Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field

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Date November 2015

Editors Jan van Elk & Dirk Doornhof

General Introduction

In the development of the seismological model (Ref. 1 and 2) extensive use is made of the very rich data set of subsidence and compaction for the Groningen field. The subsidence data set consists of several acquisition methods: levelling surveys, satellite measurements and GPS stations. It covers the period from 1963 to the present day. Several methods have been developed to estimate the reservoir compaction from the subsidence data (Ref. 3). Additionally, compaction is monitored in the reservoir using observations well (Ref. 4). The compaction derived from the subsidence data combined with the direct measurements of the compaction at reservoir level provides an extensive data set, which was used by NAM in the development and calibration of a strain based seismological model.

Alternatively a seismological model could also be formulated based on the subsurface stress and stress changes. Geomechanical modelling of seismicity on faults and fault systems in the Groningen field requires detailed knowledge of the stress distribution in the vicinity of these fault systems. However, since the stress data for Groningen field is very sparse, calibration of such a model would be problematic and result in a model relative unconstrained by data.

This report provides an overview of all stress data available for the Groningen field.

References:

1. An activity rate model of induced seismicity within the Groningen Field, (Part 1), Stephen Bourne and Steve Oates, February 2015.
2. An activity rate model of induced seismicity within the Groningen Field, (Part 2), Stephen Bourne and Steve Oates, June 2015.
3. Regularised direct inversion to compaction in the Groningen reservoir using measurements from optical levelling campaigns, S.M. Bierman, F. Kraaijeveld and S.J. Bourne, March 2015.
4. In-situ compaction measurements using gamma ray markers, Pepijn Kole, June 2015

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Place in the Study and Data Acquisition Plan	Study Theme: Seismological Model / Geomechanics Comment: In the development of the seismological model (Ref. 1 and 2) extensive use is made of the very rich data set of subsidence and compaction for the Groningen field. The subsidence data set consists of several acquisition methods: levelling surveys, satellite measurements and GPS stations. It covers the period from 1963 to the present day. Several methods have been developed to estimate the reservoir compaction from the subsidence data (Ref. 3). Additionally, compaction is monitored in the reservoir using observations well (Ref. 4). The compaction derived from the subsidence data combined with the direct measurements of the compaction at reservoir level provides an extensive data set, which was used by NAM in the development and calibration of a strain based seismological model. Alternatively a seismological model could also be formulated based on the subsurface stress and stress changes. Geomechanical modelling of seismicity on faults and fault systems in the Groningen field requires detailed knowledge of the stress distribution in the vicinity of these fault systems. However, since the stress data for Groningen field is very sparse, calibration of such a model would be problematic and result in a model relative unconstrained by data. This report provides an overview of all stress data available for the Groningen field.				
Directliy linked research	(1) Seismological Models (2) Subsidence and compaction studies. (3) Geomechanical studies.				
Used data	Data description.				
Associated organisation	NAM				
Assurance	Internal Review and with Shell/PTU.				

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1 Introduction

Both the magnitudes and the directions of the principal stresses are key parameters for designing and drilling of possible infill wells in the Groningen Field and can provide a better understanding of possible reactivation of faults in and surrounding the reservoir of the Groningen Field. This note describes the current state of knowledge on principal stresses in and surrounding the Groningen reservoir. A review was performed of previously reported information on the stresses, also including the latest data from the geophone wells ZRP-2 and 3. The results were derived from various sources, like minifrac data, Leak-off tests (LOT), earthquake focal mechanisms, image logs, cores and sonic scanner. Furthermore, legacy drilling data was inspected to obtain information on losses in the reservoir.

Chapter 2 of this report describes the available data to retrieve possible values for the magnitudes of the three total principal stresses. Chapter 3 presents an overview of the possible directions for the horizontal stress.

2 Principal stress values

Almost any geomechanical study requires knowledge on the values for the principal stress components. This chapter outlines the possible sources and data that contain information on principal stress values in the Groningen reservoir. In this report we assume that the direction of the maximum principal stress is aligned with the vertical axis of the earth, therefore also both the intermediate and the minimum principal stresses have a direction in the horizontal plane. This assumption is confirmed by van Gent et al. (2009) by mapping Late Tertiary faults that evolved from a stress system with a near vertical direction for the maximum principal stress.

2.1 Vertical stress

The vertical stress is considered to be the maximum principal stress in a normal faulting structural domain and can be calculated by the integration of the rock density over the depth. This calculation requires the existence of (near) complete density logs over the full well trajectory.
Yan and Guises (2013) documented the most complete investigation of the vertical stress for the Groningen field. Bad sections and incomplete section for the density log were filled in using the Gardner equation (Gardner, 1974). Thirteen wells were investigated showing a variation of the vertical stress gradient between 2.19 and 2.35 SG at a reference level of 3000m TVDGL (ground level) or TVDNAP (NAP: Normaal Amsterdams Peil). This difference in vertical stress gradients is mainly caused by Zechstein salt thickness variations.

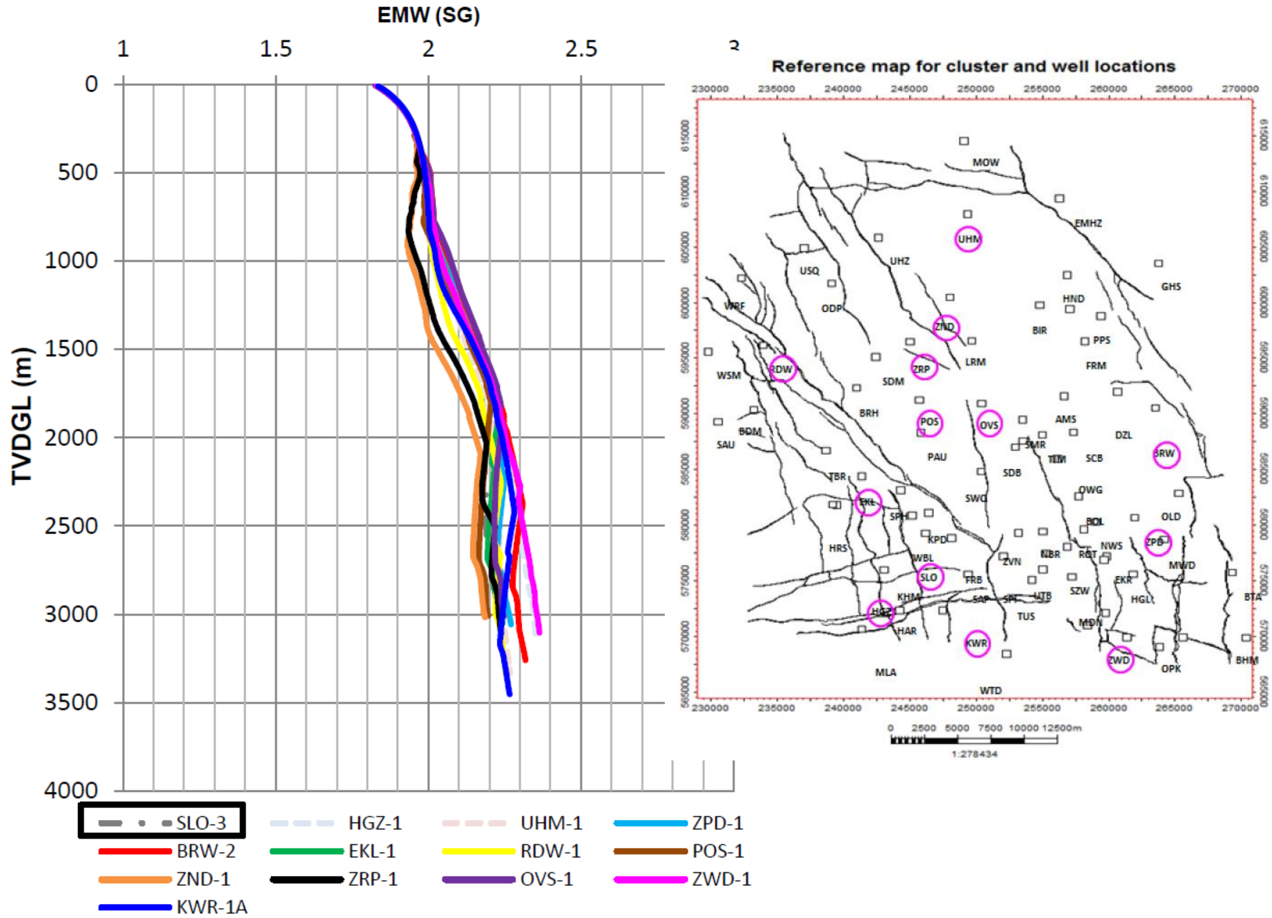

Figure 1 **Vertical stress gradients (SG) for thirteen wells in the Groningen area. The overburden gradient varies from 2.19-2.35 SG at 3000m TVDGL (from Yan and Guises, 2013). To the right a map of the Groningen field showing the locations of the wells.**

2.2 Minimum total horizontal stress (S_h)

Perhaps the most important geomechanical parameter is the value of the minimum principal stress. As pointed out before, we assume that its direction is within a horizontal plane.

2.2.1 Information from minifrac tests

In the past, stress values from minifrac data were reported by Bouts (2000) Hettema et al. (2000) and Schutjens et al., (2001). These authors reported fracture closure pressures from minifrac tests, where it is generally assumed that the fracture closure pressure that can be deduced from the tests best represents the magnitude of the minimum principal stress. The most detailed report on these values, including a visualization of the uncertainty, is given in Hettema (2000). All mentioned publications refer to three minifrac tests done in the Groningen field. However, these publications do not mention that ZLV-6 was not drilled into the Groningen reservoir, but in the Annerveen field, south of the Groningen field. All authors mention as well that the virgin stress points (points within the red circle in Figure 2) originate from a source other than a minifrac test. According to Bouts (2000) the virgin data points were derived from leak-off tests, while Hettema et al. (2000) and Schutjens et al. (2001) suggested that the values were based on mud losses during drilling (see Figure 3).

Considering the importance, this apparent contradiction in the description of the data prompted a more thorough investigation into the origin of the values, to derive possible conclusions on the validity of these points. The investigation is presented in detail in Appendix A. The main conclusion from this investigation is that the only minifrac tests done in Groningen are the tests in Zand-12 at two different levels of the ROSLU (Riezen and Bohm, 1986). They were done in the same period at a constant pore pressure and therefore depletion level. It is also concluded that the one reported value was obtained from a minifrac test performed in another field (ZLV-6 in the Annerveen field), while the two other values were deduced from a different source. No minifrac information is available from the wells drilled in the first 20 years of the lifetime of the field, implying that mud losses are the only source for stress information. Examination of possible mud losses led to the unfortunate conclusion that the values of the virgin stress mentioned in these reports or publications need to be rejected because of wrong interpretation of the losses events. The losses happened either in a different zone of the well (Uiterburen-7), at an unclear depth (Spitsbergen-205) or in the case of Slochteren-1, may not have happened at all as no record of a loss event could be found in the weekly drilling report.

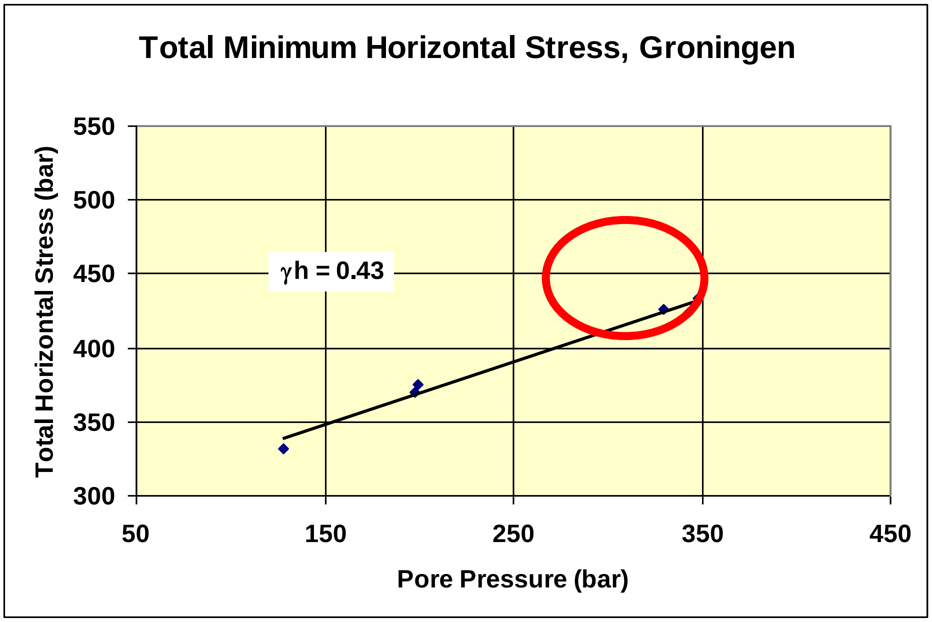

Figure 2 Stress information from LOT tests (points within the red circle) and minifrac tests from wells in the Groningen field (Bouts, 2000), the γh in the document is the slope of the straight line and refers to the depletion constant.

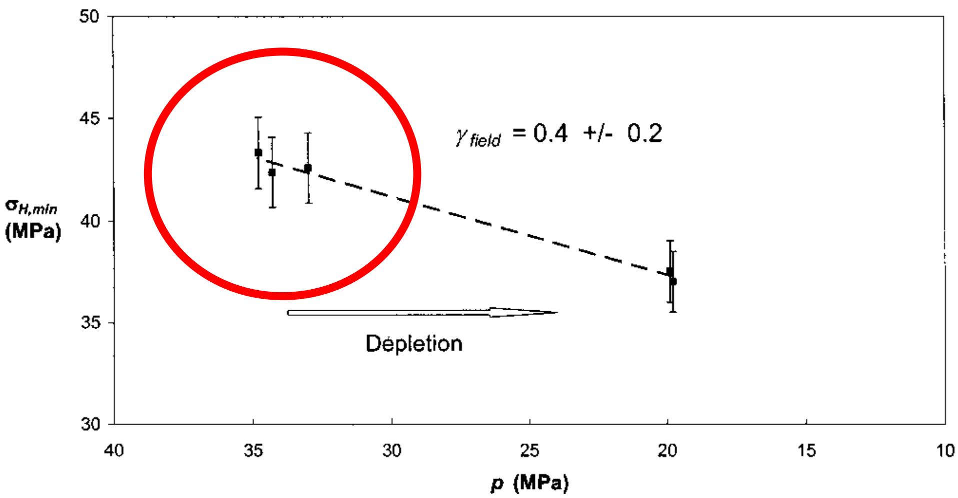

Figure 3 Stress information from losses (points within the red circle) and minifrac tests from wells in the Groningen field (Hettema, 2000).

2.2.2 Information from drilling losses

With the absence of minifrac tests and leak-off tests in the reservoir at virgin condition, possible losses in the first wells drilled in the field could reveal information on Sh. After the discovery of the field, a drilling campaign was carried out to construct the southern clusters in the Groningen field. The wells in these clusters were drilled at the moment the reservoir was still in a virgin pore pressure situation, indicated by the static pressure data for this period of time presented in Figure 4. This figure shows that irst signs of depletion appeared in 1968.

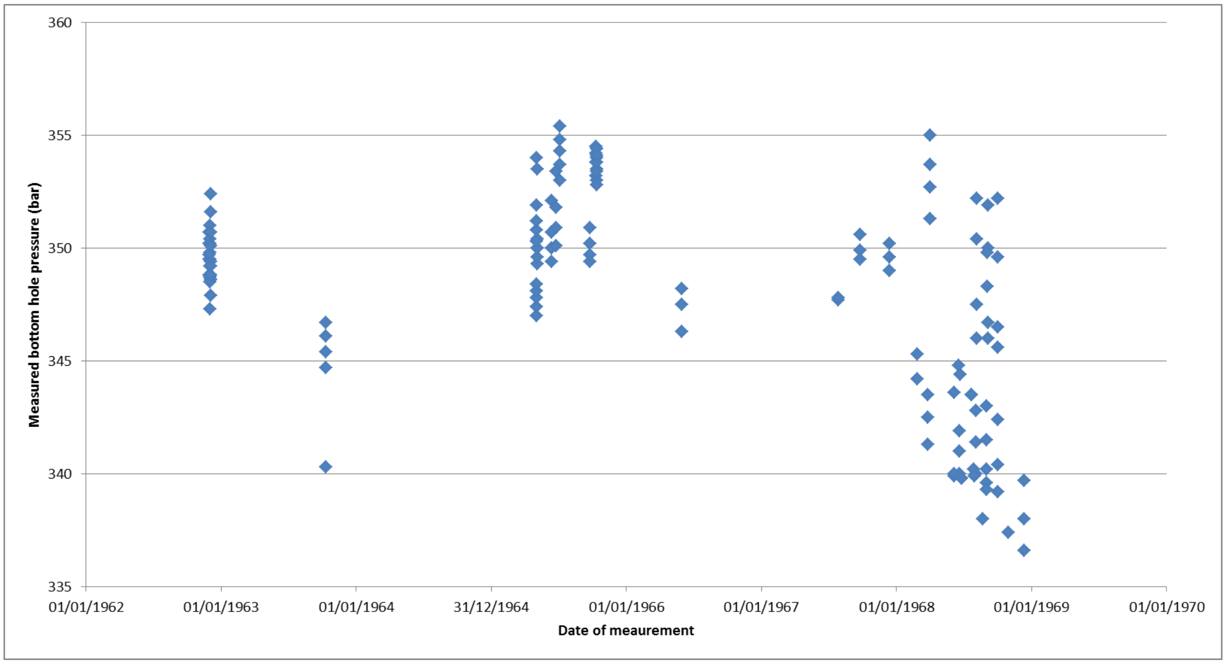

Figure 4 **Measured bottomhole pressures in the Groningen field between 1962 and 1969.**

Possible loss circulation events from wells drilled before 1968 could therefore give information on the virgin stress of the field. The weekly drilling reports for these first 72 wells were examined for possible losses and results are presented in Figure 5. Seven out of 72 wells reported losses in the Slochteren Group (RO) or in the Carboniferous Limburg Group (DC). If the mechanism behind the losses was a mechanical failure of the borehole wall or reopening of existing fractures, one would expect that the losses occur dominantly at higher mud weights. However observing the data in Figure 5 we can conclude that there seems to be no relation between losses and mud weights as losses were observed over the full range of mud weights. Moreover it is unlikely that the stress can reach values as low as 1.35 sg in a field with ambient pressures at a depth of 3 kilometer. It is more likely that mud was lost in high permeability zones (high in-situ permeability, open faults, fractures) knowing that all wells were drilled with an overbalance according to a maximum virgin pore pressure gradient of around 1.28 sg. This implies also that it is difficult to characterize the cause for the losses in the Slochteren-2 well, which experienced losses at a mud weight of 1.55 sg. Even in this case it could well be possible that the losses were caused by flow into a high permeability zone without causing mechanical failure or reopening of existing fractures (the mechanism that possibly could be connected to a value of the minimum total principal stress). Therefore we conclude that no information on stress can be extracted from losses events in these wells.

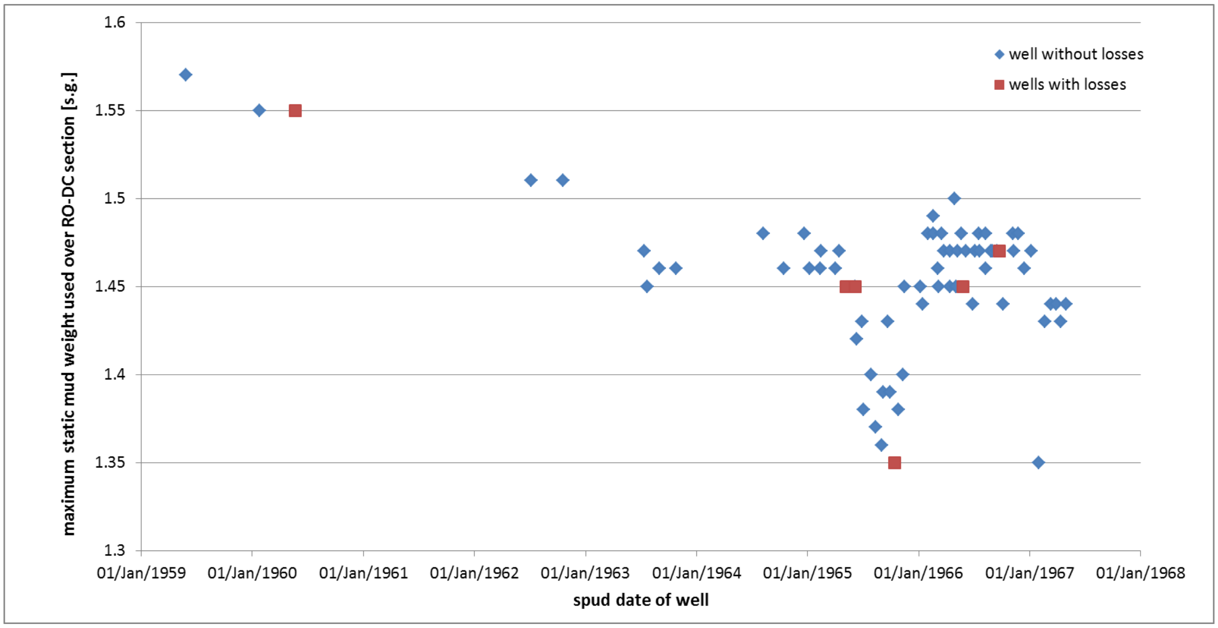

Figure 5 **Maximum static mud weight reported over the RO and DC section for the first 72 wells drilled in the Groningen RO reservoir.**

2.2.3 Losses event in 't Zandt-11B

The well 't-Zandt-11B was drilled as a sidetrack from the 't-Zandt-11A well. The potentially undepleted sand streaks of the Ten Boer Member above the reservoir required a relative high mud weight of 1.36 sg to drill the depleted (100-120 bar pore pressure) reservoir as well. Seepage losses were observed during drilling but these losses were all manageable. The manageable losses were followed by a total losses event after a clean out trip and led finally to abandonment of the well.

The total losses event was investigated by Roggeband and van Eijs in 2012. An ECD (Equivalent Circulating density) calculation (black thick horizontal line in Figure 6) showed that the losses appeared around the value of the predicted fracture breakdown gradient. Further analyses showed as well that the losses stabilized at an annulus pressure of around 327 bar, a value that confirmed the predicted value for the minimum horizontal stress using the actual measured data for the well after drilling. We assumed in this case that the losses were connected with a mechanical failure of the well where a substantial fracture was developed. Because of the abandonment of the well no further acquisition could be performed to confirm that assumption. The losses stopped at a value of around 310 bar and in our opinion this point can be accepted as a value for the minimum total stress albeit with a high "best guessed uncertainty" of around 20 bar.

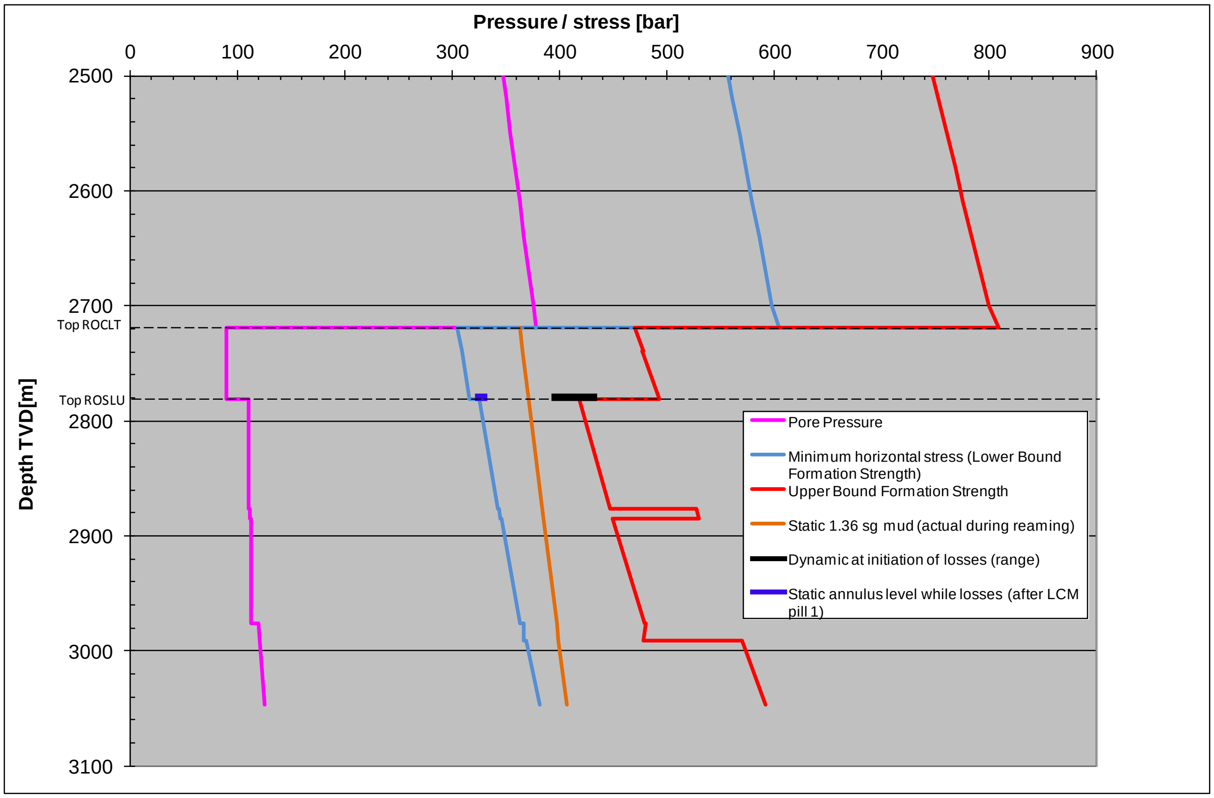

Figure 6 Mud weights during drilling and during and after the losses event compared to the prediction of Sh and fracture breakdown pressure based on the measured pore pressure and actual well inclination and azimuth.

2.2.4 Losses event in Zeerijp-2

Severe losses are reported in 2014 for the Zeerijp-2 geophone monitoring well during drilling of the reservoir section. Two formation strength tests were executed after the losses event to investigate at which mud pressure leakage is observed (Kole, 2015) by increasing the surface pressure. Both tests show a mud pressure gradient of around 1.31 bar/10m just before leak-off and far above the pore pressure gradient. These values can be considered to represent the reopening pressure of an existing natural or induced fracture and therefore close to the value of the minimum stress. This value was higher than expected prior to the incident (1.1 bar/10m) and could point to a higher value of the (local) ambient stress before production or to a lower value for the (local) depletion constant.

2.2.5 Borgsweer-5 minifrac test

The water injection well Borgsweer-5 was drilled in 2013 in the eastern part of the Groningen field. The urge for more data led to the decision to do a full logging program over the open hole section including image logging and a circumferential sonic tool (Sonic Scanner from Schlumberger) that could give a value for the ratio between the vertical stress and minimum stress. Outcome of this analysis will be described in the chapter on stress directions. To get the values for the horizontal principal stress it was decided to do a minifrac test as well. Two (out of two) cycles gave the same value of 395 ± 5 bar for the fracture closure pressure while a depletion of 150 bar was measured (van der Bas, 2013).

2.2.6 Conclusion

The number of data points reflecting a possible value for the minimum total stress is extremely limited as presented in Figure 7. The value for both an average field depletion constant as an average field virgin stress value cannot be extracted from these four data points. The spread in the data might be explained by local variation of both the value of ambient stress and/or the value of the depletion constant.

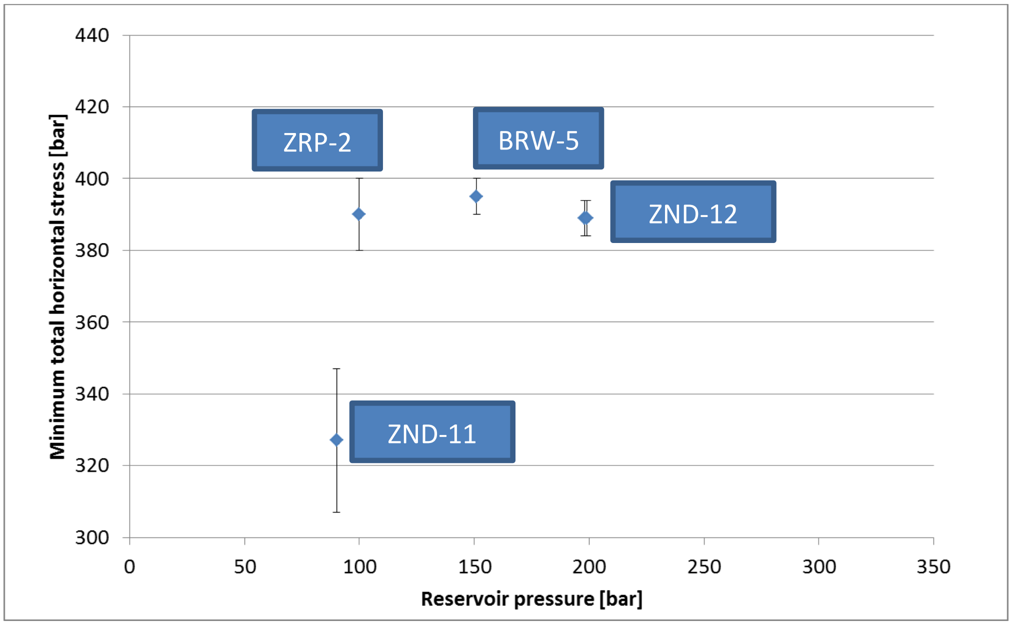

Figure 7 Minimum total stress data points in the Groningen field. BRW-5 and ZND-12 are based on minifrac measurements while the other points are based on the interpretation of a losses event.

2.3 Intermediate principal stress or maximum horizontal stress (S_H)

The intermediate stress magnitude cannot be measured directly but needs to be inferred using information on the value of the other two principal stresses and, in the case of breakouts, the strength of the rock. Legacy data is mainly based on differential strain analysis on core material. More recently, a circumferential sonic tool was used in the Borgweer-5 injection well and Zeerijp geophone wells, drilled in the period 2013-2015. Also in 2013 GMI-Baker Hughes conducted a break-out analysis on legacy image logs providing an estimate of the SH magnitude.

2.3.1 SH/Sh ratio based on differential strain analysis

The magnitude of the maximum horizontal stress is “guestimated” (according to Veeken et al. 1990) for 5 plugs from a core taken in well ‘t-Zandt-9 from differential strain analysis (DSA). Both DSA as ASR (anelastic strain recovery) are techniques to determine in-situ stress directions from strain measurements on recovered and oriented (!) core material. Both methods assume that the neotectonic in-situ stress state affects the deformational characteristics of the rock (de Bree, 1988). In DSA the relaxed core (in the laboratory) is subjected to a hydrostatic pressure and the strains in different directions are measured in compression as a function of applied pressure. Different amounts of strain in different direction would reflect the state of stress, where the most compressible horizontal direction is aligned with the maximum horizontal stress. The main purpose of the method is to find the direction of the horizontal stress components ,but the method was also used for the derivation of stress magnitudes assuming that all anisotropy is fully controlled by subsurface stress and not by intrinsic or compositional anisotropy. The DSA analysis for ‘t Zandt showed values between 1.22 and 1.42 for the compressibility ratio of CH (or compressibility in the direction of the maximum horizontal stress) over Ch (or compressibility in the direction of the minimum total stress) with an average of 1.32.

According to de Bree, 1988 this ratio links to the effective stress (σ') and total stress:

$$\sigma'_H = \frac{C_H}{C_h} \cdot \sigma'_h \quad and \quad \sigma'_H = \sigma_H - P,\ \ \sigma'_h = \sigma_h - P \qquad (2)$$

For a CH/Ch ratio of 1.32 this results in the following equation.

$$\sigma_H = 1.32 \cdot (\sigma_h - P) + P = 1.32 \cdot \sigma_h - 0.32 \cdot P$$

For a virgin pressure and an assumed minimum virgin stress gradient of 1.6 bar/10m this results in an estimate of the SH/Sh ratio of around 1.07. Applying the variance in the measured ratios and an uncertainty of 0.1 bar/10m for the minimum virgin stress gradient, the range for the ambient stress ratio is between 1.04 and 1.09.

Sample	Depth (m)	Pressure Interval (MPa)	Orientation θ_H (E of N)	Pressure Interval (MPa)	C_V/C_h	C_H/C_h
1	2934.25	1-25	43	7-11	2.3	1.42
2	2937.77	1-20	-6	5-11	2.4	1.22
4	2943.39	1-25	-36	7-10	2.1	1.38
5	2945.65	1-22	1	1-25	1.9	1.26

Figure 8 DSA interpretation of 't-Zandt-9 (from Veeken et al., 1990).

2.3.2 SH/Sh ratio based on sonic scanner in the Borgsweer- 5 well

The Sonic Scanner that was run in the Borgsweer-5 calculates the stress anisotropy from circumferential slowness anisotropy analysis. Tahi et al. (2013) give an overview of the data and interpretation and concluded that shear anisotropy can be seen in the following intervals:

Interval MD (m)	Formation/ member	Direction SH	Stress ratio SH/Sh
2455-2463	RBSHM	Non conclusive	Non conclusive
2475-2497	RBSHM	NE003	Non conclusive
3050-3190	ROSL	N-S	1.04-1.09

2.3.3 SH/Sh ratio based on sonic scanner in the Zeerijp-2 well

Weatherford's CXD dipole sonic tool was run over the RO/DC section to obtain possible information on the horizontal stress anisotropy. There is limited information on the quality of the data and analysis but a value of 2 to 3 % anisotropy is mentioned in the conclusions by Weatherford (2015).

2.3.4 SH/Sh ratio based on sonic scanner in the Zeerijp-3A well

Weatherford's CXD dipole Sonic tool was run in very favorable conditions for anisotropy analysis (vertical well and in gauge). The data quality is good and show consistent results over the whole interval. The anisotropy values obtained are on average of 2-4% over the interval from 3540.0-3731.0 m AHRT (ROSL) and interpreted as stress induced features.

2.3.5 SH/Sh ratio based on borehole break-out inversion

Breakouts were identified for two well near the Groningen field. GMI-Baker Hughes conducted an inversion study for the breakouts in the ROCLT and DC formations observed in KWR-1A and RDW-1. Stress ratios (SH/Sh) varied between 1.08 and 1.19 using the GMI SFIB^{TM} software (Zheng and Guises, 2013).

2.3.6 Conclusion

All investigations show a relative low anisotropy for the two horizontal stress components. It is noted that some of the methods used are based on assumptions that are difficult to validate.

3 Stress directions

In-situ stress direction can be inferred from borehole breakouts using image logs, oriented caliper and sonic scanner interpretation. Earthquake focal mechanisms are an important source as well, but when derived from an induced seismic event they are likely to be affected by induced stresses not necessarily aligned with the ambient tectonic stresses. Still these observations form a useful source for calibrating geomechanical models.

3.1 Stress direction from image logs (legacy data)

Image logs in a (near) vertical well can reveal information on a possible horizontal anisotropic stress field (Plumb and Hickman, 1985, Brudy and Kjørholt, 2001) when it is assumed that one of the principal stress directions is aligned parallel with the vertical axis. Previously an enquiry in the NAM database was performed for image logs in the Groningen area. This approach was pursued and reported by van Eijs and Dalfsen (2004) where stress directions were mapped for the available image and oriented caliper data in the Netherlands. In addition a search was performed for additional Groningen Field data. All paper logs and films have been digitally scanned in NAM and this database was queried for the following image log tools: ast, cbil, star, fms, ubi, fmi. Besides breakout information, useful information can be derived from source mechanism information from the induced seismic events themselves (Dost et al, 2012), also described in this note.

Six wells in the Groningen area (Wildervank-4, Rysum-Z-1, Rodewolt-1, Oude Pekela-2, Kiel-Windeweer-1, Bierum-13) were found to contain image log data. Only two of these (Rodewolt-1 and Kiel-Windeweer-1) contained clear expressions of breakouts. Kiel-Windeweer -1 has a good quality image and shows breakouts over multiple sections. 132 sections were picked by the contractor and statistics is presented in Figure 9. An example of a section is visible in Figure 10.

Mean	69
Standard Error	0
Median	69
Mode	70
Standard Deviation	5
Range	41
Minimum	56
Maximum	97
Sum	9135
Count	132

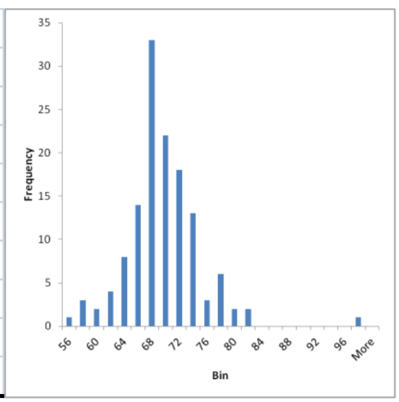

Figure 9 Basic statistics of the Kiel-Windeweer-1 breakout picks.

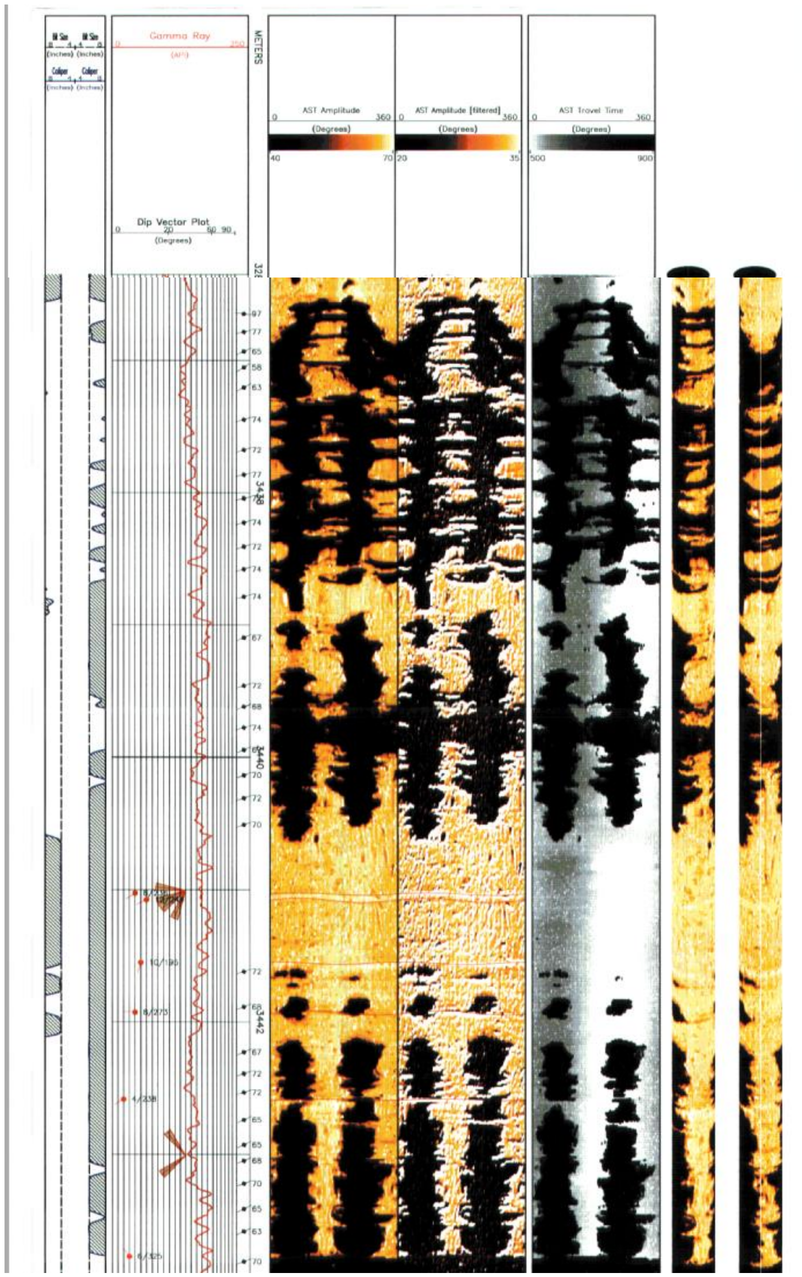

Figure 10 **Part of the Kiel-Windeweer-1 image log showing a consistent pattern of breakouts.**

The average direction for the SH this data is 160° (or 340°). The Rodewolt-1 well contained poor data for only three sections of breakouts. An estimated direction for the SH in this well is 155°-335°. The SH directions that were retrieved from these wells are plotted in Figure 12.

3.2 Stress direction from CMI measurements in Zeerijp-2

Weatherford's Compact microimager (CMI) was run in the 5" section of the Zeerijp-2 geophone well (Weatherford, 2015). Breakout sections were observed in the more shaly intervals (GR>50 api) showing a consistent direction in NE-SW directions. This direction is aligned with the regional stress where the maximum horizontal stress direction is around 310°.

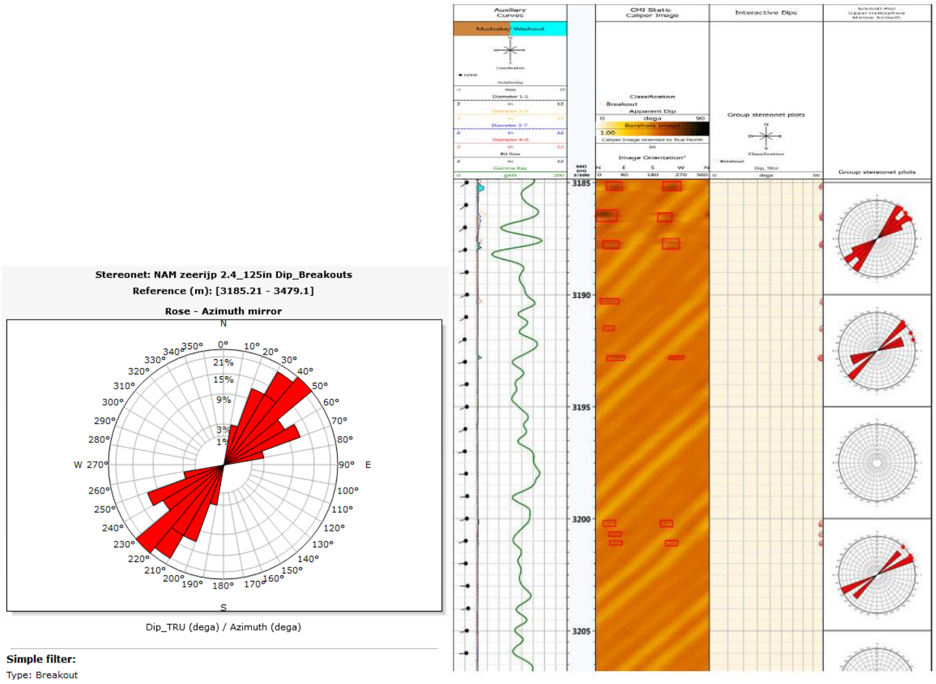

Figure 11 Left: Rose diagram of breakout directions. Right: Example breakouts appearing in the 5" section of the well Zeerijp-2.

3.3 Stress direction from acoustic and image logs in Zeerijp-3A

Zeerijp-3A is a microseismic monitoring well (like Zeerijp-2) drilled in the northwestern part of the Groningen field. One of main objectives of extensive logging is to estimate the in situ stress orientation and identify intervals of stress induced anisotropy across the ROCLT, ROSL and DC (6" section) by both a circumferential sonic (CXD) and microimager tool (COI). The results of COI microimager and CXD sonic processing and analysis are summarized below (Ishmukhametova, 2015):

- During interpretation the intervals of borehole breakouts and ovalization /elongation in Ten Boer and Carboniferous, and intervals of drilling induced fractures in Carboniferous were identified with the main direction of SH to be 323° NW- 143° SE (induced fractures direction) and the main direction of Sh to be 245° SW - 65° NE (breakout direction)
- CXD sonic processing, anisotropy interpretation and dispersion analysis were done by Weatherford. Anisotropy direction - Fast Azimuth direction SH is 345° NW – 165° SE.
- Stress orientation from COI and CXD data are consistent and follow the orientation of the SH in the nearby area

3.4 Stress direction from oriented core measurements

The main objective of differential strain analyses is to obtain the direction of the principal stresses, in this case the direction of the maximum horizontal stress (Veeken, 1990). Figure 8 summarizes the results for ‘t-Zandt-9, showing a range of directions from 334° to 43° having an average of 1° with respect to the North.

3.4.1 Oude Pekela-2

Anelastic strain recovery (ASR) data has been obtained from a core taken from the Rotliegendes reservoir section in the Oude Pekela-2 well. The well is drilled in a block that is disconnected, like Kiel-Windeweer, from the Groningen main block. Both on-site as well as laboratory ASR experiments have been performed to get an estimate of the direction of the principal strain directions. In a homogeneous sandstone one would expect that these directions are aligned with the directions of the principal stresses as well, which is assumed in the report by Halliburton (1991). All measurements point consistently to a direction of the intermediate principal strain or stress that is orthogonal to the regional stress field. The azimuth (degrees east of north) varies between 34° to 47° with an average direction of around 40°.

3.5 Stress direction from oriented caliper

This paragraph summarizes the borehole breakout analysis performed for selected (close or in the Groningen field) wells with available oriented four-arm caliper logs. The selected wells are near vertical (except for BRW-5 with maximum inclination of 20°). Criteria for data QC are aligned with those suggested by the World Stress Map Project (Reinecker et al., 2003).

Table 1 summarizes the available data and interpretation results. Out of the 30 wells checked, only two wells have interpretable breakouts, i.e. Beerta-1 and Norg-Zuid-1. Borehole breakouts observed in these two wells point to East-West SHmax azimuth (approximately 90° in Beerta-1 and 120° in Norg-Zuid-1). The breakout observed in Beerta-1 occurs in the Main Claystone Member of the Lower Germanic Trias Group just above the Zechstein salt. Therefore active diapirism can have a local effect on the stress direction in the Main Claystone Member. Farmsum-1 only showed hole enlargement in the salt formation, whereas the other wells either had no clear breakouts (Westbeemster-1, Wildervank-4 and Zuidbroek-1) or did not allow a consistent interpretation of the data (Blijham-2 and Winsum-1). Caliper logs and borehole breakout picks for each well are given in Appendix 1.

3.6 Conclusions for stress direction

All information on stress direction in the Groningen is visualized in one map (Figure 12) together with existing information retrieved from wells in the neighboring fields and published on the world stress map. The new data in the map point out that the stress direction is more variable than expected. The scarcity of data doesn’t allow for the definition of trends in certain regions of the field. Any geomechanical model should account for this uncertainty.

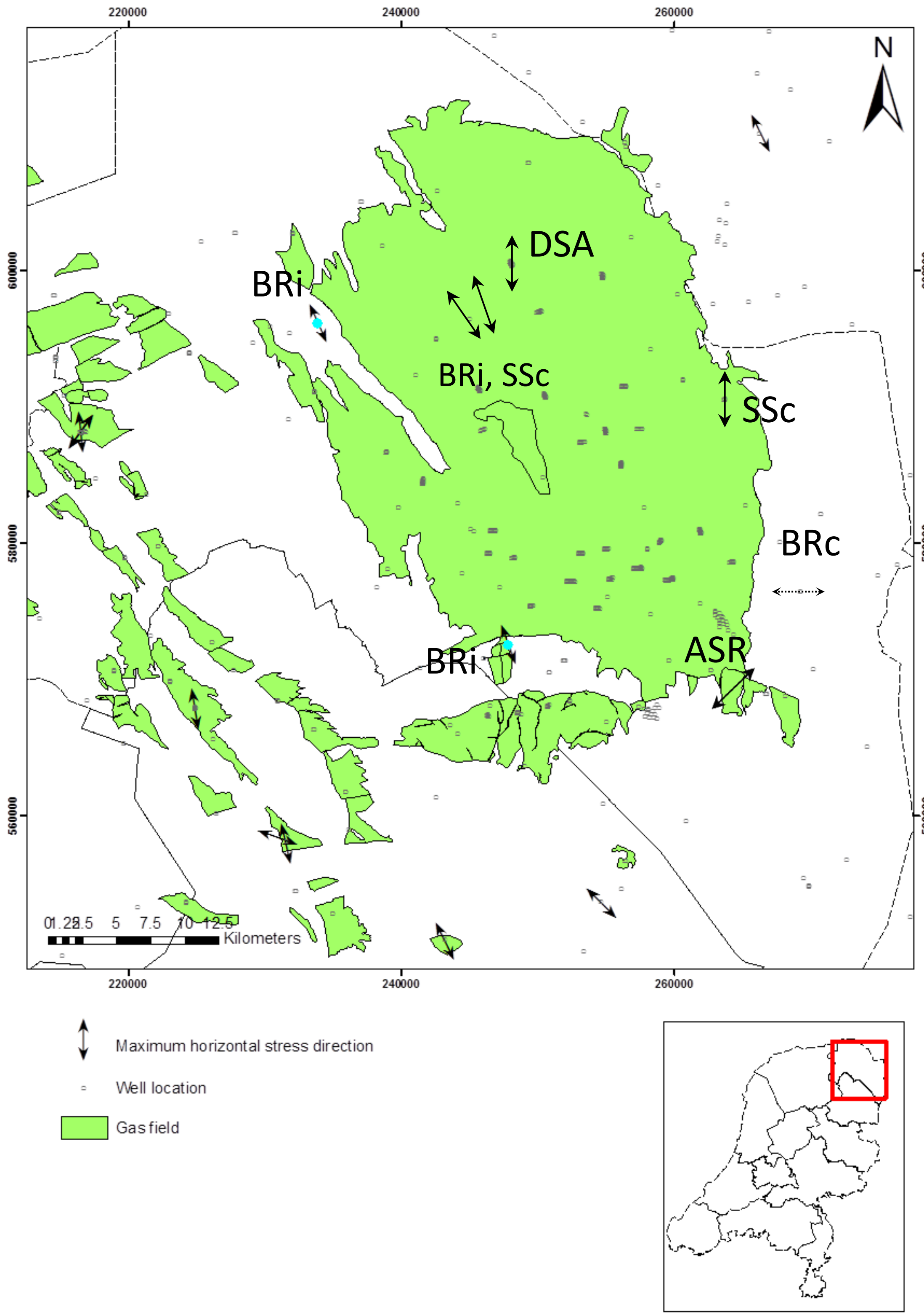

Figure 12 SH directions for the Groningen area. Data was taken from formations below the Zechstein except for the data point in Beerta-1A (dotted E-W arrow) which was observed in the Triassic section above the salt. Abbreviation used in this figure: BRi: Breakout from image logs; BRc Breakout from cailiper logs; ASR anelastic strain recovery measurements; DSA differential strain analysis; SSc sonic scanner measurement.

3.7 Focal mechanisms

Focal mechanisms of natural earthquakes are the major source of stress information for the compilation of the world stress map [(www.world-stress-map.org).](http://www.world-stress-map.org) Dost et al. (2012) found solutions for 4 "Groningen" induced events showing a normal faulting mechanism at a steeply dipping fault with a strike of around 290° (uncertainty is 20°). One event fit best to a normal fault with a strike of 325° (Figure 13). The use of focal mechanisms retrieved from induced events to interpret virgin stress conditions is less trivial. Induced events are caused by stress perturbations as a result of gas production. The observations agree however with a model having a normal stress condition, with a NW-SE direction for the maximum principal stress and where the events are induced on faults at the reservoir level. This information aligns with information retrieved from the image and sonic data in that area.

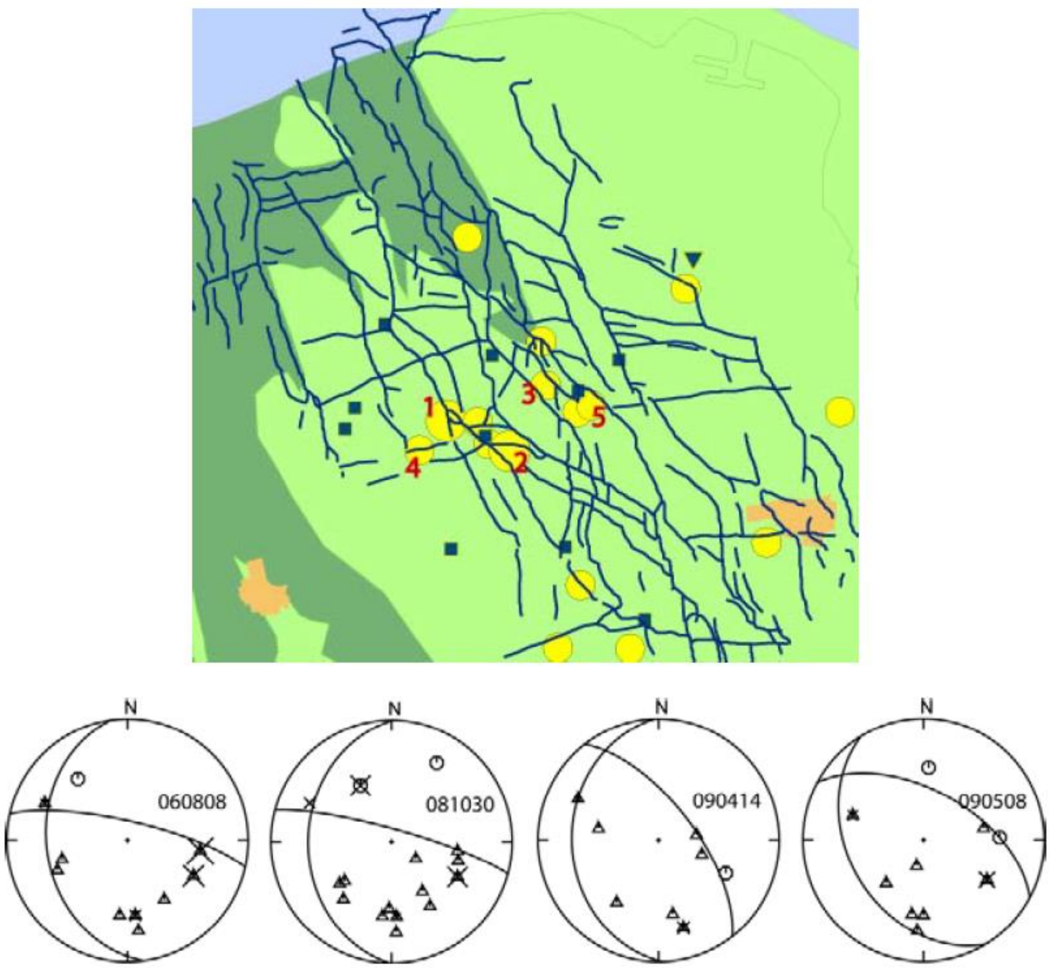

Figure 13 Earthquake mechanisms for 4 earthquakes in the Groningen field and their location. 1=060808, 2=081030, 4=090414, 5= 090508. For event 3 (090201) no stable solution was found. Circles denote positive polarities, triangles negative polarities. Amplitude ratio's are indicated with a cross (source, Dost et al., 2012).

4 Conclusions

The conclusions on stress value and direction information available for the RO and DC formations of the Groningen field are summarized below:

- Vertical stress values derived from density logs for thirteen wells show values between 2.19 and 2.35 SG at a reference level of 3000m TVDGL.
- The number of data points reflecting a possible value for the minimum total stress is limited to only 4 data points. Neither an average field depletion constant or an average field virgin stress value could be extracted. The spread in the data might be explained by local variation of both the value of ambient stress and/or the value of the depletion constant.
- The value for the maximum horizontal total stress is derived from indirect measurements. Observation from various methods pointed to a relative low stress anisotropy for the two horizontal stress components.
- Data retrieved from distinct sources indicate that the stress direction is variable. The scarcity of data does not allow for the definition of trends in certain regions of the field.
- Stress direction from focal mechanism is aligned with regional stress data from other sources.
- An overview of all data is presented in Table 1. Map coordinates in RD projection are given for the location of the total well depth.

Table 1 Overview of the data used in this study

Well	Well spud [year]	test type	Formation	TD easting (RD)	TD Northing (RD)	depth mTVDNAP	pore pressure [bar]	value Sh [bar]	Sh gradient [sg]	SH/Sh	SH orientation degree from north
BRW-5	2013	circumferential sonic	RO	263894	591205	various	151			1.07	0
BRW-5	2013	Minifrac	ROSL	263894	591205	3060	151	395	1.32		
KWR-1a	1997	image log	RO/DC	247476	572354	various	382			1.12	160
OPK-2	1990	anelastic strain recovery	ROSL	263896	568990	2981	330				40
RDW-1	1998	image log	RO/DC	233986	596180	various	352			1.12	155
t Zandt -1b	2010	losses	ROSL	248300	600082	2780	110	310	1.14		
t Zandt-12	1986	Minifrac	ROSL	247713	600613	2840	199	373	1.34		
t Zandt-9	1976	DSA	ROSL	248434	600727	2855	240			1.07	1
ZRP-2	2014	circumferential sonic	RO	243881	596057	various	100			1.03	
ZRP-2	2014	image log	RO	243881	596057	various	100				130
ZRP-2	2014	losses	ROSL	243881	596057	2968	100	390	1.34		
ZRP-3	2015	circumferential sonic	RO/DC	246630	596798	various	93			1.03	165
ZRP-3	2015	image log	RO/DC	246630	596798	various	93				149

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Appendix A
Investigation of reported losses events in wells Uiterburen-7, Spitsbergen-205 and Slochteren-1

Uiterburen-7

This well was spudded in 1970 while the field was mildly depleted with 20 bar according to the information in Bouts (2000). The 9 5/8" open hole section was run from top chalk to TD in the Carboniferous. Losses in the Zechstein Group after a flow were reported in daily drilling reports and in the end of well report. The values of around 1.5 s.g. at the moment that the losses were stopped are typical for pore pressure values in this area and therefore the losses are more an indicator for the pore pressure in an open fracture system than an indicator for stress. More losses in this well were reported when they ran in the last casing but it wasn't mentioned where these losses happened but it is likely that these losses happened in the same Zechstein section. The conclusion is that no stress information could be retrieved for this well.

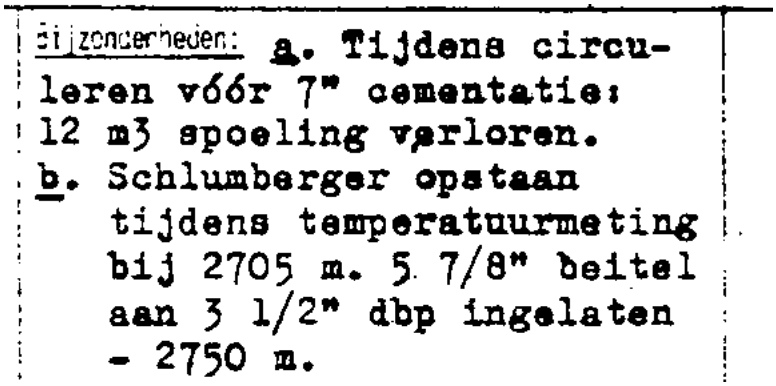
30.5. ●	2572 2576 2584	Zout + anhydriet Anhydriet Kalksteen dolomi- tisch	Geboord - 2584 m. Put loopt over. Gereedschap opgetrokken, put ingesloten. Standpipe druk 0 kg/cm2. Back pressure druk 10 kg/cm2. Doodgepompt met spoeling s.g. 1,45 (min. s.g. vergaste spoeling 1,06). Put geopend. Gecirculeerd. Tijdens circuleren spoelingsverliezen (totaal ± 70 m3) s.g. opgelopen tot 1,50 door ontgassen van de spoeling. Spoeling geconditioneerd en mica toegevoegd. Gereedschap getrokken tot 2012 m. Spoeling: 1,45-49-(20-10-1/3)-2,4-300-0,5-13-19-22.

Bijzonderheden:
Tijdens 9 5/8" boren gaswerking
± 70 m3 spoelingverlies
s.g. verhoogd van 1,38 - 1,45
put dood.
Gekernd van 2688,1 - 2711,1 m.
Geen opbrengst door versleten
kernvanger.
Bij einde inlaten 7 5/8" casing ± 20 m3 spoelingverlies.

Figure 14 Reports from the losses seen in uiterburen-7. The first report refers to losses in the Zechstein. The second report below mentions losses while running in the casing without knowing the location of the losses. No other losses and no values of a LOT test were reported.

Spitsbergen-205

The daily drilling reports mention losses of 12 m^3 when the last casing section was run in while flushing the hole and annulus. No depth position of the losses was mentioned and it is possible that the losses happened at the weakest spot of the open hole section somewhere in the Chalk Group.



Bijzonderheden: a. Tijdens circu-
leren vóór 7" cementatie:
12 m3 spoeling verloren.
b. Schlumberger opstaan
tijdens temperatuurmeting
bij 2705 m. 5 7/8" beitel
aan 3 1/2" dbp ingelaten
- 2750 m.

Figure 15 Drilling report mentioning the losses before the cementation of the 7” casing

There are no reports on a leak-off test done for this well so no stress information can be deduced for the ROSLU from this information.

Slochteren-1

This well was the discovery well for the Groningen field and was drilled in 1959. The last 6”section was drilled from the bottom formation of the Zechstein (ZEZ2C) to TD in the ROSLU. The maximum mud weight that was used was 1.56 sg but there are no comments in the drilling reports that refer to losses. Therefore it is unknown why this well selected to serve as a reference point for stress information. It is likely that this well was interchanged with the losses observed in the Slochteren-2 well.

Appendix B
Borehole breakout picks.

Table 2 Available data and SHmax orientation from borehole breakouts.

Well	Inclination (degrees)	Formations covered by caliper log	Oriented 4-arm caliper available?	SHmax orientation
Andel-6	33		Yes	
Beerta-1	1	From Main claystone to Carboniferous	Yes	90 ˚
Bierum-13	45		Yes	
Bierum-13A	32		Yes	
Bierum-13B	40		Yes	
Blijham-2	9		Yes	Data do not make any sense
Blijham-4	29		Yes	
Blijham-5B	34		Yes	
Blijham-6	3			
Borgsweer-5	20	From Lower Buntsandstein to Z1 Carbonate	Yes	No clear breakout
De Eeker-5	17		No	
De Paauwen-6	8		No	
Eemskanaal-12	20		No	
Farmsum-1	47		Yes	
Farmsum-1A	19	From Lower Zechstein salt to Upper Rotliegend Group	Yes	Hole enlargement in salt
Farmsum-1C	57		Yes	
Hoogenweg-1	14		No	
Kolham-1	38		Yes	
Lekermeer-1			No	
Norg-4	39		Yes	
Norg-5	32		No	
Norg-Zuid-1	7	From Z2 Carbonate to Carboniferous	Yes	120 ˚
Oude Pekela-2A	45		No	
Sappemeer-15A	14		No	
Stadskanaal-1	24		Yes	
‘T Zandt-12B	15		No	
Vierhuizen-2	50		Yes	
Westbeemster-1	5	From Z1 Lower Anhydrite to Carboniferous	Yes	No breakout

Well	Inclination (degrees)	Formations covered by caliper log	Oriented 4-arm caliper available?	SHmax orientation
Wildervank-4	9	From Z1 (Werra) to Carboniferous	Yes	No clear breakout
Winsum-1	14		Yes	Data do not make any sense
Zuidbroek-1	1	From Slochteren (ROCYM Unit) to Carboniferous	Yes	No clear breakout
Zuidwending-2A	49		Yes	

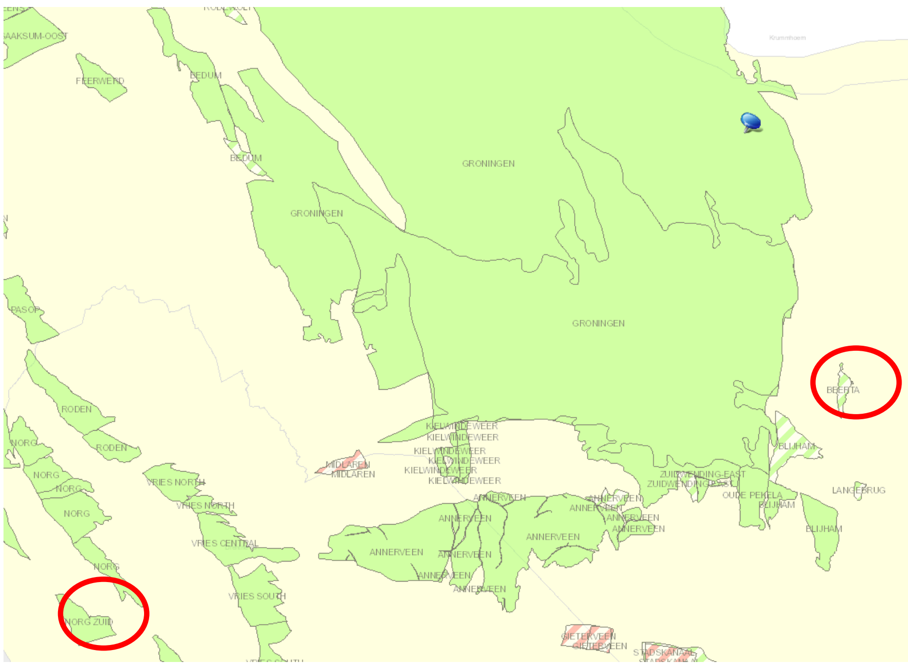
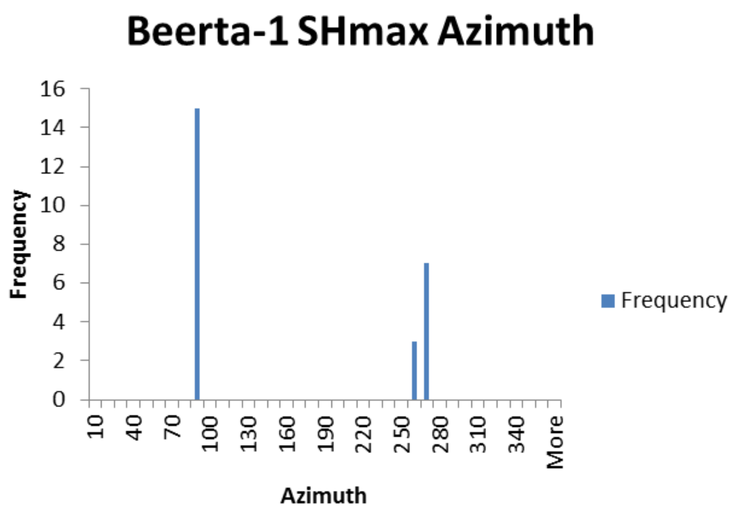
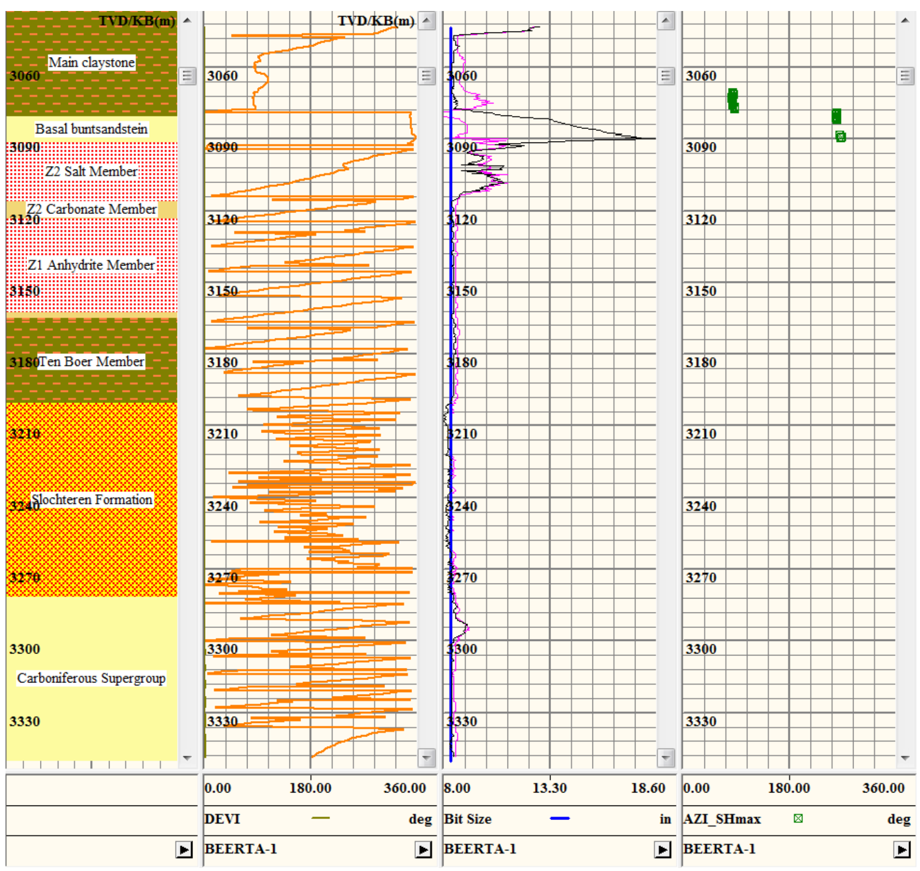


Figure 16 **Location of wells with interpreted breakouts.**

Beerta-1


Beerta-1 SHmax Azimuth
Frequency
Azimuth
16
14
12
10
8
6
4
2
0
10
40
70
100
130
160
190
220
250
280
310
340
More
Frequency


TVD/KB(m)
Main claystone
Basal buntsandstein
Z2 Salt Member
Z2 Carbonate Member
Z1 Anhydrite Member
Ten Boer Member
Slochteren Formation
Carboniferous Supergroup
3060
3090
3120
3150
3180
3210
3240
3270
3300
3330
0.00
180.00
360.00
DEVI
deg
BEERTA-1
8.00
13.30
18.60
Bit Size
in
BEERTA-1
0.00
180.00
360.00
AZI_SHmax
deg
BEERTA-1