal exploration and operations. During drilling and for well design, understanding of the stress field along the entire well track is important to decide on mud weights and casing design parameters. At the target depth, the stress field is an important factor in fault strength, potential for (induced) seismicity, and for controlling permeability magnitudes and permeability anisotropy in fractured media. As such, a stress field characterization study of the Dinantian carbonates was included in the SCAN program.

In this study the aim was to deliver the following:

1) A comprehensive overview of stress measurements in the Dutch Dinantian formation;
2) A Dinantian stress map, giving spatial context to the data;
3) A best practice description of:
    a. How to use existing stress measurements in the context of a local project;
    b. What data acquisition can be done during a geothermal project to improve local and regional knowledge of the stress field

The overview of stress measurements in the Dinantian is a deliverable of this project and will be published on www.nlog.nl. For each well, the raw data used, and the interpretation of the data are linked to the overview. This allows the user to not only use the final result, but also see the basis of that result.

The stress maps are also published on www.nlog.nl, along with outlines of the extent of the Dinantian carbonate platforms. A number of different versions of the map is available. Some of these also include stress measurements from the Limburg Group, which is directly overlying the Dinantian strata in much of the Netherlands. We hypothesize that these can be taken to be fairly representative of the stress state in the Dinantian. The orientation of the stress field of the Limburg Group is taken from Mechelse (2017).

Geological setting

For the realization of UDG projects the Dinantian carbonate platforms are of particular interest. The possible locations of these platforms are shown in Figure 3. The figure also indicates the boreholes that have reached the Dinantian, both in the Netherlands and in Germany and Belgium. A full list of boreholes reaching the Dinantian carbonates and extensive analyses of the well data can be found in Mozafari et al. (2019) and in Carlson (2019).. Although the number of wells reaching Carboniferous number around 60, less than half of those penetrate the Dinantian carbonates of the Zeeland Fm. The majority of the wells do not provide information on the state of stress in the Dinantian. For each well included in this study, it has been indicated whether the lack of stress field interpretation is due to a lack of data availability, or because the data does not contain sufficient stress field indicators.[1] The formations and members within the Namurian to Devonian are shown in Figure 2.

[1] For example, whether no four-arm caliper data was obtained, or whether the four-arm caliper data did not provide information on the orientation of the stress field.

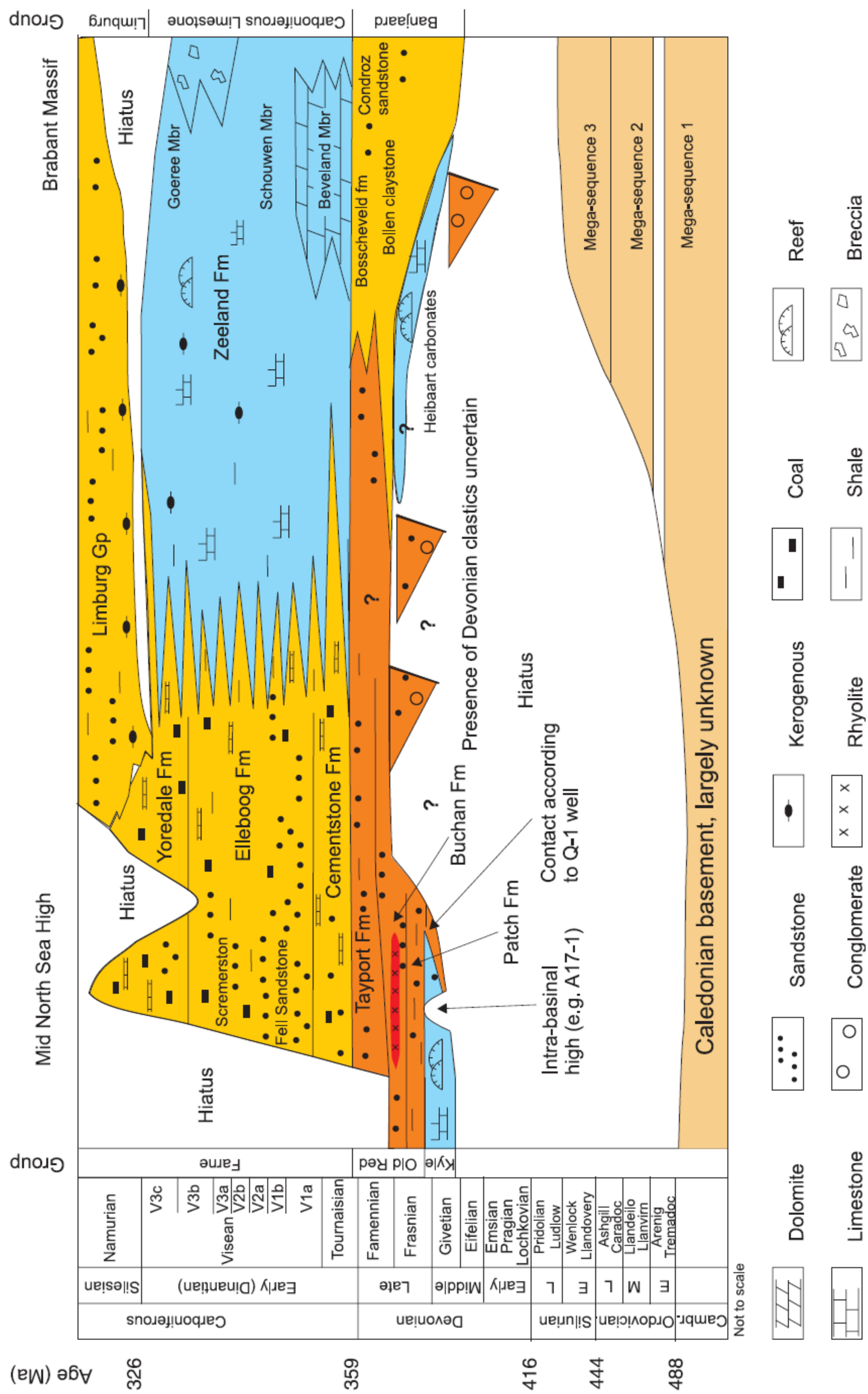
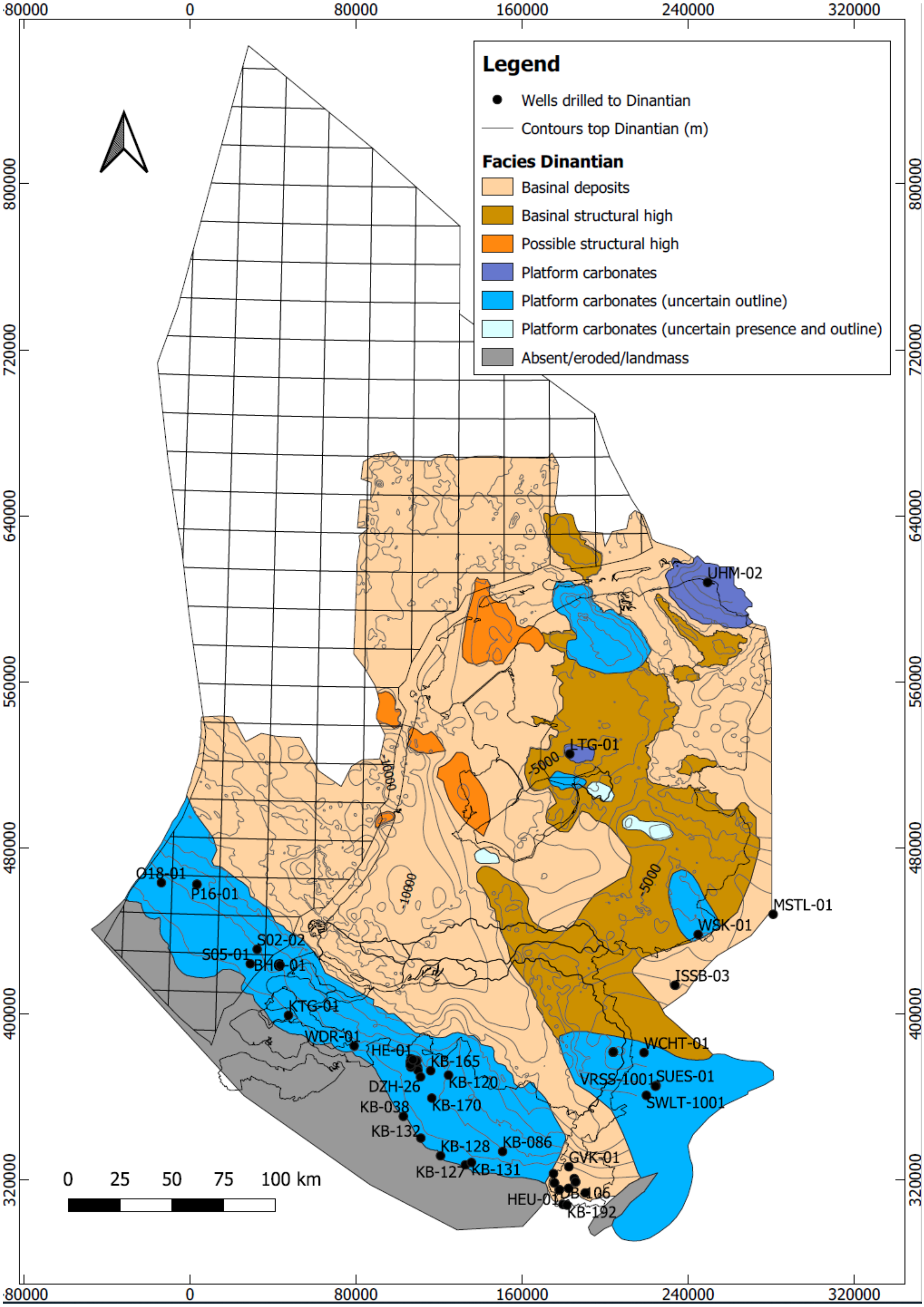


Figure 2 Schematic stratigraphy of the pre-Silesian (Namurian and older) based on boreholes drilled in the Dutch on- and offshore, and surrounding areas. After Geluk et al., in Wong et al. 2007. Stratigraphiess that are looked at in this study are Zeeland Fm, Goeree Mb, Schouwen Mb, and Beveland Mb.



s

Figure 3: Subdivision of the structures of the Dinantian (Seq. 2 & 3) (from Mozafari et al., 2019) with all wells in the Dutch subsurface reaching the Dinantian.

Methods

A full characterization of the stress field for a given point includes:

1) The three principal directions (the normal vectors of the planes which are not subjected to shear stress)
2) The three principle magnitudes (the values of the stress in the principal directions/ the values of the normal stress on the planes normal to the principal direction)
3) The pore pressure

In practice, it is difficult and costly to obtain all this information for a given point. Typically, the assumption is made that one of the principal directions is vertical, since the earth's surface cannot sustain shear stresses. At increasing depth, the influence of the surface decreases, loosening the basis for this assumption. Especially around highly ductile formations, such as salt domes and shales, there may be local deviations from a vertically aligned stress field.

For the purpose of this study, we work with the typical assumption that one of the principal components is vertical, at least on a regional scale. This automatically means that the other two principal components must be horizontal.

The direction of the horizontal stress components can be determined in a number of ways. As part of the SCAN program (scanaardwarmte.nl) the orientation of the stress field (SHmax) of the Dinantian has been determined for several boreholes. The orientation of the stress field is important for the realization of ultradeep geothermal (UDG) systems. The determination is mainly based on data that are available in the public domain on NLOG. The used data consist of 4-arm caliper logs and borehole image logs. Also data from boreholes close to the Dutch border drilled in Germany, England and Belgium have been used. Because only a small number of boreholes has been drilled deep enough to reach the Lower Carboniferous, data availability to determine the orientation of the stress field is sparse. To fill in data gaps, an analysis has been carried out to see if the orientation of the stress field changes between the overlying Limburg Group and the Dinantian. The orientation of the stress field of the Limburg Group is taken from Mechelse (2017).

The magnitude of the minimum horizontal stress (Shmin) can be determined from mini-frac tests, leak-off tests (LOTs), extended leak-off tests (XLOTs), and Step-Rate tests (SRTs). All of these tests have in common that a well is pressurized until a fracture is formed. This fracture forms normal to the minimum stress direction, since opening a fracture in this direction is energetically most favorable (assuming an isotropic bulk rock strength). The well pressure needed to open this fracture corresponds to the value of the stress in that direction. Since the vertical stress is assumed to be significantly larger than both horizontal stress components in the Netherlands (normal faulting regime, De Jager, in Wong et al. 2007), such tests can be used to evaluate Shmin. For the Dinantian carbonates, no publicly available data was found to exist. For a general overview of Shmin and LOT values in the Dutch subsurface, the reader is referred to Van Wees et al. (2014) and Figure 4.

The magnitude of the maximum horizontal stress (SHmax) is very difficult to obtain. For a normal faulting regime, the magnitude of SHmax lies between the magnitudes of Sv and Shmin. No effort has been made in this work to obtain values for SHmax. When a value for Shmin has been obtained (for example through one of the methods described above), the width of breakouts can be used to estimate the magnitude of SHmax (Zoback, 2007):

$$S_{Hmax} = \frac{\left(C_0 + 2P_p + \Delta P + \sigma^{\Delta T}\right) - S_{hmin}(1 + 2\cos(2(\pi - w_{bo})))}{1 - 2\ \cos(2(\pi - w_{bo}))}$$

where C_0 is the cohesion, P_p is the pore pressure in the formation, ΔP is the difference between the well pressure and the pore pressure, $\sigma^{\Delta T}$ is the thermal stress associated with drilling and w_{bo} is the angle of the wellbore breakout. This approach requires a lot of knowledge/estimation of parameters and should be applied with appropriate care.

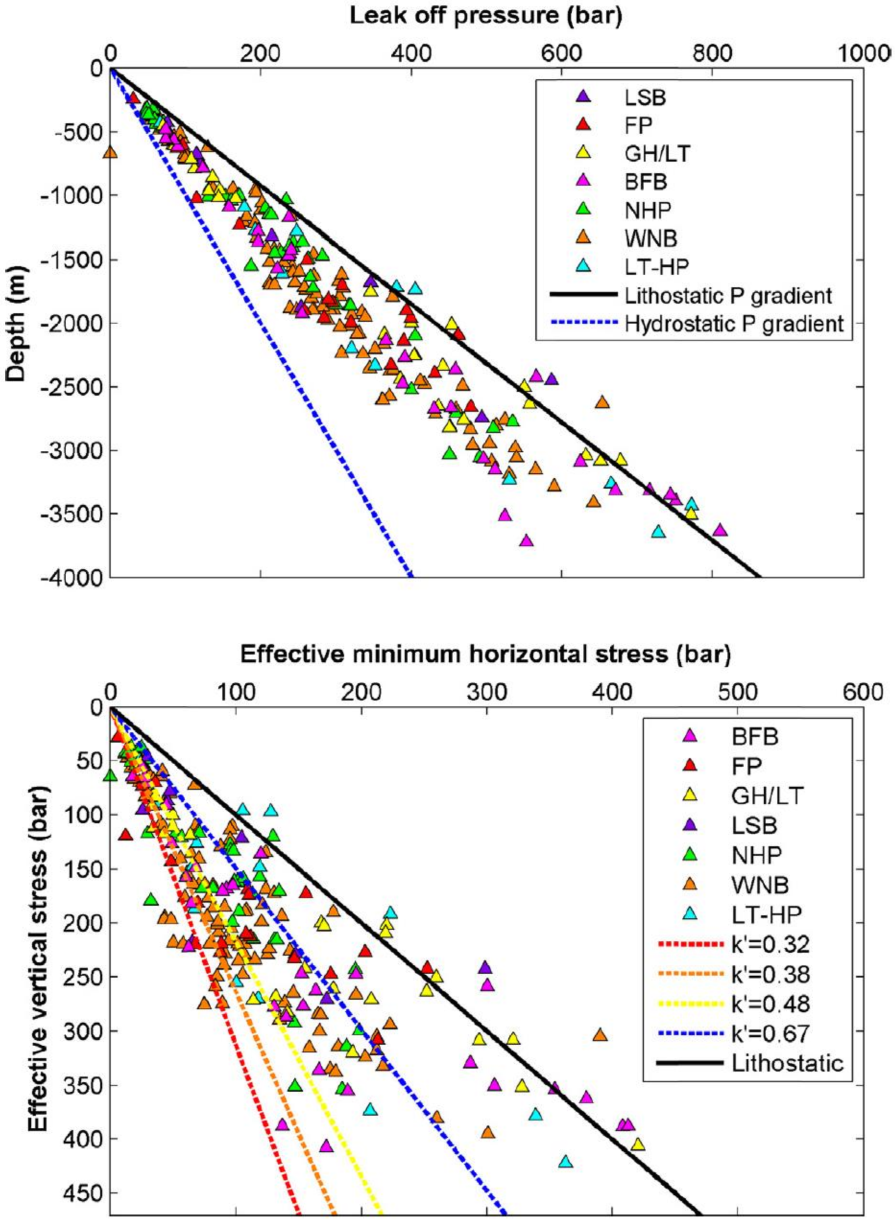


Figure 4: Leak-off pressures with depth and derived effective Shmin vs effective Sv, from Van Wees et al. (2014). BFB = Broad Fourtheens Basin, FP = Friesland Platfrom, GH/LT = Groningen High/Lauwerszee Trough, LSB = Lower Saxony Basin, NHP = Noord-Holland Platfrom, WNB = West Netherlands Basin, LT-HP = Lauwerszee Through-Hantum Platform. Derivation of effective stresses is described in van Wees et al. (2014) and is based on additional assumptions.

Interpretation borehole breakouts and electrical image logs

The results of borehole breakout analysis and the interpretations of the electrical image logs are reported in the following chapter. In Appendix 3 an overview of all boreholes that have been drilled into the Dinantian is given. The locations of these boreholes are also shown in Figure 3. The overview is based on boreholes documented on NLOG (overview generated in august 2019) and it contains not only boreholes drilled in the Dutch territory, but also boreholes drilled in Germany and Belgium. Also an offshore well drilled in the UK territory is interpreted. Because this analysis didn't result in a direction of the stress field, this well isn't shown in Figure 3.

Bore hole breakout analysis
In Appendix 3 for each borehole is indicated if data are available that can be used to determine the orientation of the stress field.

Not all individual breakouts are shown in these diagrams. To increase the reliability of the calculated orientations and to improve the clarity of the diagrams only the average orientation of at least three subsequent breakouts are shown. This minimum of three subsequent breakouts is also used to calculate the average orientation of SHmax per well. In Figure 5 the results of the calculated orientations are shown. From these figures it can be concluded that only very few boreholes could be analysed. Of the more than 60 available boreholes only 5 could be used to identify the orientation of the stress field. This was due to several reasons: the absence of 4-arm caliper data, incomplete data sets, bad quality of data or no presence of breakouts.

The rose diagrams in Figure 5 show two main directions of SHmax roughly perpendicular to each other: the first in a direction of roughly 320° and the second in a direction of roughly 45° (Table 1). The fact that two distinct orientations are present might indicate a small difference in magnitude between Shmin and SHmax. In such a situation, small changes in stress magnitude may cause Shmin and SHmax to effectively switch orientation. However, for breakouts to form in such a setting, where Shmin and SHmax magnitudes are close to one another, the rock strength has to be relatively low.

The WSM interpretations guidelines state that the difference between caliper size and bit size should be at least 10% (Tingay et al., 2014). However due to the small amount of usable data it was decided to use in some cases (O8-01, S02-02 and S05-01) a smaller difference (5%). This smaller difference was believed to be justified because a visual check of the caliper sizes did show some recognizable breakouts.

Table 1 Results borehole breakout interpretations.

Well ID	Breakout length vert. [m]	Breakout length hor. [m]	Direction of SHmax [°]	STD [°]
CAL-GT-01	5.0	0.7	310	3
LTG-01	24.2	4.7	310	47
O18-01	27.5	3.3	40	19
S02-02	74.9	56	330	21
S05-01	144.9	10.9	70	5
WSK-01	19.4	17.7	45	4

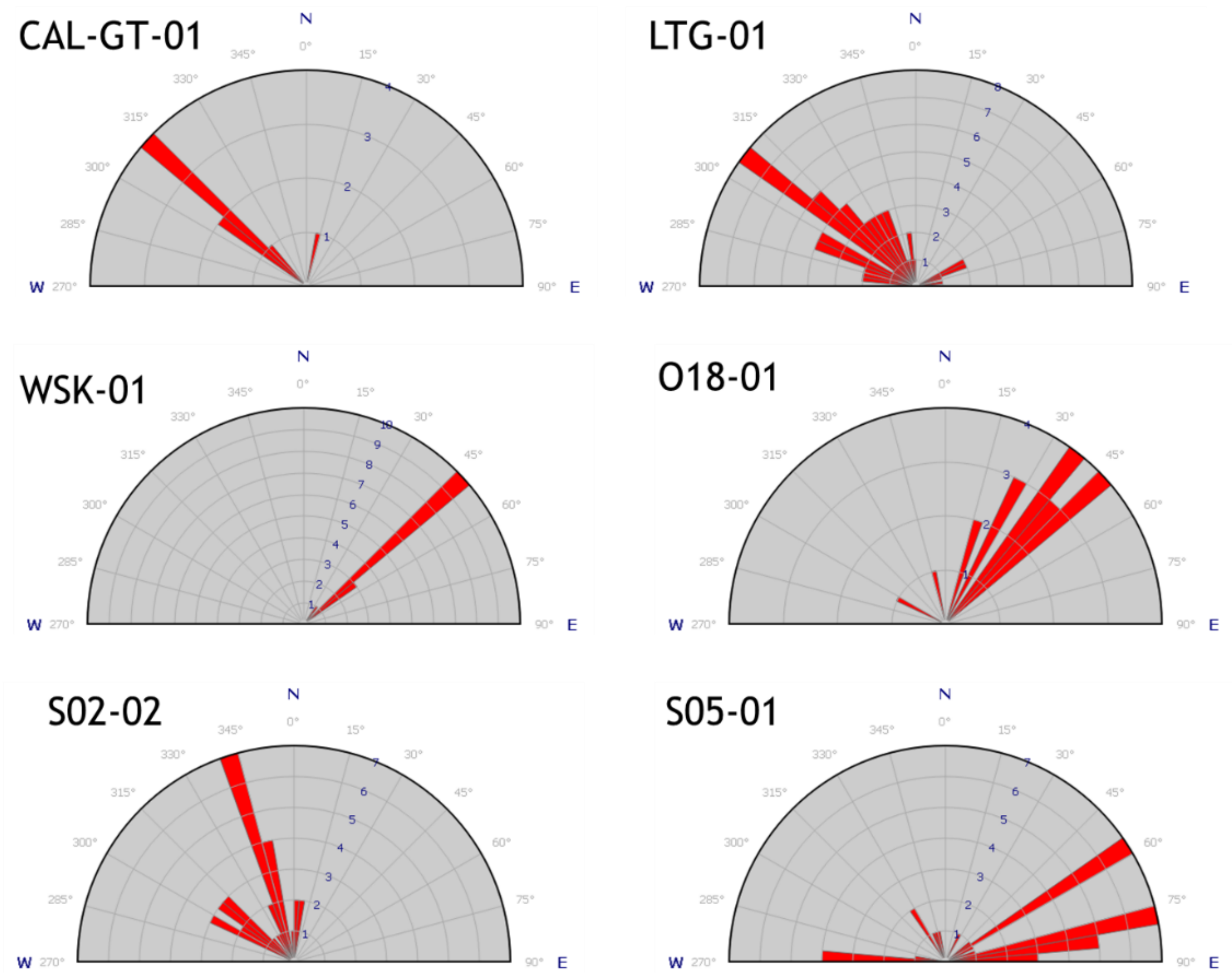


Figure 5 Rose diagrams of the interpreted orientation of SHmax for several boreholes drilled into the Dinantian.

Electrical image log analysis

A more reliable method of indicating the direction of the stress field is the use of an electrical image log. On an electrical image log, breakouts will be displayed as broad features of high conductivity. These breakouts are often poorly resolved when the pads cannot make full contact with the borehole wall. As a consequence, the tool will measure the resistivity of the borehole fluid rather than the properties of the formation (Heidback et al., 2016). In Figure 6 an example is shown of a resistivity image from LTG-01.

For only a few wells that reach into the Dinantian electrical image logs are available. In Table 2 the results of the image log interpretations are summarized. Figure 7 and Figure 8 show the rose diagrams of the interpretation of CAL-GT-01 and LTG-01, respectively.

In Figure 9 the visual interpretation of the image log of P-16-01 is given. On this log induced fracs are visible as paired thin vertical conductive cracks. These vertical cracks indicate the direction of SHmax (e.g. Zoback, 2007). The interpreted depth interval is just above the Dinatian (~25m). Because of the small depth difference between the interpreted section and the target, it is assumed that the determined orientation is representative for the target as well.

Table 2 Results image log interpretations

Borehole ID	Direction [°]	Source	Quality
CAL-GT-01	301	Van Leverink and Geel, 2019	High
LTG-01	320	Van Leverink and Geel, 2019	High
P16-01	300	This work	Moderate, visual interpretation

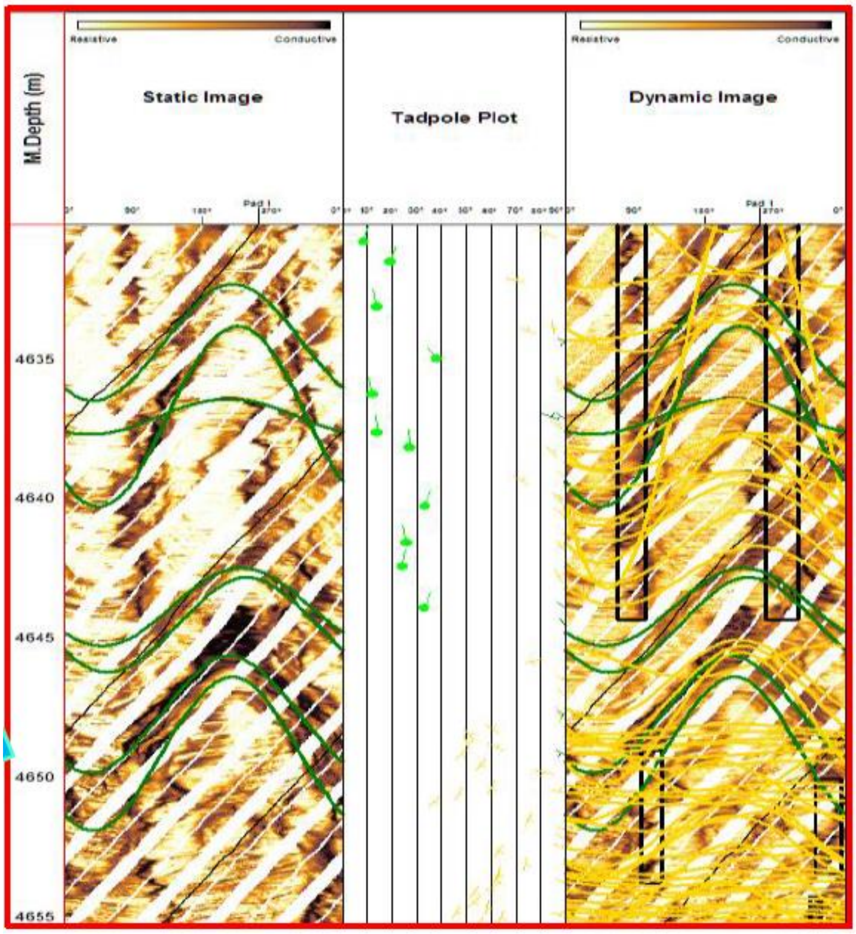


Figure 6 Example of highly fractured interval, partial conductive (yellow) and continuous conductive (dark green) fractures, LTG-01.

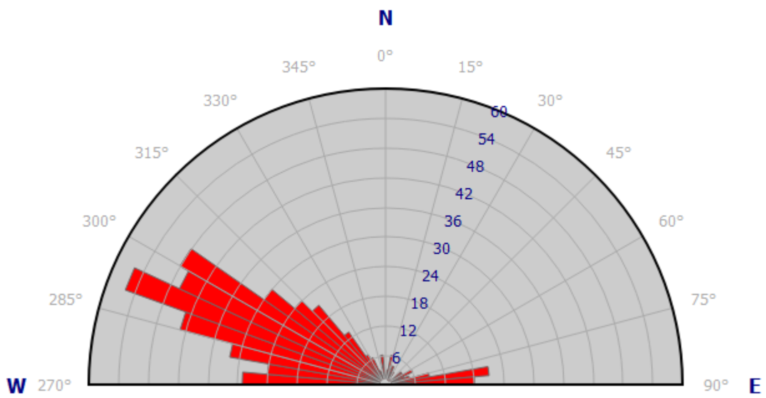


Figure 7 Interpretation FMI CAL-GT-01, all natural fractures, depth range 1583-1736 mMD. Average orientation 301° (Van Leverink and Geel, 2019).

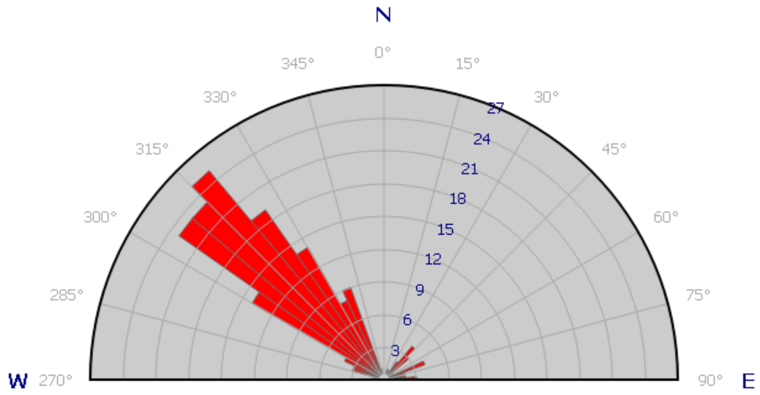


Figure 8 Interpretation FMI LTG--01, depth range 4655-4741 mMD. Average orientation 320° (Van Leverink and Geel, 2019).

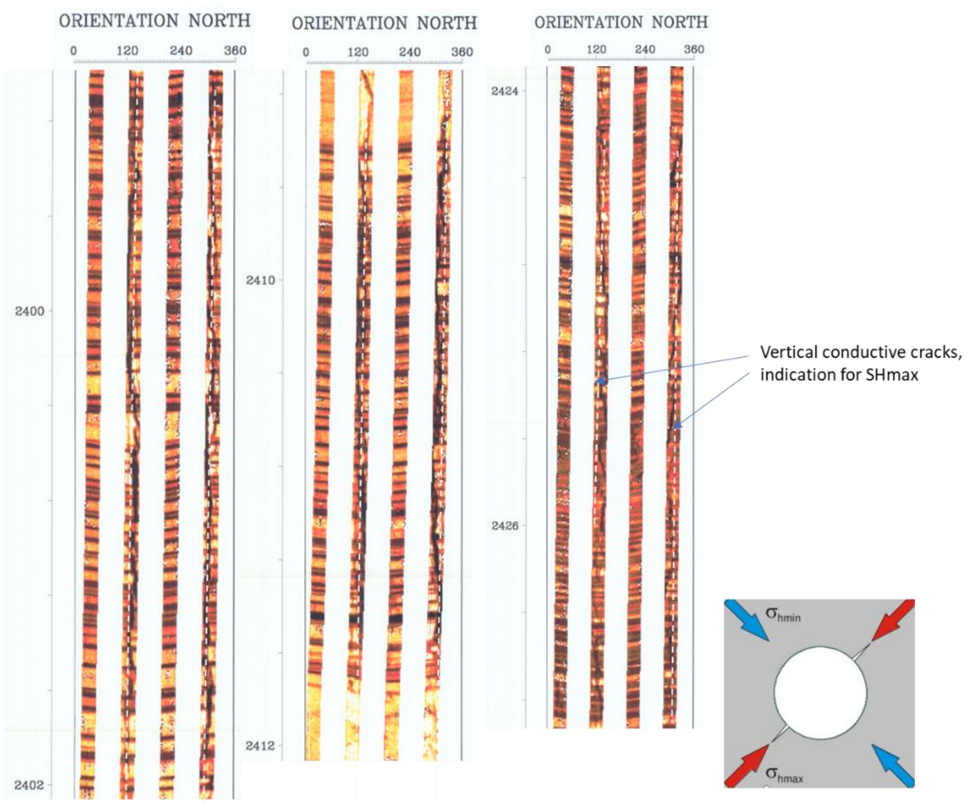


Figure 9 Interpretation FMI P16-01, depth range 2400 - 2426 mMD. Slightly above target. Average orientation around 300°.

Stress map Dinantien

Figure 10 shows the stress map of the Dinantian. Stress orientations based both on image log interpretations and borehole breakout interpretations are shown on this map.

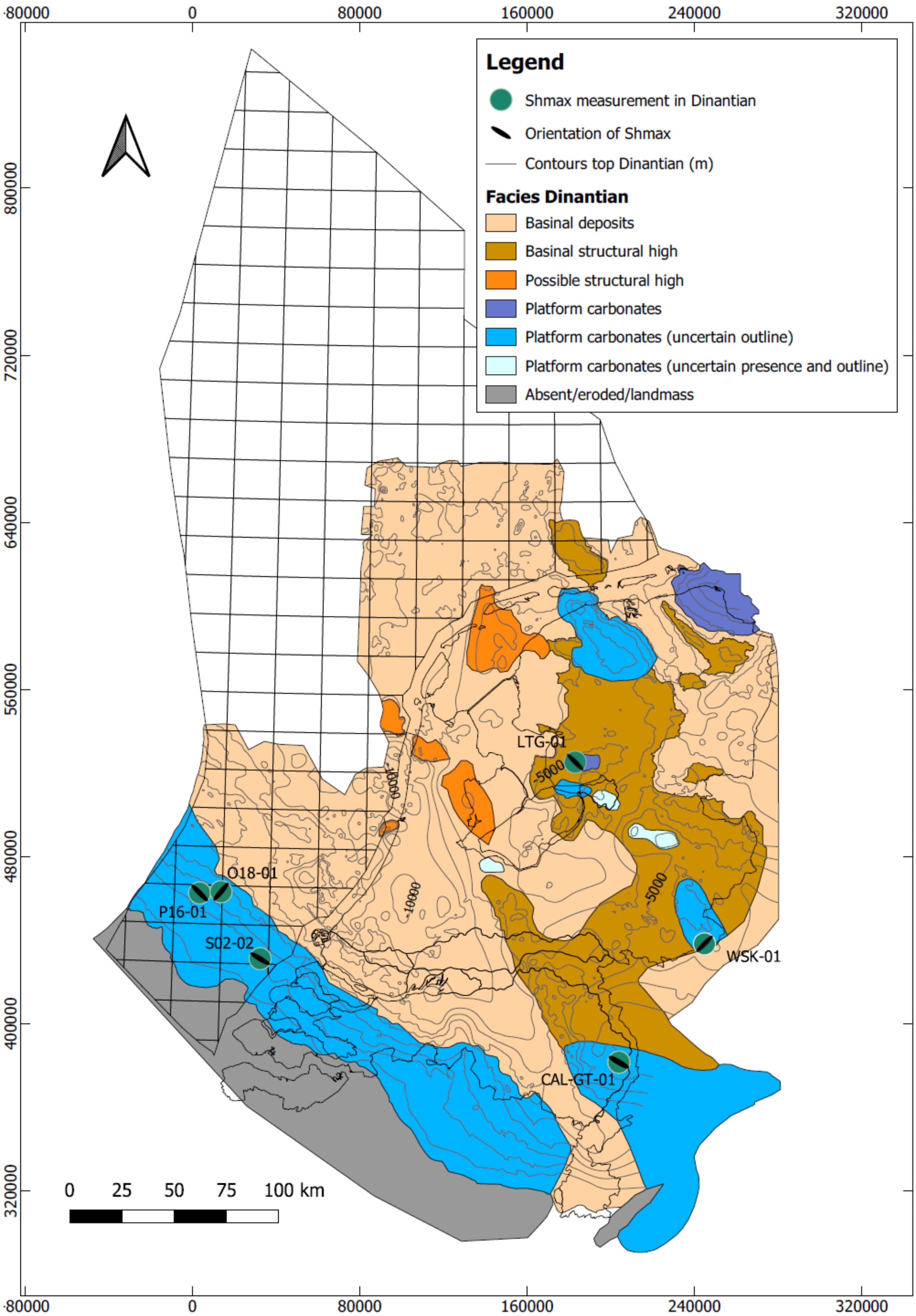


Figure 10 Map indicating for each well the average S_{Hmax} direction in the Dinantien.

Stress Field Limburg Group

Mechelse (2017) reported on research about the variations in the direction of SHmax in the Netherlands. For this study several databases[2] containing data about stress magnitudes and stress orientation in the Netherlands were reviewed and combined. Based on these data, maps with stress directions for different stratigraphic groups were constructed. The map with the stress direction in the Limburg Group is given in Figure 11. The Limburg Group was the deepest stratigraphy for which a map was constructed. In this current study, the results from Mechelse (2017) for the Limburg Group have been used directly, and no additional review of the analyses has been carried out.

According to Mechelse (2017), the mean direction of SHmax in the Limburg Group is around 325°. The mean direction of SHmax in the Dinantien is around 317°. For one well (WSK-01), the direction of Shmin could be dermined in both the Limburg Group and the Dinantian. Both formations have derived an orientation of 45° for SHmax. This general alignment of the stress field in the Limburg Group and the Dinantian suggests that the orientation of the stress field in the Dinantian is not very different from the overburden, and that the overburden stress state can be seen as indicative for the stress state in in the Dinantian. This is supported by the general lack of ductile formations separating the Dinantian from the direct overburden, which would be required for vertical decoupling of the stress state. However, the Numarian formations overlying the Dinantian in some regions can contain a significant amount of shale. In these situations, stress decoupling could be achieved through creep in the shale formation.

[2] Sources: NLOG.nl, world-stress-map.org,Rondel & Everaars (1993), Van Eijs (2015)

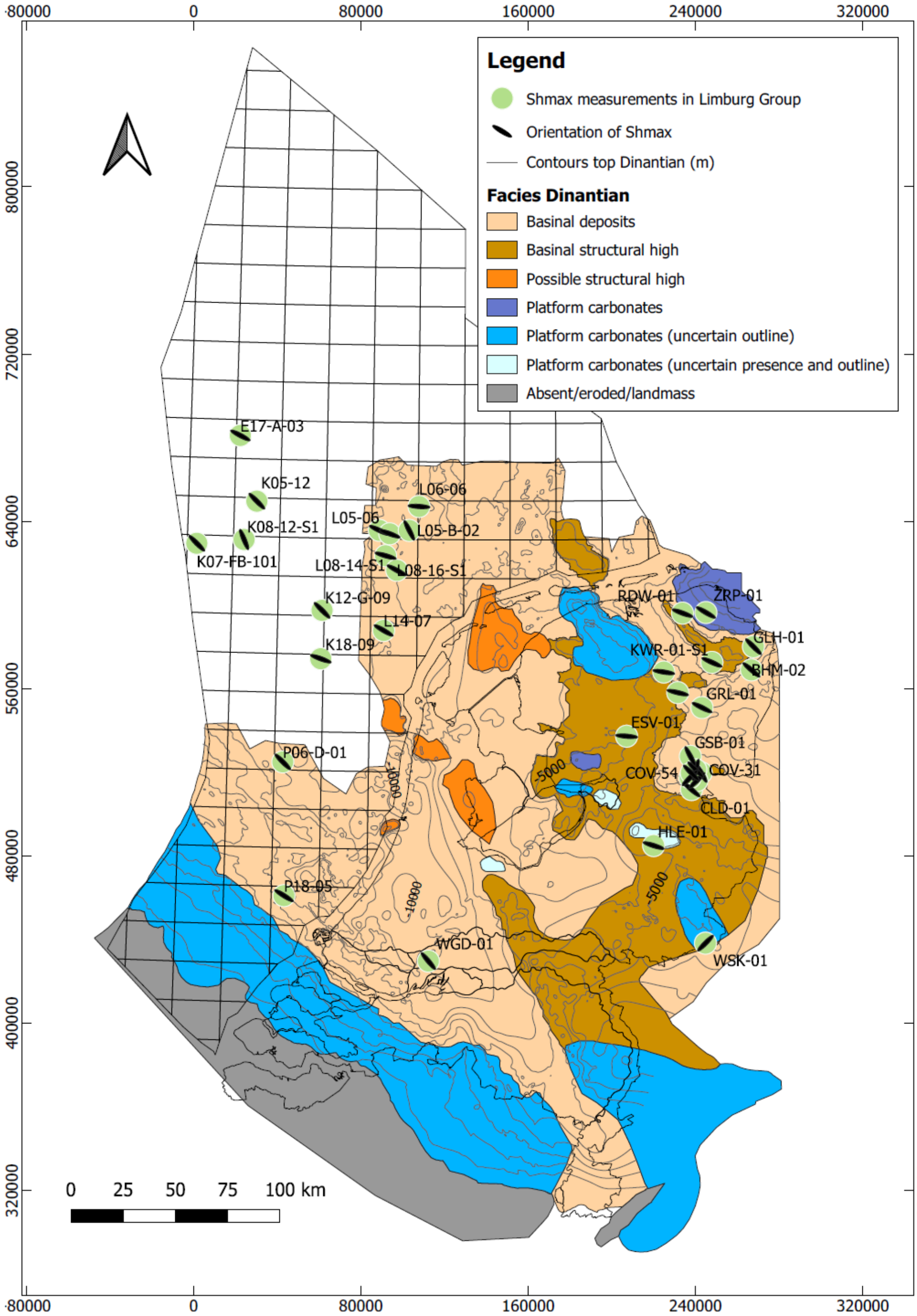


Figure 11 Dutch Stress Map indicating for each well the average SH direction in the Limburg Group (Mechelse, 2017)

From national/regional scale to local scale

The data gathered and presented in this project give a global picture of the stress state in the Dinantian, to the extent that public data on this is available. However, as stated in the introduction of this report, it is also our aim to provide a best practice description on:

1) How to use existing stress measurements in the context of a local project;
2) What data acquisition can be done during a geothermal project to improve local and regional knowledge of the stress field

This section is aimed at providing information on these two topics.

On the magnitude and orientation of the horizontal stress components
The magnitude of horizontal stresses can vary significantly within the subsurface. In general the following conditions apply to the Dutch subsurface (largely based on observations at depths of up to ~3km):

- Both Shmin and SHmax can be assumed to be lower than Sv (normal faulting regime, De Jager, in Wong et al., 2007).
- The lack of distinct breakouts in many wells, combined with some 90 degree rotations in the directions of breakouts suggests that Shmin and SHmax are relatively close to each other in magnitude (see also Van Eijs (2015)). A good starting assumption, in absence of data, is SHmax ~5-20% higher than Shmin.
- The general trend of leak-off tests indicates leak-off pressures approaching the lithostatic gradient with increasing depth (Gaarenstroom et al., (1993); Breckels and Van Eekelen (1982); van Eijs, pers. comm)
- If no other data is available, a first order estimate for Shmin in the Dinantian is 18MPa * [depth in km] based on an extrapolation of available lower bound curves to LOT data (van Eijs, pers. comm). This estimate is based on a depth range of ~3-4 km.
- The state of stress becomes more isotropic in formations that exhibit plastic creep deformation, such as salt and clayey shales.
- Leak-off test results are significantly influenced by the borehole stress perturbation due to the limited fluid volumes involves, which causes their length to be limited. As a result, they may overestimate the value of Shmin. By combining data and taking the lower bound, you obtain a value that's likely to be least influenced by borehole effects and closest to the value of the Shmin
- The potential for overpressures increases with depth, lowering the effective stresses and decreasing stability of wells and faults
- As a data source for Shmin, extended leak-off tests (XLOT) or minifrac tests are (much) preferred over standard leak-off tests. The extra cycles in an XLOT ensure that the created fracture propagates away from the wellbore. This minimizes the influence of the borehole.
- Stress rotation (principal axes of the stress tensor no longer aligned with vertical) may occur near salt domes due to salt's inability to sustain shear stresses over geological time. Since there is no data available, it is unknown to what extent a similar processes occur near platform edges. The change in mechanical properties is expected to be much more gradual in most cases, which would imply that stress rotation are not expected to play a major role near platform edges. However, stress rotation may also be expected near damage zones of large faults, which can occur near the platform boundaries.

Using existing stress measurements in the context of a local project

For any given UDG project, the pre-drill stress state at target depth will be subject to large uncertainty. By far the easiest stress component to estimate is the total vertical stress, which can be obtained by integrating the density of the overburden. The density of the overburden is usually relatively well known. Although it is advisable to create a number of realizations of overburden density profiles, the uncertainty in vertical stress at target depth is expected to be limited. Using the points mentioned above and the resources provided in this report and on nlog.nl, an estimate of Shmin and SHmax magnitude and orientation can be obtained. Due to the large uncertainties involved, the use of many simple models is preferred over one/few complicated models.

If there are no salt diapirs, major faults and/or tectonic structures nearby, a one dimensional earth model (MEM) can be constructed with a reasonable degree of confidence. First, the total vertical stress is calculated by integrating the density log and all stress data, such as (X)LOT, drilling events (lost circulation) are used to constrain the minimum stress. If no further data is known, the horizontal stress can be estimated from nearby analogue wells or using simple K_o models based on uniaxial strain assumption or fault friction angle, using vertical stress and pore pressure and a MEM as input. Rock mechanical parameters such as *UCS* and friction angle can be estimated from empirical correlations using only V_p input by Horsrud (2001). Also the friction angle can be estimated as suggested by Lal (1991). The maximum horizontal stress can be confined using wellbore breakout width as input (Zoback et al., 1985; Barton et al., 1988), the shear strength and the mudweight and pore pressure during the drilling.

Acquiring new data during a UDG project.

New stress data acquisition during a UDG project is likely to be based on well data. A number of options for stress data acquisition are available.

- Image log/FMI, preferably in combination with an Shmin magnitude determination.
- A less commonly known, but potentially attractive means to obtain the magnitude of Shmin is through a Step-Rate test (SRT). In such as test, several constant flow rate intervals are used to determine when fractures open up. This information can be used to obtain the value of Shmin, and the Formation Parting Pressure (FPP). In addition to Shmin, these tests also contain information about the permeability and injectivity of the formation, both at pressures below the FPP and above. An SRT can be performed as part of a typical post-drill well-test and as such may be easier to incorporate in a characterization effort.
- Circumferential Vs/Vp sonic scanner: Gives direction on SHmax/Shmin and the ratio between their magnitudes. It is a relatively expensive tool to employ, but potentially provides more information than an image log/FMI or 4-arm caliper run. When combined with an XLOT or minifrac, this would provide a full characterization of the stress field at depth. However, interpretation of the results of this tool are complex and are associated with significant uncertainty.

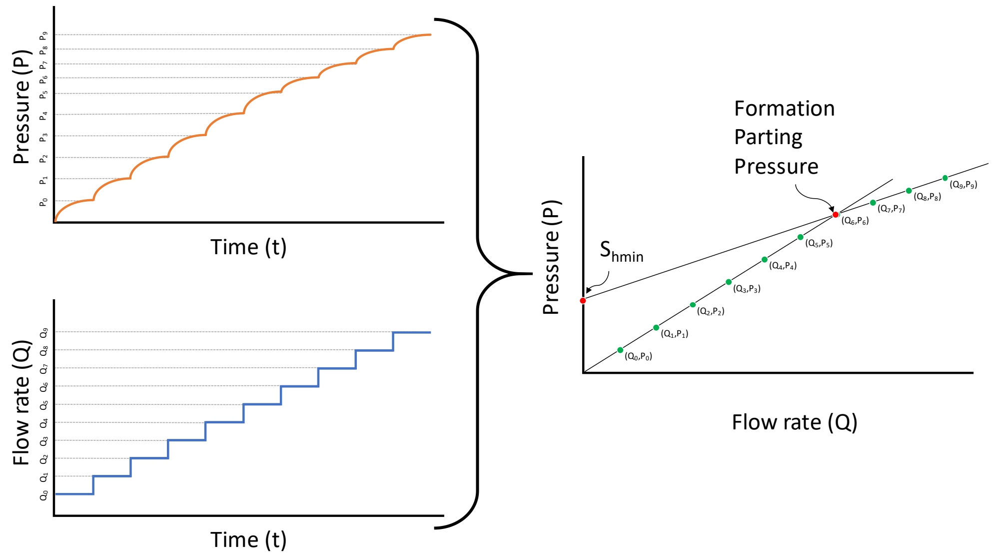


Figure 12: Schematic representation of a Step-Rate test

Discussion

In this report, we have compiled all publicly available data on the stress field in the Dinantian. Data density is low, leading to an incomplete picture on a national scale. From the limited data that is available, it appears that horizontal stress azimuths and gradients obtained in overlying formations nearby can be used to estimate the state of stress in the Dinantian. It is hypothesized that this is caused by the lack of 'decoupling' lithologies such as creeping salt or shale between the Dinantian and overlying formations. This hypothesis may not hold in areas where Namurian shales cover the Dinantian carbonates.

A national effort to develop UDG plays would benefit from a more detailed understanding of the state of stress in the Dinantian, especially since much of the permeability at these depths will necessarily come from fractures/faults. In some regions (such as Limburg), focal mechanism inversion may lead to additional insights into the stress field. In other regions, the main potential source of additional data will have to be wells drilled into the Dinantian during UDG exploration. For such wells, potential steps to obtain data on the stress fields have been described. Public availability of such new data would greatly increase the value the data for UDG operators in the Netherlands.

References

Barton, C. A., Zoback, M.D., Burns, K.L., (1988). In-situ stress orientation and magnitude at the Fenton geothermal site, New Mexico, determined from wellbore breakouts. Geophysical research letters, Vol. 15, No. 5. 467-470.

Breckels, I. M., & van Eekelen, H. A. M. (1982, September 1). Relationship Between Horizontal Stress and Depth in Sedimentary Basins. Society of Petroleum Engineers. doi:10.2118/10336-PA

Carlson, T. (2019). Petrophysical Report of the Dinantian Carbonates in the Dutch Subsurface (SCAN). Downloadable from www.nlog.nl

De Jager, J.: Geological development. In: Wong, Th.E., Batjes, D.A.J. and De Jager, J. (2007). Geology of the Netherlands.

Gaarenstroom, L., Tromp, R. A. J., De Jong, M. C. & Brandenburg, A. M. 1993. Overpressures in the Central North Sea: implications for trap integrity and drilling safety. In: Parker, J. R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London 2, 1305–1313.

Geluk, M.C., Dusar, M. and De Vos, W.: Pre-Selisian. In: Wong, Th.E., Batjes, D.A.J. and De Jager, J. (2007). Geology of the Netherlands.

Heidbach, O., Barth, A., Müller, B., Reinecker, J., Stephansson, O., Tingay, M., & Zang, A. (Last update 2016a, December). *Scientific Technical Report 16-01* [online: web]. Retrieved February 4, 2017, from http://www.world-stress-map.org/fileadmin/wsm/pdfs/WSM_STR_16_01.pdf

Horsrud, P., (2001). Estimating mechanical properties of shale from empirical correlations. SPE Drilling Completion, 16, 68-73.

Lal, M., (1999). Shale stability: drilling fluid interaction and shale strength. SPE 54356, presented at SPE Latin American and Caribbean Petroleum Engineering Conference, Caracas, Venezuela, 21–23 April. Tulsa, OK: Society of Exploration Geophysicists.

Mardia, K.V.,Jupp. P.E., 1999. Direction Statistics. John Wiley & Sons.

Mechelse, E., 2017. The in-situ stress field in the Netherlands: Regional trends, local deviations and an analysis of the stress regimes in the northeast of the Netherlands, Faculty of Civil Engineering and Geoscience, Delft University of Technology.

Mozafari, M., Gutteridge, P., Riva, A., Geel, C. R., Garland, J., and Dewit, J. (2019). Facies analysis and diagenetic evolution of the Dinantian carbonates in the Dutch subsurface (SCAN). Downloadable from www.nlog.nl

Rondel, H.E., & Everaars, J.S.L. (1993). Spanning in noordoost Nederland: een breakoutanalyse. Not available. Data reported in Mechelse (2017)

Tingay, M., Reinecker, J., and Müller. B., 2014. Borehole breakout analysis from four-arm caliper logs. (https://www.researchgate.net/publication/242290975_Borehole_breakout_analysis_from_four-arm_caliper_logs)

Tingay M., Reinecker J., and Müller B., 2008. Borehole breakout and drilling-induced fracture analysis from image logs. (http://extras.springer.com/2010/978-1-4020-8443-

0/WSM%20Release%202008/WSM_website/pub/guidelines/WSM_analysis_guideline_breakout_imag.pdf)

Van Eijs, R. (2015). Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field. (https://nam-feitenencijfers.data-app.nl/download/rapport/b7a3cb12-46c3-4783-86f0-5905882cb0f6?open=true)

Van Leverink, D.J. and Geel, C.R. (2019). Fracture Characterization of the Dinantian Carbonates in the Dutch Subsurface (SCAN). Downloadable from: www.nlog.nl

Van Wees, J. D., Buijze, L., Van Thienen-Visser, K., Nepveu, M., Wassing, B. B. T., Orlic, B., & Fokker, P. A. (2014). Geomechanics response and induced seismicity during gas field depletion in the Netherlands. Geothermics, 52, 206-219.

Zoback, M. D., D. Moos and L. Martin., (1985). Wellbore breakout and in-situ stress. Journal of Geophysical Research, Vol 90, Nr. B.7. 5523 – 5530

Zoback, M. D. (2010). Reservoir geomechanics. Cambridge University Press.

Appendix 1: Additional stress maps

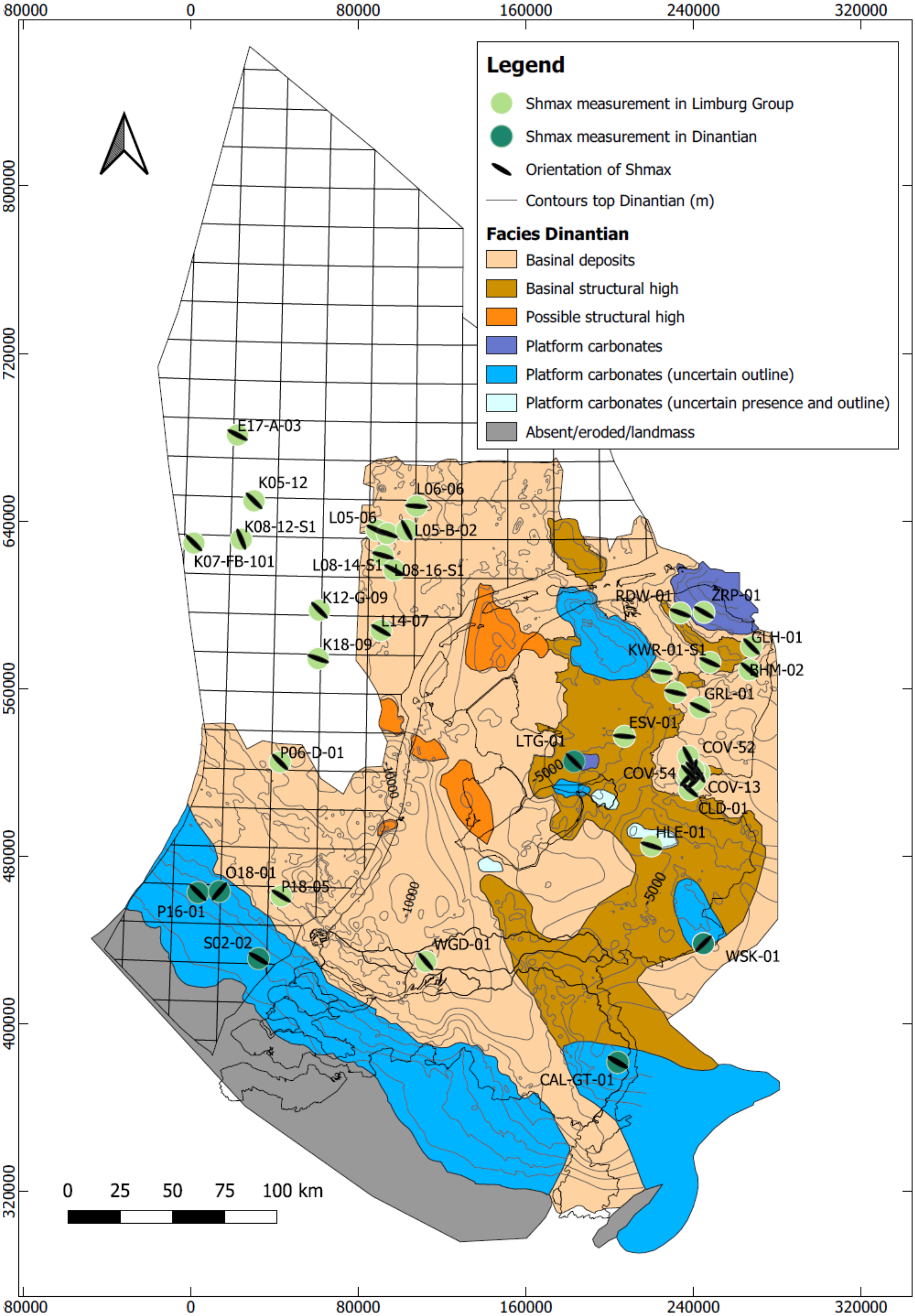


Figure 13: Combination of all S_{Hmax} orientation data in both the Limburg Group (Mechelse, 2017) and the Dinantian (this work). Dinantian facies map (Seq 2 & 3) from Mozafari et al, 2019

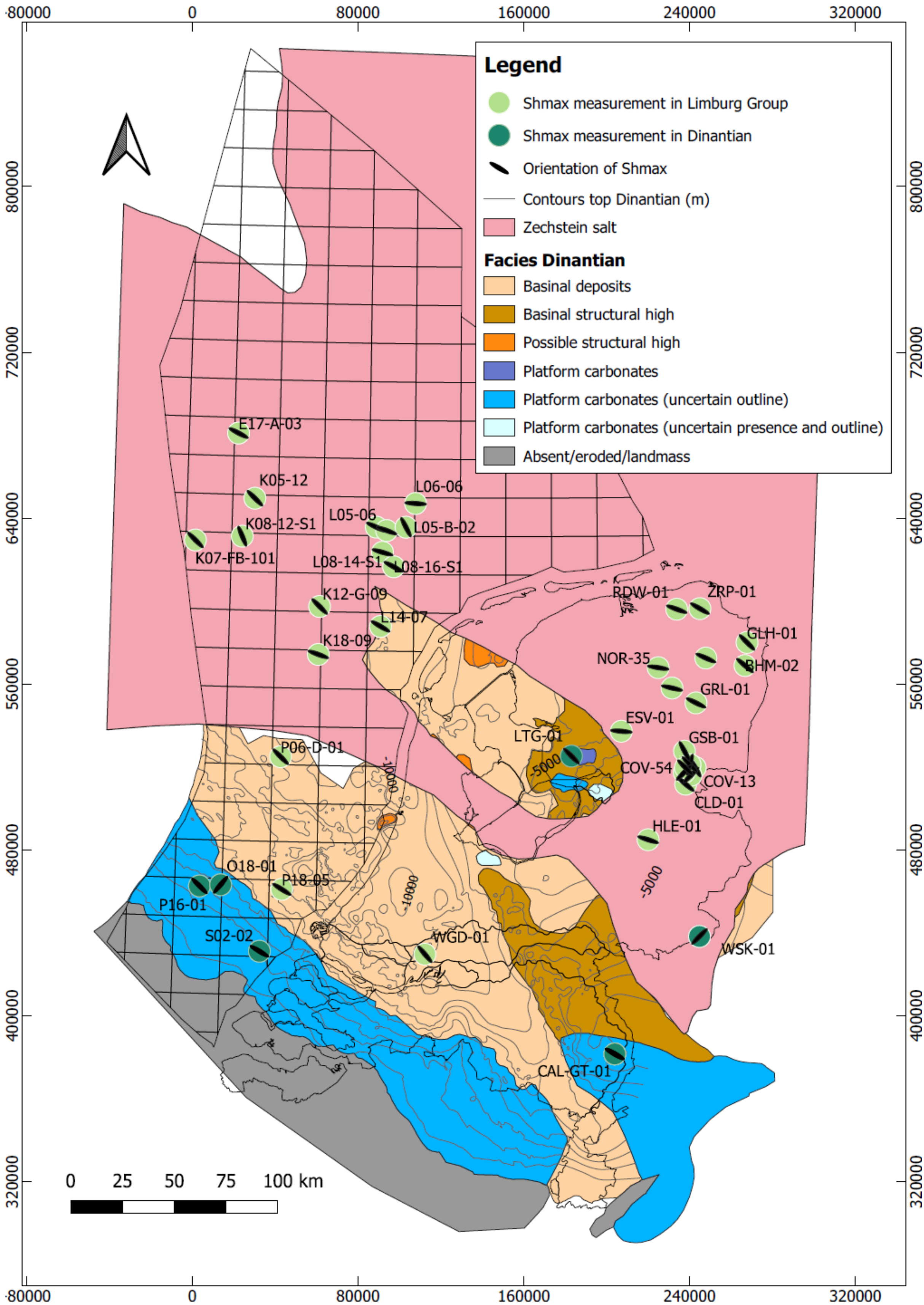


Figure 14: As Figure 13, but including the extent of the Zechstein salt. Dinantian facies map (Seq 2 & 3) from Mozafari et al, 2019

Appendix 2: Interpretation of borehole breakouts

The description and interpretation of borehole breakouts is done using the guidelines and quality checks as described in Tingay et al. (2008) and Tingay et al. (2014)

A borehole breakout is an important indicator of horizontal stress direction. It is a stress-induced enlargement of the wellbore that occurs when the stresses around a borehole exceed the required stress to cause compressive failure of the borehole wall. The stress concentration around a vertical borehole is greatest in the direction of the minimum horizontal stress (Shmin). Hence, the borehole breakouts are oriented approximately perpendicular to the maximum horizontal stress orientation (SHmax), see Figure 15. Although borehole breakout data can in principle be used to constrain the ratio between the magnitudes of Shmin and SHmax, this requires additional information on the strength of the surrounding material. Due to the lack of such data, the decision was made here to not pursue this route.

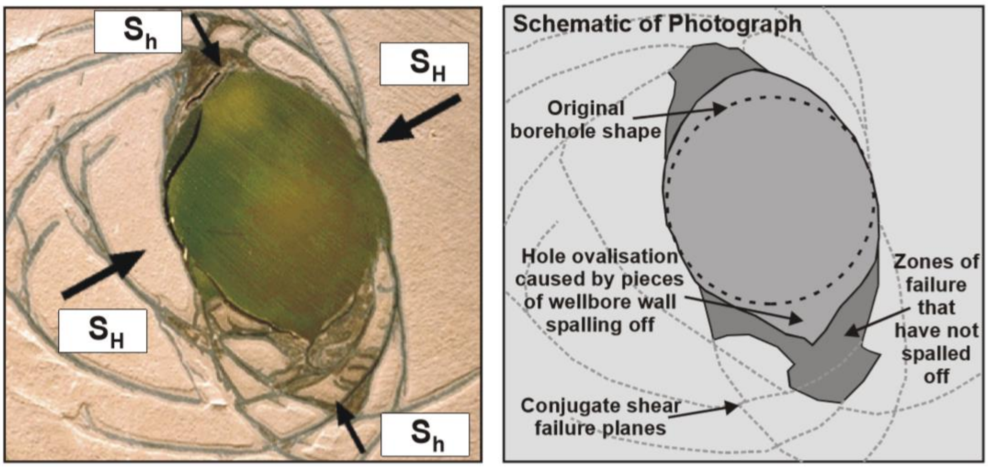


Figure 15 Results of a hollow cylinder lab test simulating borehole breakout (performed by the CSIRO Division of Geomechanics Tingay et al., 2014). Intersection of conjugate shear failure planes results in enlargement of the cross-sectional shape of the wellbore. SHmax and Shmin refer to the orientations of maximum and minimum horizontal stress respectively.

Four-arm caliper tool

Four-arm caliper tools are commonly run to obtain information about the formation (primarily strike and dip of bedding) and to estimate the volume of cement required for casing. However, unprocessed oriented four-arm caliper logs can also be used to interpret borehole breakouts.

The logs needed for interpretation are the following (explanation given in Figure 16):

- Azimuth of pad 1 (P1AZ) relative to magnetic north;
- Diameter of the borehole in two orthogonal directions ‘Caliper 1’ (C1) between pad 1 and 3 and ‘Caliper 2’ (C2) between pad 2 and 4;
- Borehole deviation (DEVI) from vertical;
- Azimuth of borehole drift (HAZI), and;
- Bearing of pad 1 relative to the high side of the hole (RB).

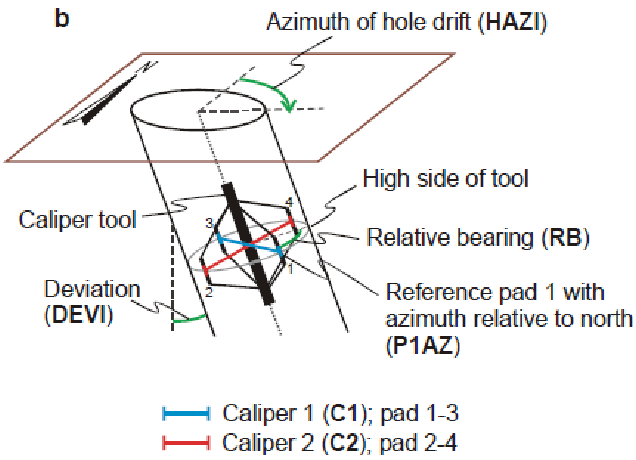


Figure 16 Geometry of the four-arm caliper tool in the borehole and data used for interpreting borehole breakouts (Tingay et al., 2014)

Depth, C1, C2 and DEVI must be available to interpret breakouts. However, only two of P1AZ, RB and HAZI are necessary as the missing log can be calculated using following equation:

P1AZ = HAZI + arctan [tan RB / cos DEVI]

In Figure 17 the criteria for interpreting a 4-arm caliper data are given.

1. Tool rotation must cease in the zone of enlargement.
2. There must be clear tool rotation into and out of the enlargement zone.
3. The smaller caliper reading is close to bit size. Top and bottom of the breakout should be well marked.
4. Caliper difference has to exceed bit size by 10 %.
5. The enlargement orientation should not coincide with the high side of the borehole in wells deviated by more than 5°.
6. The length of the enlargement zone must be greater than 1 m.

Figure 17 Criteria for interpreting borehole breakouts from 4-arm caliper data (Tingay et al., 2014).

Word stress map (WSM) quality ranking

The World Stress Map (WSM) is a global compilation of information on the crustal present day stress field, maintained since 2009 (http://www.world-stress-map.org/). All data in the WSM database are quality ranked to make comparison between different indicators of stress orientation possible. The quality ranking criteria for stress orientations determined from breakouts interpreted from 4-arm caliper logs is presented in Figure 18.

A-Quality	B-Quality	C-Quality	D-Quality	E-Quality
Wells that have ten or more distinct breakout zones with a combined length > 300 m; and with s.d. ≤ 12°	Wells that have at least six distinct breakout zones with a combined length > 100 m; and with s.d. ≤ 20°	Wells that have at least four distinct breakouts zones with a combined length > 30 m; and with s.d. ≤ 25°	Wells that have less than four breakouts zones or a combined length < 30 m or with s.d. > 25°	Wells with no reliable breakouts detected or with extreme scatter of breakout orientations (s.d. > 40°)

Figure 18 World Stress Map quality ranking criteria for breakouts (s.d. = standard deviation) Tingay et al., 2008

Besides 4-arm caliper logs other methods are available to derive the direction of the stress field. Image logs, for instance, provide a much more reliable interpretation of borehole breakouts than 4-arm caliper logs. Therefore, stress orientations determined from image log data are quality ranked separately from borehole breakouts, see Figure 19.

A-Quality	B-Quality	C-Quality	D-Quality	E-Quality
≥ 10 distinct DIF zones and combined length ≥ 100 m in a single well with s.d. ≤ 12°	≥ 6 distinct DIF zones and combined length ≥ 40 m in a single well with s.d. ≤ 20°	≥ 4 distinct DIF zones and combined length ≥ 20 m in a single well with s.d. ≤ 25°	< 4 distinct DIF zones or < 20 m combined length with s.d. ≤ 40°	Wells without reliable DIFs or with s.d. > 40°

Figure 19 World Stress Map quality ranking criteria for drilling-induced fractures from images logs in a single well (s.d.= standard deviation) Tingay et al. 2008.

Average horizontal stress orientation

Borehole breakout orientations are bimodal data. This means that data between 180° and 360° are equivalent to those from 0° to 180°. According to Mardia and Jupp (1999) the standard way to deal with axial data is to convert them to circular data by doubling the angles, i.e. transforming θ to 2 θ, and so removing the ambiguity in direction (in all following equations the azimuths are in radians).

$$\theta^* = 2\,\theta$$

Each direction can be regarded as a unit vector x, or as a point on an unit circle. The mean direction θ_m^* of $\theta_1^*,\ldots,\theta_n^*$ is the direction of resultant of the unit vector $x_1+\ldots+x_n$. Since the Cartesian coordinates of x_j are $\cos\theta_j^*$ and $\sin\theta_j^*$ (for j = 1,…,n), the Cartesian coordinates of the centre of the mass are C_m and S_m, where:

$$C_m = \frac{1}{n}\sum_{j=1}^{n} \cos\theta_j^*$$

$$S_m = \frac{1}{n}\sum_{j=1}^{n} \sin\theta_j^*$$

in the case of a number weighted mean, or

$$L = \sum_{j=1}^{n} l_j$$

$$C_m = \frac{1}{L}\sum_{j=1}^{n} l_j \cos \theta_j^*$$

$$S_m = \frac{1}{L}\sum_{j=1}^{n} l_j \sin \theta_j^*$$

in the case of length weighted mean. l_j is the length of the borehole breakout j with orientation θ^*.

Therefore θ_m^* is the solution of the equations:

$$C_m = R_m \cos \theta_m^*$$

$$S_m = R_m \sin \theta_m^*$$

$$\theta_m^* = 0.5 \arctan \frac{S_m}{C_m}$$

Provided that $R_m > 0$, the mean resultant length R_m is given by

$$R_m = (C_m^2 + S_m^2)^{0.5}$$

And the standard deviation is derived as

$$STD = \{-2 \log R_m\}^{0.5}$$

Appendix 3: Overview of data used

An overview of the data as used in this study is found in the remainder of this Appendix

Wells CL

Summary of all raw and interpreted data per well as used/generated in this study is found in the separate document:

SCAN Dinantian Stress field characterization Dinantian carbonates report-Appendix3A.pdf

Data MSc Thesis Mechelse 2017

Data as obtained from Mechelse (2017) and used in this study is found in the separate document:

SCAN Dinantian Stress field characterization Dinantian carbonates report-Appendix3B.pdf