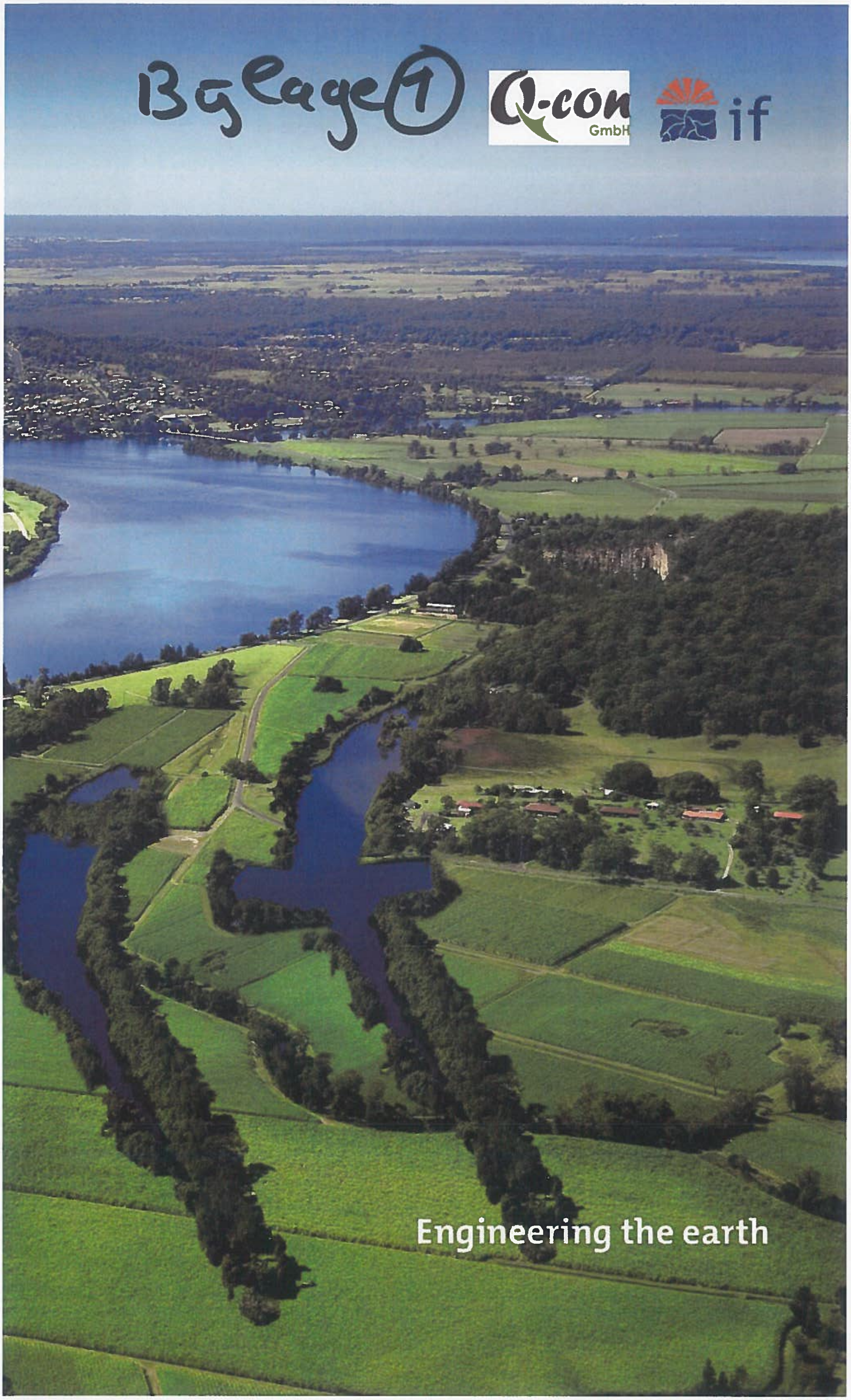
Overzicht gedeelde rapporten SodM

Nr	Oplevering	Bureau	Titel
1	31-mei-16	Q-con /IF Technology bv	Hoofdrapport Seismic Hazard Analyse
2	27-jul-16	SGS	Proposal SRA
3	29-jul-16	Q-con /IF Technology bv	Offer Geothermical Study ant TLS Design for the Depleted Scenario
4	12-aug-16	Q-con	Geomechanical Study and TLS Design IRP
5	12-aug-16	Q-con /IF Technology bv	Definition of depletion scenarios
6	29-aug-16	Q-con /IF Technology bv	Offer Geomechanical Study additional work
7	13-sep-16	SGS	Proposal SRA, sensitivity Analyses
8	23-dec-16	SGS	SRA Phase 1 summary Report
9	15-mrt-17	SGS	SRA Phase 2 summary Report



Hoofdrapport Seismic Hazard Analyse

Geothermie WarmteStad Groningen

Q-con GmbH

if

Engineering the earth

Hoofdrapport Seismic Hazard Analyse

Geothermie WarmteStad Groningen

Hoofdrapport Seismic Hazard Analyse

Geothermie WarmteStad Groningen

Opdrachtgever **WarmteStad**
Griffeweg 99
Postbus 1
9723 DV GRONINGEN
T 050 367 8746 | E @WarmteStad.nl
Contactpersoon: de heer

Adviseur **IF Technology bv**
Velperweg 37
Postbus 605
6800 AP ARNHEM
T 026 @iftechnology.nl
Contactpersoon: de heer

Colofon **Auteur:**
Versie: Definitief 1.0
Gecontroleerd door: de heer
Vrijgegeven door: de heer

Paraaf:

Inhoudsopgave

Samenvatting

WarmteStad BV is voornemens een geothermie systeem te realiseren om duurzame warmte te kunnen leveren aan het toekomstige Warmtenet Noordwest. Eén van de risico's die WarmteStad wil uitsluiten is het risico op seismiciteit als gevolg van haar geothermische operatie.

IF Technology en Q-con hebben in opdracht van WarmteStad een onderzoek uitgevoerd om de kans op seismiciteit te evalueren. Belangrijkste vragen zijn of er seismiciteit kan optreden en of dat risico met beheersmaatregelen kan worden gemitigeerd.

Er zijn twee belangrijke scenario's voor het reservoirblok waarin het geothermisch systeem gerealiseerd wordt. Uit het onderzoek blijkt dat deze scenario's apart van elkaar benaderd moeten worden:

- non-depleted: in het reservoirblok heerst de oorspronkelijke reservoir druk, er is geen sprake van beïnvloeding door het Groningen gasveld.
- depleted: in het reservoirblok is (enige mate van) drukdaling opgetreden als gevolg van de gasproductie in het Groningen gasveld.

Onze verwachting is dat er niet of nauwelijks beïnvloeding door het Groningen gasveld is (non-depleted). Om hierover zekerheid te krijgen zou een put geboord moeten worden tot in het reservoir.

Het non-depleted scenario is op een kwantitatieve manier uitgewerkt volgens bestaande en gebruikelijke methoden. Het depleted scenario is kwalitatief uitgewerkt, omdat door de unieke combinatie van mechanismen (depletie én geothermische operatie) die bestaande en gebruikelijke methoden niet bruikbaar zijn.

De conclusie voor het non-depleted scenario is dat de kans op seismiciteit minimaal is. Mocht seismiciteit toch optreden, dan kan worden ingegrepen ruim voordat de seismiciteit ongewenste gevolgen heeft. Daardoor is er in dit scenario geen sprake van een veiligheidsrisico. Hiervoor dient dan een beproefd monitoring systeem ingericht worden, een zogenaamd "Traffic Light System" (TLS).

Binnen de scope van dit onderzoek geldt dat voor het depleted scenario de kwantificering van de effecten door de unieke combinatie van mechanismen niet mogelijk is. Met de kwalitatieve benadering, welke binnen dit onderzoek voor het depleted scenario is gehanteerd, is het niet mogelijk een TLS te ontwerpen dat geschikt is om het risico op

seismiciteit te mitigeren. In de bestaande opzet van een TLS kan een dergelijk monitoring systeem op voorhand ook geen uitsluitsel geven over de oorzaak van de eventuele seismiciteit: depletie door het Groningen gasveld en/of de geothermische operatie (wie is verantwoordelijk?). Hierbij is van belang dat WarmteStad geen invloed heeft op de depletie als gevolg van de gaswinning.

De verwachting is echter dat een kleine depletie niet of nauwelijks extra risico oplevert. Echter, omdat het niet kwantificeerbaar is kan geen onderbouwde maximale depletie aangeven worden, waarbij het risico op seismiciteit klein geacht wordt en waarbij een TLS zou kunnen werken. De ervaringen van de NAM onderbouwen de verwachting dat de kans op seismiciteit bij injectie in depleted reservoirs klein is.

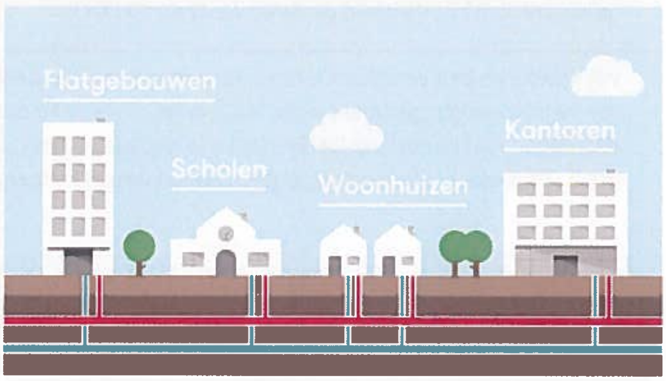
Wij adviseren een vervolgonderzoek te starten in samenwerking met seismiciteits-experts van het Groningen gasveld (zoals TNO) en een evaluatie uit te voeren van de NAM ervaringen met betrekking tot de injectie in depleted reservoirs. Een dergelijk onderzoek is gecompliceerd, echter beide zouden meer uitsluitsel kunnen geven.

1

Inleiding

1.1 Geothermie WarmteStad Groningen

In Groningen is men voornemens het Warmtenet Noordwest te realiseren. Met het Warmtenet Noordwest kan duurzame en lokale warmte worden geleverd aan meer dan 10.000 huishoudens en wordt jaarlijks 19.800 ton CO_2 bespaard. De warmte wordt geleverd door heet water uit de diepe ondergrond, geothermie of aardwarmte genoemd.
Het warmtenet is een project van WarmteStad, het gezamenlijke duurzame nutsbedrijf van gemeente Groningen en Waterbedrijf Groningen. Het is de bedoeling om in 2018 de eerste warmte te leveren aan vooral woningen in Paddepoel en Selwerd en aan kennisinstellingen op Zernike.



Op basis van reeds uitgevoerde onderzoeken blijkt dat geothermie in Groningen technisch haalbaar is, maar dat er nog wel onzekerheden en risico's zijn. In de huidige fase van de projectontwikkeling wil WarmteStad die risico's beter in kaart brengen. Eén van de mogelijke risico's is het veroorzaken van seismiciteit tijdens de operationele fase, zogenaamde "induced seismicity".

1.2 Onderzoek naar seismiciteit door IF en Q-con

In opdracht van WarmteStad heeft IF Technology in samenwerking met Q-con een onderzoek uitgevoerd naar de risico's op seismiciteit als gevolg van geothermie. Het adviesbureau IF Technology is een specialist op het gebied van energie en ondergrond. IF heeft diverse geothermie studies uitgevoerd en realisaties begeleidt. Het Duitse adviesbureau Q-con is een specialist op het gebied van seismische studies en seismische monitoring. Q-con is betrokken bij de seismische monitoring van een aantal Nederlandse geothermie projecten.

Het doel van het onderzoek was een analyse naar de kans op het voorkomen van seismiciteit als gevolg van de geothermische operatie (de hiervoor gebruikte Engelse benaming is Seismic Hazard Analysis: SHA).

Het uitgangspunt is dat een analyse wordt uitgevoerd van de kans dat de seismiciteit zich voordoet. De bovengrondse gevolgen van deze eventuele seismiciteit, zoals schade of veiligheidsrisico's maken geen onderdeel uit van de analyse. Het achterliggende idee is dat significante seismiciteit moet worden voorkomen en daarmee ook de daaraan gekoppelde risico's.

Buiten de scope van de opdracht zijn de maximaal verwachte magnitudes in worstcase situaties berekend en zijn de mogelijkheden geëvalueerd om eventuele risico's op seismiciteit middels beheersmaatregelen (Traffic Light System) te mitigeren.

1.3 Aanpak onderzoek en uitgevoerde deelonderzoeken

IF en Q-con hebben in eerste instantie een quick scan uitgevoerd op de voorgenomen geothermische operatie door WarmteStad. Op basis van deze quick scan zijn een aantal aandachtspunten en scenario's vastgesteld.

Voor het reservoirblok, waarin het geothermisch systeem wordt gerealiseerd, zijn twee belangrijke reservoirdruk scenario's onderscheiden:

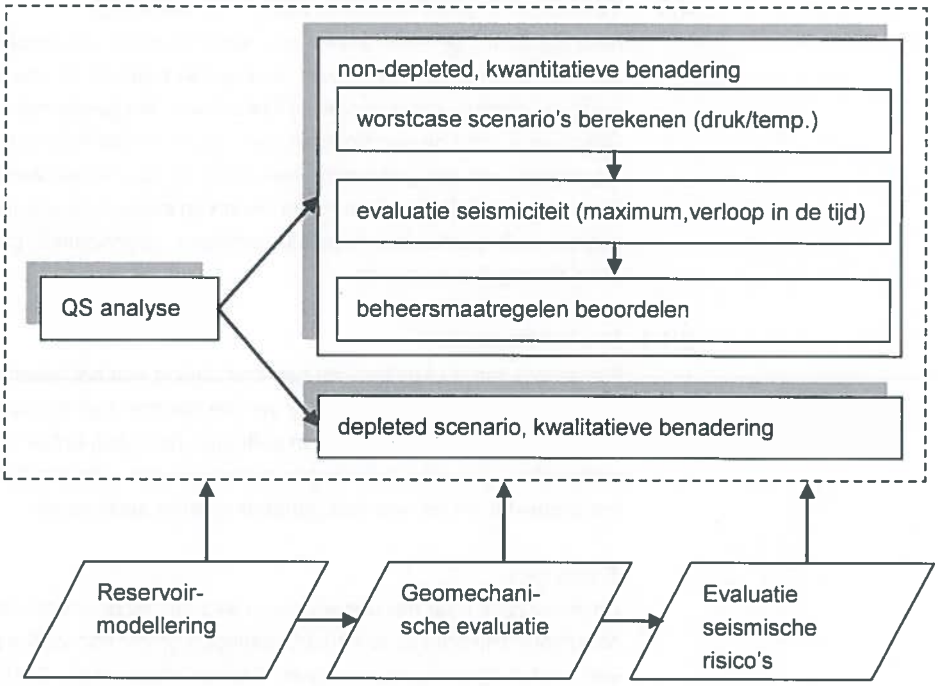
- non-depleted: in het reservoirblok heerst de oorspronkelijke reservoir druk, er is geen sprake van beïnvloeding door het Groningen gasveld.
- depleted: in het reservoirblok is drukdaling opgetreden als gevolg van de gasproductie in het Groningen gasveld.

Het non-depleted scenario is uitgewerkt volgens bestaande en gebruikelijke methoden: De worstcase situaties voor het non-depleted scenario zijn gekwantificeerd. Op basis van die resultaten is bepaald of seismiciteit kan optreden en of de eventuele risico's gemitigeerd kunnen worden door middel van een Traffic Light System (monitoring op seismiciteit in combinatie met beheersmaatregelen als enige mate van seismiciteit wordt waargenomen).

Het depleted scenario is kwalitatief uitgewerkt.

In het hoofdrapport is gebruik gemaakt van de resultaten uit 3 verschillende deelonderzoeken:

- Reservoir modellering:
  Dit onderzoek zou oorspronkelijk worden uitgevoerd door de RUG. Om praktische redenen heeft IF dit in overleg met de RUG en WarmteStad middels een aanvullende opdracht zelf uitgevoerd. Dit onderzoek was nodig om de maximaal verwachte druk- en temperatuurveranderingen als gevolg van de geothermische operatie te berekenen. Daarnaast is in dit deelonderzoek een analyse gemaakt van de aanwezigheid en doorlatendheid van de breuken.
- Geomechanische evaluatie:
  Deze evaluatie is bedoeld om te bepalen hoe kritisch het breuksysteem rondom het projectgebied is en vanaf welke stressverandering de breuken in het projectgebied gereactiveerd kunnen worden en daarmee seismiciteit kunnen veroorzaken.
- Evaluatie van de seismische risico's en mitigerende maatregelen.
  Op basis van de resultaten uit de bovengenoemde deelonderzoeken, literatuur, ervaringskentallen en algemeen toegepaste protocollen is een analyse gemaakt van:
  - de kans op seismiciteit,
  - de maximale seismiciteit in de worstcase situatie en
  - de mogelijkheden om dit risico te mitigeren.



1.4 Hoofdrapport

De voorliggende rapportage is het hoofdrapport. In dit hoofdrapport zijn de belangrijkste stappen in het onderzoek en de belangrijkste resultaten en conclusies verwoord. De genoemde deelonderzoeken zijn apart gerapporteerd en opgenomen als bijlagen bij het hoofdrapport.

De bedoeling van het hoofdrapport is dat WarmteStad in één goed leesbaar rapport de belangrijkste informatie kan terugvinden. Dit betekent dat niet alle details uit de deelonderzoeken zijn opgenomen in het hoofdrapport. Die zijn te vinden in de bijlagen.

2

Quick Scan Analyse

2.1 Welke mechanismen zijn van belang

Seismiciteit wordt veroorzaakt door verschuivingen van geologische afzettingen of gesteentes langs een breukvlak. Bestaande breuken zijn zwakke plekken in het gesteente. Voor de vorming van een nieuwe breuk moet het gesteente eerst worden gebroken. Daardoor is voor de vorming van een nieuwe breuk meer kracht nodig, dan voor het reactiveren van een bestaande breuk. Als er seismiciteit wordt veroorzaakt, dan gaat het daarom vrijwel altijd om het reactiveren van bestaande breuken. Bij het reactiveren van bestaande breuken door menselijk ingrijpen (zogenaamde geïnduceerde seismiciteit) zijn er twee belangrijke oorzaken:

2.1.1 Drukverlagingen

Als gevolg van drukdaling kan samendrukking van het reservoir optreden, ook wel compactie genoemd. Ter plaatse van de breuken kunnen daardoor spanningen ontstaan, zeker als er een groot verschil in zettingen nabij een breuk ontstaat (differentiële compactie). Als deze spanningen te ver oplopen, dan kan dat leiden verschuivingen langs het breukvlak en de hiermee gepaard gaande seismiciteit.

Ervaringen

Uit onderzoek naar het optreden van seismiciteit door drukdalingen bij gaswinningen in Nederland blijkt dat alleen bij drukdalingen groter dan 28% van de initiële reservoirdruk seismiciteit is waargenomen (van Thienen-Visser et al., 2012). In het Groningen gasveld ligt deze grens aanzienlijk hoger, namelijk op 54% (van Wees et al., 2015).

Vertaling naar geothermie WarmteStad Groningen

In seismische analyses voor geothermie projecten wordt meestal geen focus gelegd op de drukdaling als gevolg van de productie. De drukdaling is in de meeste gevallen te beperkt om een mechanisme als "differentiële compactie" te veroorzaken.
Op basis van de ervaringsgetallen is voor de locatie van het geothermie minimaal een drukdaling van ruim 100 bar (28%) of 200 bar (54%) nodig voordat seismiciteit veroorzaakt zou kunnen worden. De drukdaling bij 200 m³/uur is volgens de Doubletcalc berekeningen van TNO (2015) in een ongunstig scenario (P90) 50 bar in de productieput. Bij de breuken op enige afstand van de productieput is de drukdaling echter al aanzienlijk minder. Hieruit volgt dat de drukdalingen die worden veroorzaakt door het beoogde geothermie systeem geen seismiciteit zullen veroorzaken als gevolg van "differentiële compactie".

2.1.2 Drukverhogingen (injectiedruk)

Bij een verhoging van de waterdruk in een breuk kunnen beide zijden van het breukvlak als het ware uit elkaar worden geduwd en wordt de weerstand tegen verschuiving langs het breukvlak verlaagd. Door het verhogen van de waterdruk in de breuk kan verschuiving langs de breuk en dus seismiciteit optreden.

Voor seismiciteit analyses bij geothermie projecten wordt dan ook de focus gelegd op dit mechanisme.

2.1.3 Afkoeling

In de injectieput wordt afgekoeld water geretourneerd. Dit kan gevolgen hebben voor de spanningen op de breuken. Dit is nog niet meegenomen in deze quick scan en is verder uiteengezet in paragraaf 3.2.2.

2.2 Aanpak quick scan

Voor de quick scan naar het risico op seismiciteit bij een op geothermische operatie zijn de beschreven ervaringen door Evans et al. (2012) als uitgangspunt genomen.

De ervaringen met geïnduceerd seismiciteit bij het injecteren van vloeistoffen in het kader van geothermie en CO_2-opslag in Europa zijn door hem beschreven. Hierbij is voor 41 locaties verspreid over Europa onderzocht in hoeverre seismiciteit is waargenomen. In de publicatie wordt geconstateerd dat:

- de kans op seismiciteit toeneemt als er sprake is van netto injectie: meer injecteren dan oppompen (en hoe groter de netto geïnfiltreerde hoeveelheid, hoe groter de kans);
- er geen voelbare seismiciteit is waargenomen op locaties met een lage natuurlijke seismiciteit;
- de kans op seismiciteit groter is bij injectie dichtbij of in een breukzone;
- op alle locaties met injectie in kristallijn gesteente seismiciteit is waargenomen (meestal niet schadelijk);
- in sedimentaire formaties op slechts 4 van de 25 locaties seismiciteit is waargenomen. Alle 4 de locaties injecteren in kalksteen. Van deze 4 locaties liggen er 3 in seismisch actief gebied en op de andere locatie wordt geïnjecteerd in een breuk direct boven de kristallijne basis;
- bij de 7 projecten waarbij wordt onttrokken en geïnfiltreerd (geen netto injectie) in zandsteen reservoirs is geen seismiciteit waargenomen;
- bij netto injectie in van zandsteen reservoirs (reservoir stimulatie) zijn alleen zeer lage magnitudes (< 0) gemeten.

Naast de ervaringen beschreven door Evans et al. zijn door Zoback (2012) richtlijnen beschreven om het risico op seismiciteit bij de injectie van restwater te beheersen. De belangrijkste adviezen zijn om niet te injecteren in actieve breukzones (komt overeen met constatering Evans et al) en de injectiedruk te beperken. Daarnaast wordt aangegeven een seismologisch meetnetwerk te installeren, en beheersmaatregelen vast te stellen die worden uitgevoerd als een bepaalde mate van seismiciteit wordt gemeten. Hierbij is het uitgangspunt dat de seismiciteit in eerste instantie zeer zwak is en geleidelijk in sterkte toeneemt. Als een vooraf gestelde sterkte wordt overschreden dan wordt ingegrepen om te voorkomen dat ongewenste gevolgen optreden.

Samengevat zijn de belangrijkste indicatoren die de kans op seismiciteit verhogen:

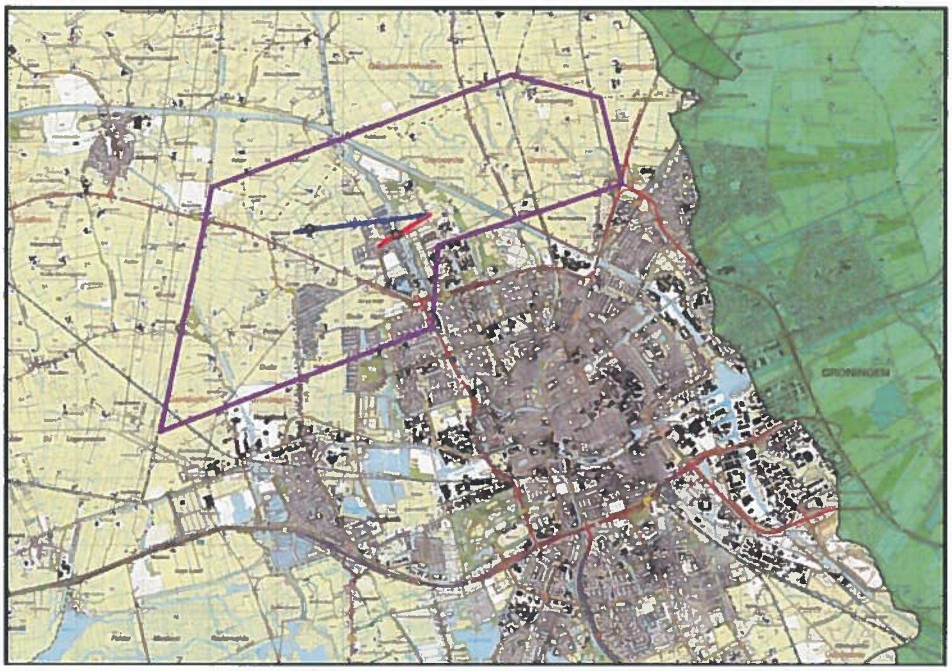
- tektonisch actief gebied;
- injectie direct in een breuk;
- netto injectie (dus minder oppompen dan injecteren)
- injectie in een kristallijn gesteente (weinig risico in een sedimentaire afzetting zoals een zandsteen);
- hoge injectiedrukken.

In het vervolg van deze paragraaf is op quick scan niveau het project geëvalueerd naar deze risico indicatoren die seismiciteit door de geothermische operatie kunnen veroorzaken.

2.3 Het geothermie systeem

2.3.1 De putlocaties

Om de winning van aardwarmte mogelijk te maken worden twee putten aangelegd tot een diepte van ongeveer 3,5 km. De put die wordt gebruikt voor het onttrekken van het hete water wordt de producer (productieput) genoemd. De put die wordt gebruikt voor het terugvoeren van het afgekoelde water wordt de injector (injectieput) genoemd. De locaties en de beoogde boortrajecten van de putten zijn weergegeven in Figuur 1 (de ondergrondse locaties van de putten komen uit het detail ontwerp (WEP, 2014)).



Figuur 1
Beoogde boortrajecten van de producer (rode lijn) en injector (blauwe lijn). Beide boringen worden vanaf dezelfde oppervlaktelocatie gestart. De zwarte cirkels op beide lijnen laten zien waar de bovenkant van het reservoir wordt aangeboord. Het gebied van de opsporings-vergunning is paars omlijnd. Het groene gebied oostelijk van de stad is het Groningen gasveld.

2.3.2 Operationele aspecten

WarmteStad Groningen heeft aangegeven dat het systeem is uitgelegd op maximaal 200 m³/h, maar de werkelijke debieten gedurende de geothermische operatie variëren. De opgepompte hoeveelheden zijn gelijk aan de geïnjecteerde hoeveelheden (er is geen sprake van netto injectie). Het systeem zal worden geëxploiteerd voor tenminste 30 jaar, waarbij het uiteindelijk de bedoeling is om zoveel mogelijk uren te draaien gedurende het jaar. De onttrekkingstemperatuur uit het reservoir is ca. 120 °C. De retourtemperatuur kan variëren en bedraagt minimaal 35 °C.

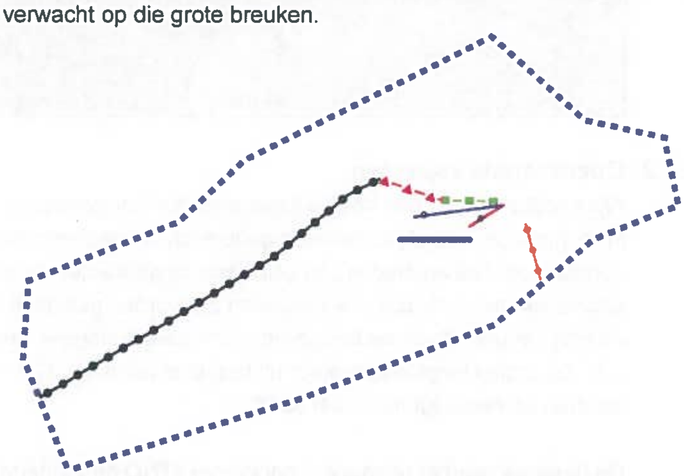
Op basis van eerder uitgevoerd onderzoek (TNO en Panterra) is geconcludeerd dat de injectiedrukken en verlagingen in de productieput redelijk groot zijn. Bij een P50 scenario (gemiddelde geologische eigenschappen) zijn in deze eerder uitgevoerde onderzoeken injectiedrukken berekend van ca. 165 bar bij een debiet van 230 m³ per uur. Bij een P90 scenario (slechte geologische eigenschappen van het reservoir) zullen vergelijkbare injectiedrukken optreden bij een debiet van 160 m³ per uur. Deze informatie bevestigt dat de doorlatendheid van het reservoir niet erg goed is en dat daardoor relatief hoge injectiedrukken nodig zijn tijdens geothermische operatie. Een hoge injectiedruk betekent meer kans op invloed nabij de breuken en dus op seismiciteit.

2.4 Geologie, natuurlijke seismiciteit en breuken

De warmte wordt gewonnen uit de Slochteren formatie. Dit is een zandsteen reservoir. Het is een vergelijkbaar reservoir als het reservoir van het Groningen Gasveld ten oosten van de projectlocatie.

Het geothermische project wordt in een niet-tektonisch actief gebied gerealiseerd. Natuurlijke seismiciteit komt hier niet voor.
De breuken in de directe omgeving lijken niet kritisch gestrest. Men spreekt van een lage "slip tendency", ofwel de breuken hebben een lage neiging om te gaan schuiven.

Het reservoirblok waarin de geothermie operatie plaatsvindt, is met breuken gescheiden van de naastgelegen reservoirs. Dit zijn de grotere breuken. De grotere breuken liggen ver verwijderd van de putlocaties, derhalve wordt geen invloed van het geothermie systeem verwacht op die grote breuken.



Figuur 2
Ligging van de grote breuken rondom het reservoirblok, waarin de geothermische operatie plaats vind (buitenste geblokte blauwe lijn) en de kleinere breuken binnen het reservoirblok (overige lijnen).

Binnen het reservoirblok liggen kleinere breuken. Deze breuken liggen nog op redelijke afstand tot de putten, maar worden mogelijk wel beïnvloed door de drukveranderingen die plaatsvinden als gevolg van de geothermische operatie (met name de breuken in het rood, groen en doorgetrokken blauw in figuur 2). Op basis van onze breuk analyse is het niet waarschijnlijk dat water direct in of zeer nabij een bestaande breuk geïnjecteerd wordt.

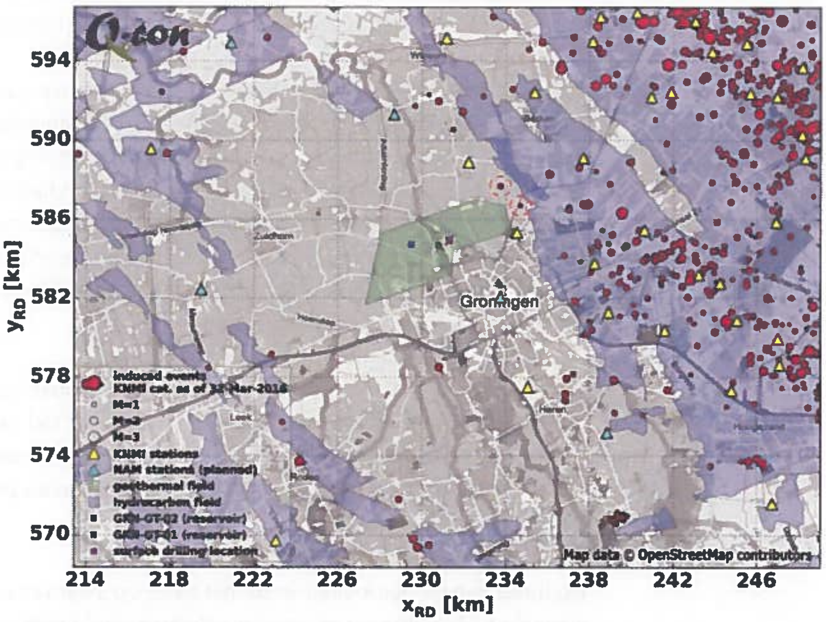
Op basis van de breuken analyse kan verder gesteld worden dat de breuken geen compartimentalisatie zullen veroorzaken, waarbij de injectie en de productie volledig van elkaar gescheiden worden. Er zal altijd drukcommunicatie zijn tussen de injectie en de productieput. Hieruit kan geconcludeerd worden, dat er geen netto injectie kan plaatsvinden in een door breuken begrenst compartiment.

2.5 Invloed van naastgelegen gasvelden

Ten oosten van het reservoirblok waarin de geothermische operatie plaatsvindt, ligt het Groningen Gasveld. Door de NAM wordt nog volop gas gewonnen uit dit gasveld. Op twee manieren kan het gasveld invloed uitoefenen op de geothermische operatie:

1) De gasproductie gaat gepaard met seismiciteit. Die seismiciteit kan ook voelbaar zijn in het geothermisch reservoirblok. Het is van belang dat er onderscheid gemaakt kan worden tussen eventuele seismiciteit die vanuit het Groningen gasveld is ontstaan en seismiciteit die is veroorzaakt in het reservoirblok zelf.

Figuur 3
Overzicht van door de gaswinning geïnduceerde seismiciteit



if Q-con GmbH

De bronlocaties voor seismiciteit liggen op grotere afstand van het geothermisch projectgebied. Verwacht mag worden dat bij een goed ontworpen monitoringssysteem de seismiciteit in het geothermisch projectgebied kan worden onderscheiden van de seismiciteit als gevolg van het Groningen gasveld.

2) Door de gasproductie wordt de druk in het Groningen gasveld verlaagd. Indien de grote breuken tussen het geothermisch reservoirblok en het Groningen gasveld enigszins permeabel zijn, dan ontstaat er een soort systeem van communicerende vaten. De druk in het geothermisch reservoirblok kan om die reden ook gedaald zijn. Er zijn geen rechtstreekse metingen in het geothermische reservoirblok beschikbaar. Uit een eerdere expertpanel discussie door TNO, RUG en WarmteStad is geconcludeerd dat een bepaalde mate van depletie niet nauwkeurig te bepalen is.
Met de combinatie van depletie en een geothermische operatie is geen ervaring. De te verwachte effecten zijn niet goed kwantificeerbaar en een reguliere ontwerp voor het monitoring beheerssysteem TLS ("Traffic Light System": een monitoringsbeheerssystemen) is hiervoor niet zomaar toepasbaar. Dit depleted scenario is derhalve als een apart scenario behandeld in hoofdstuk 4.

Opmerkelijk zijn wel de twee metingen ten noordoosten van de projectlocatie waar een niet voelbare seismiciteit is gemeten van 0,96 en 0,53 magnitude (met stippellijnen omcirkeld in figuur 3). De metingen liggen net buiten het Groningen gasveld, in een klein reservoirblok net boven het geothermisch reservoirblok. Het is onduidelijk of die bronmetingen door onnauwkeurigheid eigenlijk binnen het gasveld hadden moeten liggen, of dat het mogelijk een randeffect is op of in de grote breuk van het gasveld of dat er mogelijk toch significante depletie in dit blok naast het Groningen reservoir heeft plaatsgevonden welke die seismiciteit heeft kunnen veroorzaken.

Ten westen ligt het kleinere Pasop gasveld. Dit gasveld is niet meer in productie. Op basis van de ontrokken hoeveelheden gas is nagerekend dat de effecten op de rest van het reservoirblok slechts minimaal kunnen zijn. Er kan daarom geen significante depletie in het geothermisch reservoir blok ontstaan als gevolg van de productie uit dit gasveld.

2.6 Resultaten quick scan

Op basis van de quick scan wordt het risico op seismiciteit over het algemeen laag ingeschat, vergelijkbaar met andere Nederlandse geothermie projecten:

- In Groningen is sprake van een (zeer) lage natuurlijke seismiciteit.

- Er wordt niet direct geïnjecteerd in een breukzone;
- Er is geen sprake van netto injectie;
- Er is geen sprake van injectie in een kristallijn gesteente. Het betreft een sedimentaire afzetting: een zandsteen.

Risico verhogende aandachtspunten in dit project zijn:
- Een hoge injectiedruk als gevolg van een relatief slecht doorlatend reservoir in combinatie met hoge debieten. Hierdoor is de kans op stressveranderingen op de nabijgelegen breuken groter;
- De invloed van het naastgelegen Groningen gasveld en dan met name de kans dat hierdoor depletion in het geothermisch reservoirblok kan zijn opgetreden of nog kan optreden. Het is op basis van de huidige kennis en informatie niet mogelijk om de eventuele effecten van een combinatie van depletion en geothermische operatie te kwantificeren.

Voor de verdere SHA is besloten om de twee scenario's "non-depleted" en "depleted" los van elkaar te behandelen. In Hoofdstuk 3 wordt het non-depleted scenario uitgewerkt volgens bestaande en gebruikelijke methoden. De worstcase situaties voor het non-depleted scenario worden gekwantificeerd. Op basis van die resultaten is bepaald of seismiciteit kan optreden en of de eventuele risico's gemitigeerd kunnen worden door middel van een Traffic Light System (monitoring op seismiciteit in combinatie met beheersmaatregelen als enige mate van seismiciteit wordt waargenomen).
Het depleted scenario is kwalitatief uitgewerkt in hoofdstuk 4.

3

Evaluatie non-depleted scenario

3.1 Worstcase scenario's bepalen voor non-depleted

Om te bepalen of seismiciteit kan voorkomen is het van belang worstcase situaties te definiëren, welke theoretisch zouden kunnen voorkomen. Daarna is het van belang om te bepalen of er voor de theoretische worstcase situaties beheersmaatregelen kunnen worden opgesteld.

Voor het bepalen van de worstcase situaties bij het non-depleted scenario dienen voor drie soorten parameters uitgangspunten bepaald te worden:

- operationele parameters,
- bodem- en modelparameters,
- geomechanische parameters.

Operationele parameters

In overleg met WarmteStad zijn de volgende belangrijkste operationele parameters bepaald voor het model:

- debiet: 200 m³/uur;
- retourtemperatuur: 35°C;
- max. aantal draaiuren per jaar: 8000 uur/jaar;
- Levensduur: 30 jaar.

Het debiet van 200 m³/uur is het maximale debiet dat het systeem technisch continu zou kunnen draaien. Het is echter een theoretische situatie, want WarmteStad heeft aangegeven dat tijdens de ingroeifase (steeds meer klanten aansluiten) dit debiet nog niet wordt gehaald. Ook dag en nacht en seizoenen (zomer, winter) zorgen ervoor dat maar een beperkte periode van het jaar gedurende enige tijd met maximale capaciteit water opgepompt gaat worden.

Geologische en modelmatige parameters

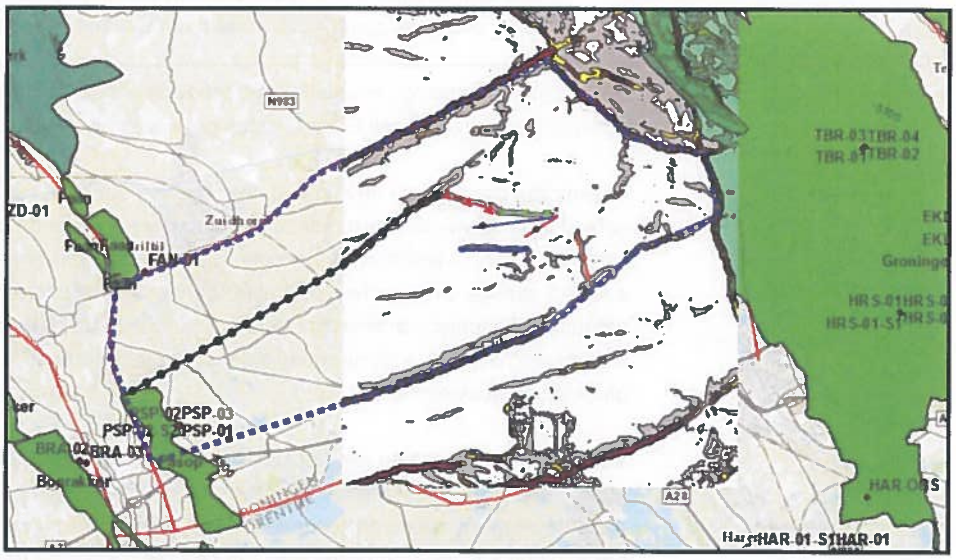
De volgende bodemparameters zijn gebruikt:

- Het reservoirblok waarin het geothermisch systeem wordt gerealiseerd is begrensd door grote breuken welke ondoorlatend zijn. Voor de drukberekeningen is dit een worstcase situatie.
- De transmissiviteit is gelijk aan de P90 waarde: 4,5 Dm. Dit is conform de door TNO bepaalde P90 (90% kans dat de werkelijke transmissiviteit hoger is).
- De dikte van het reservoir is gelijk aan de minimaal verwachte dikte: 240 m. Dit is conform de informatie van Panterra en TNO.

- De diepte van de top van het reservoir ligt op 3.400 m, hetgeen de meest reële waarde is. Dit is conform de informatie van Panterra en TNO.
- De initiële temperatuur in het reservoir bedraagt 120 °C.

De invloed van de geothermisch operatie treedt vooral op bij de breuken direct naast de putten. Dit zijn kleinere breuken dan de grote breuken die het hele reservoirblok omsluiten. In de onderstaande figuur zijn de grote afsluitende breuken met een blauwe stippellijn weergegeven, de overige kleinere breuken in het reservoir blok hebben een andere kleur (zwart, rood, groen, oranje en dikke blauwe lijn).

Figuur 4 Modelgrenzen en 5 breuken binnen het modelgebied die in het reservoirmodel zijn opgenomen. De productieput is rood en de injectieput is blauw met een cirkeltje ter hoogte van het punt waar de put het reservoir in gaat. Groene arceringen zijn gasvelden.



De druk veranderingen door de geothermische operatie nabij de kleine breuken (met name rood, groen en dikke blauwe lijn) zijn vooral afhankelijk van de doorlatendheid van die kleine breuken. Hiervoor zijn verschillende scenario's doorgerekend

- gesloten breuken: ook alle kleine breuken zijn gesloten. Dit scenario is niet waarschijnlijk, maar kan niet worden uitgesloten;
- deels gesloten breuken: een deel van de kleine breuken zal of enigszins doorlatend zijn en/of breuken zijn niet continu. Dit scenario is het meest waarschijnlijk en is in lijn met door de NAM gerapporteerde situatie in het Groningen gasveld;

- open breuken: de breuken zijn volledig permeabel. In dit scenario is ervan uitgegaan dat de breuken even permeabel zijn als het reservoir zelf. Dit is het minst kritisch, omdat er dan geen extra drukopbouw tussen de breuken optreedt.

Geomechanische parameters
De geomechanische evaluatie bestaat uit de volgende onderdelen:
- een evaluatie van het breuksysteem: is het een seismisch kritisch systeem?;
- het bepalen van een theoretische drempelwaarde: welke stressverandering zou seismiciteit kunnen veroorzaken?;
- bepalen of bij de berekende drukveranderingen (reservoirmodellering) de stress nabij de breuk zodanig verandert, dat de drempelwaarde wordt overschreden.

Uit de geomechanische evaluatie is geconcludeerd dat het van nature geen tektonisch actief gebied is (zie Quick Scan) en dus geen seismisch kritisch systeem.

Seismiciteit ontstaat als gevolg van het schuiven van breuken. In een niet-tektonisch actief gebied mag verwacht worden dat de schuifweerstand die de breuk op zijn plaats houdt ruim voldoende is om verschuiving te voorkomen. Als een breuk wel kritisch gestresst is, dan zou een geringe stress- ofwel drukverandering al seismiciteit kunnen veroorzaken. In natuurlijke tektonisch actieve gebieden zijn breuken wel kritisch gestresst en kunnen kleine veranderingen in de ondergrond al seismiciteit veroorzaken als gevolg van kleinere of grotere breukbewegingen.

Voor het bepalen van de drempelwaarde waarbij een breuk zou kunnen gaan schuiven zijn geomechanische berekeningen uitgevoerd. Hiervoor kunnen enkele paramaters eenduidig bepaald worden, maar voor andere parameters dienen aannames gemaakt te worden. Voor het bepalen van de drempelwaarde zijn de meest kritische parameter aannames gebruikt. Dit is een conservatieve aanname voor een niet-tektonsich actief gebied.

3.2 Resultaten reservoir modellering

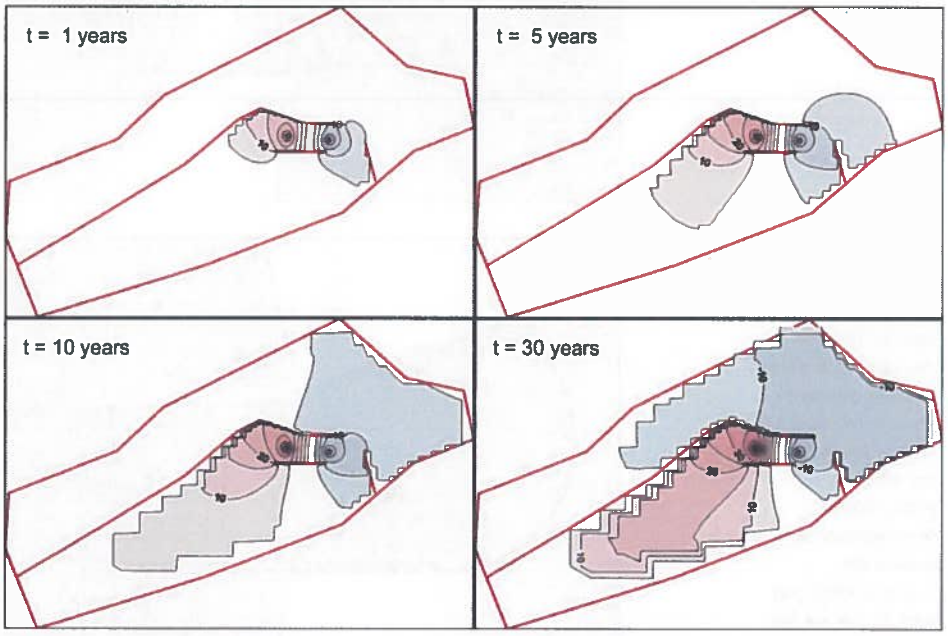
3.2.1 Drukveranderingen door de geothermische operatie

Ter hoogte van de productieput wordt het drukniveau verlaagd. Ter hoogte van de injectieput wordt het drukniveau verhoogd. De invloed van drukverlaging door het geothermisch systeem geeft geen verhoogd risico op seismiciteit. Dit is ook zeer beperkt als het vergeleken wordt met bijvoorbeeld de drukverlagingen die zijn opgetreden in het Groningen gasveld.

Voor de analyse van de kans op seismiciteit is vooral de drukverhoging nabij de injectieput van belang (zie hoofdstuk 2). Deze drukverhoging zorgt voor een verlaging van de schuifweerstand in de breuk en verhoogt daardoor de kans op seismiciteit.

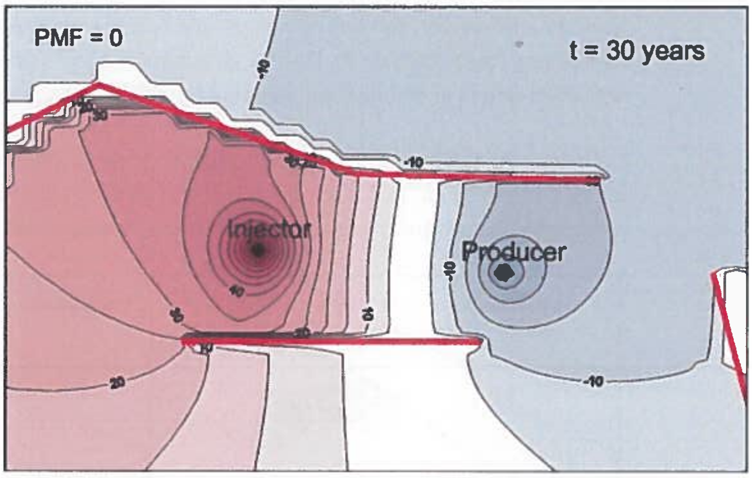
De drukveranderingen worden groter gedurende de geothermische operatie, zie onderstaande figuur. Dit is een weergave waarin de drukveranderingen in het meest ongunstige (en tevens meest onwaarschijnlijke) scenario zijn weergegeven.

Figuur 5
Voor het scenario met ondoorlatende kleine breuken berekende drukveranderingen [bar] 1, 5, 10 en 30 jaar na het opstarten van het geothermie systeem.

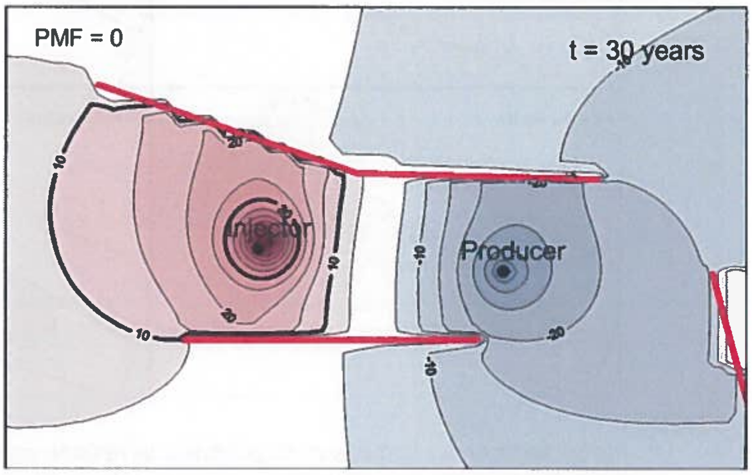


Na 30 jaar is er dus sprake van de grootste drukverandering nabij de breuken. Voor het worstcase scenario van ondoorlatende breuken, het meer waarschijnlijke scenario met deels doorlatende breuken en een gunstig scenario met geheel doorlatende breuken is de berekende maximale drukverandering na 30 jaar in de onderstaande figuren weergegeven.

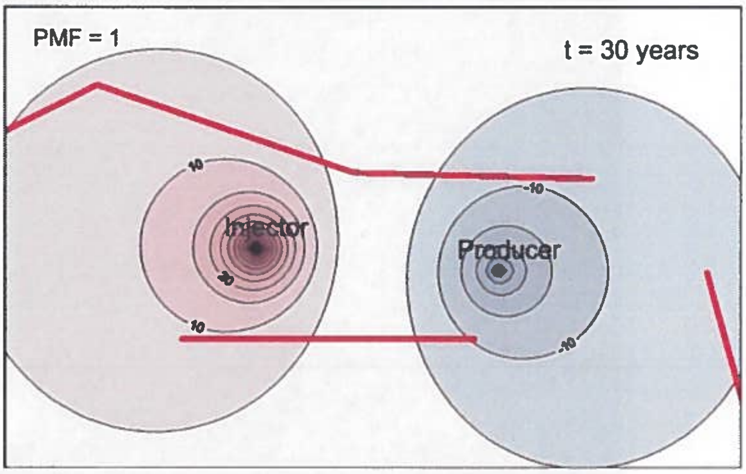
Figuur 6
Voor scenario "ondoorlatende breuken" berekende drukveranderingen [bar] 30 jaar na het opstarten van het geothermie systeem



Figuur 7
Ten opzichte van het scenario "ondoorlatende breuken" is de meest westelijk gelegen breuk verwijderd. De overige breuken zijn ook hier ondoorlatend. Weergegeven zijn de berekende drukveranderingen [bar] 30 jaar na het opstarten van het geothermie systeem



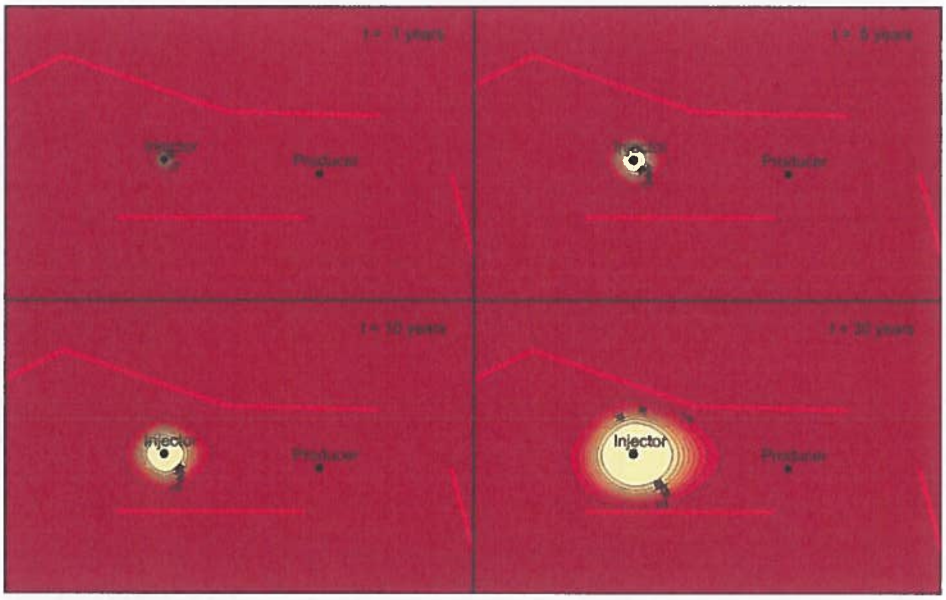
Figuur 8
Voor scenario "doorlatende breuken" berekende drukveranderingen [bar] 30 jaar na het opstarten van het geothermie systeem



Geconcludeerd kan worden dat in het meest ongunstige geval de drukveranderingen circa 30 bar zijn in het niet waarschijnlijke scenario dat de breuken geheel ondoorlatend zijn. En in het geval van deels doorlatende breuken de drukveranderingen circa 20 bar zijn. Deze informatie is gebruikt voor de vervolg analyses.

3.2.2 Temperatuurveranderingen door de geothermische operatie

De productieput onttrekt warm reservoirwater uit het reservoirblok. Na afgifte van de warmte wordt het water afgekoeld tot 35°C en weer geïnjecteerd in de injectieput. Gedurende de 30 jaar exploitatie ontstaat hierdoor een steeds groter wordende koude bel in het reservoir.



Figuur 9
Bovenaanzicht met de berekende temperaturen [°C] in het midden van het reservoir voor het scenario met ondoorlatende breuken. Weergegeven zijn de temperaturen 1, 5, 10 en 30 jaar na opstarten van het geothermie systeem. De initiële temperatuur in het reservoir is 120 °C.

Dit is een zeer onwaarschijnlijke case voor over 30 jaar, aangezien de hoeveelheid geïnjecteerd koud water sterk overschat is. Het blijkt echter dat de koude bel niet of nauwelijks tot aan de breuken zal reiken en dus geen directe invloed zal hebben.

Eén aspect is hierin echter niet meegenomen: thermische compactie van het reservoir. Door de afkoeling zal het reservoir ook krimpen. Dit levert ook stress veranderingen op. Deze stress veranderingen nemen echter veel langzamer toe dan de drukveranderingen door het injecteren van water. Deze thermische contractie is binnen deze QS niet meegenomen, aangezien de beheersmaatregel (TLS-systeem) ontworpen moet worden op de veel sneller toenemende de drukveranderingen door injectie.

3.3 Overschrijding drempelwaarde

De drukveranderingen worden omgerekend naar stress veranderingen bij de breuk. Om druk- en stressveranderingen van elkaar te onderscheiden wordt voor de drukveranderingen met eenheden "bar" gewerkt en voor de stressveranderingen met de eenheid "MPa".

Op basis van geomechanische evaluatie is berekend dat voor het schuiven van een breuk de stress veranderingen een drempelwaarde moeten overschrijven van meer dan 1,9 MPa (en bij zeer conservatieve aannames maar onwaarschijnlijke situatie 1,2 MPa). Dit is een conservatieve aanname voor een niet-tektonisch actief gebied. Kleine wijzigingen in die aannames leiden al snel tot grenswaarden van groter dan 3 MPa.

Op basis van de berekende druk veranderingen (zie 3.2) zijn met geomechanische berekeningen de stress veranderingen bij de breuken berekend. In het worstcase scenario met gesloten breuken (maximaal 30 bar drukverandering), blijkt dat de stressveranderingen bij de breuk maximaal 1,4 MPa bedragen. Dit betekent dat de berekende stressveranderingen 0,6 MPa onder de conservatieve drempelwaarde van 1,9 MPa blijven en 0,2 MPa boven de onwaarschijnlijke worstcase drempelwaarde van 1,2 MPa. Op basis van deze geomechanische berekeningen kan gesteld worden dat alleen in de onwaarschijnlijke worstcase situatie de drempelwaarde zou kunnen worden overschreden. Zie voor de geomechanische berekeningen bijlage 2.

Voor het bepalen van de mogelijkheden om de seismiciteit met beheersmaatregelen te voorkomen is uitgegaan van een nog lagere grenswaarde: 1MPa (zie ook bijlage 3). Ook op basis van literatuur en ervaringsgetallen uit andere projecten en gebieden, blijkt dit een conservatieve aanname voor niet-tektonisch actieve gebieden.

3.4 Evaluatie van de kans op seismiciteit en magnitudes

Zoals geconcludeerd uit de Quick Scan, is de kans op seismiciteit klein in het non-depleted scenario. Zelfs in de gevallen waarbij worstcase parameters (operationele, bodem- en geomechanische parameters) gebruikt worden en benodigde aannames conservatief ingeschat worden, lijkt seismiciteit niet waarschijnlijk.

Voor het onwaarschijnlijke (theoretische) geval dat in het non-depleted scenario toch seismiciteit optreedt is een maximale seismiciteit van 3,2 Magnitudes berekend als het gehele breukvlak van de meest kritische breuk in één keer verschuift. Ook dit is onwaarschijnlijk. Voorafgaand aan een maximale seismiciteit van 3,2 Magnitude, zullen bevingen met een kleinere magnitude voorafgaan. Deze seismiciteit is te monitoren en te mitigreren met een TLS (Traffic Light System) (zie. 3.5).

In de literatuur zijn nog cases uit het buitenland bekend van directe injectie in breuksystemen, waarbij een seismiciteit van 3,5 Magnitudes opgetreden zijn. Op basis van onze analyses achten we injectie direct in een breuk onwaarschijnlijk aangezien geen breuken direct ter hoogte van de injectieput zijn aangetroffen in onze analyse en zelfs de grotere breuk die wel is aangetroffen niet verder komt dan een magnitude 3,2. Mochten er toch kleine breukjes aanwezig zijn, dan zal het gaan om relatief kleine oppervlaktes die verschuiven, waardoor de bijbehorende maximale magnitude beperkt blijft.

3.5 Mitigatie mogelijkheden (TLS-systeem)

In het niet waarschijnlijke geval dat alsnog seismiciteit gaat optreden in de non-depleted situatie, is het van belang dat deze gemitigeerd kan worden. Een algemeen toegepaste maatregel om de sterkte van de eventuele seismiciteit bij injectie te beheersen/mitigeren, is het TLS (Traffic Light System).

De juiste werking van het TLS is met name gelegen in het feit dat door injectie de druk en dus de stress bij de breuken geleidelijk verandert. Die seismiciteit (als die al optreedt) zal zich dan ook opbouwen in de tijd van zeer lage magnitudes naar hogere magnitudes. Door die seismiciteit nauwkeurig te monitoren, kan ingegrepen worden ruim voordat de seismiciteit een vooraf bepaalde sterkte bereikt.

Door Q-con is een basis ontwerp voor een TLS monitoringssysteem gemaakt, waarbij is aangetoond dat een dergelijk systeem voldoende nauwkeurig kan meten. Hiervoor is uitgegaan van 5 meetstations. Dit is inclusief extra stations die nodig zijn om de redundantie te borgen (stel er valt een station uit). Het is sterk aan te bevelen om de monitoring in eigen hand te houden als WarmtStad, zodat WarmteStad niet afhankelijk is van andere partijen (KNMI) om aan te tonen dat een seismische activiteit niet het gevolg is van het geothermie systeem. Om kosten te reduceren zou het combineren met meetstations van derden nog wel een mogelijkheid zijn. De bestaande meetstations van de KNMI lijken niet geschikt om de seismiciteit voldoende nauwkeurig te kunnen meten en lokaliseren.

Figuur 10
Traffic Light System: voorstel van de grenswaarden en hieraan gekoppelde acties

TLS Status			
Definition	$M_w < 0.9$	$0.9 <= M_w < 2.0$	$M_w \geq 2.0$
Actions	regular operations	– higher alert level – no increase of injection rate – report to regulator	– stop operations – immediately report to regulator – expert panel convenes

Als onderdeel van het TLS dient naast het monitoren ook bepaald te worden wanneer ingegrepen moet worden. Een voorbeeld hiervan is opgenomen in Figuur 10. Hierbij is ervan uitgegaan dat de operatie door kan gaan, zolang blijkt dat er geen voelbare seismiciteit optreedt (M_w=1,4). De operatie dient te worden gestopt indien seismiciteit gemeten wordt die schade kan veroorzaken (M_w=2,5). Tussen die waarden dient in ieder geval het debiet niet verhoogd te worden en moet gerapporteerd worden aan SodM.
De niveau's waarbij dan ingegrepen moet worden liggen echter lager. Dit komt omdat er rekening gehouden dient te worden met zogenaamde "post-seismicity" ofwel "trailing effect". Dit is een toename van de sterkte van de seismiciteit die nog kan optreden na het stoppen van het systeem. Voor de toename van de sterkte van de seismiciteit is 0,5 aangehouden, wat volgt uit de praktijkervaring dat de "post-seismicity" toename van de magnitude maximaal M=0,5 bedraagt.

Met het ontworpen TLS is een algemeen gebruikte beheersmaatregel uitgewerkt, welke eventuele risico's op ongewenst sterke seismiciteit voorkomt. Onze verwachting is dat SodM akkoord zal gaan met deze niveau's. De niveau's van ingrijpen kunnen aangepast worden. Met de hier voorgestelde instelling kan het geothermie systeem echter veilig bedreven worden, zonder dat er vaak operationeel ingegrepen moet worden door bijvoorbeeld seismiciteit in het Groningen gasveld. Kritischer afstellen kan operationeel betekenen dat sneller overgegaan moet worden tot het beperken van het debiet, terwijl dit veiligheidstechnisch eigenlijk nog niet nodig is.

Het TLS zorgt naast een veilige bedrijfsvoering ook voor de mogelijkheid om seismiciteit in of direct nabij het Groningen gasveld te kunnen onderscheiden van de seismiciteit rondom de projectlocatie. Dit is van belang om de verantwoordelijkheid van bepaalde seismiciteit direct te kunnen bepalen en het is van belang omdat de geothermische bedrijfsvoering bij eventuele seismiciteit niet aangepast hoeft te worden, indien aangetoond wordt dat die uit het Groningen gasveld komt.

4

Evaluatie depleted scenario

In het onderstaande is een kwalitatieve beschouwing gerapporteerd in het geval het geothermisch reservoirblok (deels) depleted is als gevolg van de gasproductie in het Groningen gasveld.

4.1 Verwachting t.a.v. de mate van depletion

De mate van depletie hangt af van de doorlatendheid van de grote breuken die de reservoirs van het Groningen gasveld en die van het geothermisch reservoirblok scheiden. Ondoorlatende breuken voorkomen dat de drukdaling (depletie) in het Groningen gasveld communiceert met naastgelegen breukblokken en dus ook daar voor depletie zorgen.

Op basis van de beperkte beschikbare informatiebronnen die er zijn, wordt verwacht dat de depletie niet of minimaal aanwezig is.

- Sauwerd en Pasop putten zijn geboord in jaren '90. Er is direct na het boren geen depletie gemeten, ondanks de reeds significante drukdalingen in het Groningen gasveld toentertijd. Opgemerkt dient te worden dat deze gasputten niet in hetzelfde reservoir blok liggen als het geothermieproject. De ligging ten opzichte van het Groningen gasveld is wel vergelijkbaar.
- Aanwijzingen dat breuken rondom gasvelden ondoorlatend zijn: de PAS-01 put staat niet in contact met de rest van het geologisch blok a.g.v. (bijna) ondoorlatende breuken. Onttrokken gas hoeveelheden kunnen anders niet de gerapporteerde drukdaling verklaren.
- In het laatste winningsplan van Groningen Gasveld wordt voor het reservoir blok van het geothermie systeem geen of nauwelijks depletie gerapporteerd in de komende 5 jaar.

Om meer zekerheid over de mate van depletie te krijgen zou een put gemaakt moeten worden tot in het reservoir.

4.2 Depletie en geothermische operatie

4.2.1 Twee mechanismen

Het mechanisme van injectie gerelateerde seismiciteit, hetgeen optreed bij geothermische operatie, is bekend: drukopbouw leidt tot een langzaam kritischer wordende situatie waarin de potentie voor seismiciteit zou kunnen toenemen. Het risico kan gemitigeerd worden, omdat de opbouw in seismiciteit gemonitoord kan worden, waardoor er op tijd (voordat grenswaarden worden overschreden) gestopt kan worden, voordat ernstige seismiciteit kan optreden. Een voorbeeld is hierbij het non-depleted scenario zoals omschreven in paragraaf H3.

Het mechanisme van differentiële compactie, het werkingsmechanisme dat seismiciteit veroorzaakt na gasproductie, is minder eenduidig. Het is niet exact bekend hoe en of de seismiciteit zich in de tijd opbouwt en welke drempelwaarden overschreden moeten worden om seismiciteit te veroorzaken.
Risico's op seismiciteit bij het Groningen gasveld worden vooral empirisch en statistisch bepaald. Zo is de ervaring dat boven 28% depletie (ca. 100 bar drukdaling) als gevolg van gaswinning seismiciteit kan ontstaan. In het Groningen gasveld treedt dit pas vanaf 54% depletie (ca. 190 bar) op.

4.2.2 Combinatie van depletie en een geothermische operatie

In het geval van depletie in het geothermische reservoirblok vinden beide mechanismen tegelijkertijd plaats. Binnen de scope van ons onderzoek moeten wij vaststellen dat het niet mogelijk is de gecombineerde effecten te kwantificeren. Voor differentiële compactie is dat bij voorbaat al moeilijk (zie 4.2.1), maar het is ook onbekend hoeveel invloed een geothermische operatie in het depleted scenario heeft op bijvoorbeeld de opbouw van seismiciteit in de tijd en op de drempelwaarde waarbij seismiciteit zal optreden.
Binnen de scope van dit onderzoek, kan niet aangetoond worden dat een TLS het risico op significante seismiciteit kan mitigeren.
Indien er wel een mogelijkheid gevonden wordt om een TLS te ontwerpen dat dit risico kan mitigeren, dan kan een reguliere opzet van het TLS nog niet vaststellen welk mechanisme het meeste bijdraagt aan een eventuele opbouw van seismiciteit in de tijd. Is de NAM met name verantwoordelijk voor een noodzakelijke stop n.a.v. de gemeten oplopende seismiciteit of is WarmteStad hiervoor verantwoordelijk? Ofwel is oplopende depletie of is de geothermische operatie de trigger die de gemeten seismiciteit veroorzaakt? Een reguliere TLS opzet zal niet kunnen vaststellen welk mechanisme het meeste bijdraagt.
Daarnaast kan WarmteStad de productie van de NAM (en de depletie als gevolg daarvan) niet beïnvloeden en kan dus feitelijk niet actief reageren op signaalwaarden van het TLS.

4.2.3 Ervaringen van de NAM van injectie in een depleted reservoir

De NAM heeft voor de injectie van water in drie lege gasvelden in Twente onderzoek gedaan naar de mogelijke seismiciteit die daarvan het gevolg kan zijn. Dit is met name relevant voor de situatie dat sprake zou zijn van depletie als gevolg van beïnvloeding door het Groningen gasveld. In het addendum hierover (NAM, 2015) wordt gesteld:

Wereldwijd is gebleken dat waterinjectie in incidentele gevallen aardbevingen kan veroorzaken. Studies hebben aangegeven dat dergelijke aardbevingen voornamelijk gerelateerd zijn aan gevallen waarbij de reservoirdruk uitstijgt tot boven de oorspronkelijke reservoirdruk, iets wat in Nederland niet gebeurt omdat in vergunningen druklimieten zijn opgenomen. In Nederland wordt door NAM al tientallen jaren zonder problemen water geïnjecteerd op diverse locaties (by. Borgsweer, Pernis, Rotterdam, Schoonebeek). Er is in Nederland slechts 1 geval bekend waarbij vermoedelijk door waterinjectie een lichte aardbeving heeft plaatsgevonden. Dit was in november 2009 nabij Weststellingwerf in een gasveld van Vermilion. Deze beving had een kracht van 2,8 op de schaal van Richter.

Ook als wel sprake is van drukdalingen (depletie) door de gaswinning lijkt de kans op seismiciteit door drukverhogingen gering. Belangrijk is wel dat er in het enige geregistreerde geval van seismiciteit direct sprake was van een beving met een kracht van 2,8 op de schaal van Richter. Het is niet bekend of er middels monitoring sprake is geweest van "voorwaarschuwingen" in de vorm van bevingen met kleinere magnitudes. Dit betekent dat niet bekend is of beheersmaatregelen in deze situatie zouden hebben gewerkt.

Belangrijke conclusie van het onderzoek van de NAM is dus dat de combinatie van depletie en injectie in de meeste gevallen niet heeft geleid tot seismiciteit (althans niet gemeten). De NAM gebruikt voor de waterinjectie in depleted reservoirs een TLS. Of een dergelijk TLS ook werkt, zoals bedoeld in de geothermische operatie, kan echter niet worden geconcludeerd op basis van deze gegevens. Verder speelt bij de combinatie van depletie en geothermische operatie niet alleen het aspect injectie maar ook de extra drukverlaging als gevolg van het oppompen van water uit de productieput. Dit is geen mechanisme dat een rol speelt bij de injectie in depleted gasvelden door de NAM.

4.3 Invloed van de mate van depletie

Omdat de gevolgen van de combinatie van beide systemen niet gekwantificeerd kunnen worden, kan er geen theoretisch onderbouwde minimale depletie worden bepaald, waarbij de invloed van de depletie verwaarloosbaar is en het TLS systeem conform een non-depleted scenario gebruikt zou kunnen worden.

Gesteld kan worden dat het risico bij meer dan 100 bar depletie als gevolg van enkel het mechanisme differentiële compactie al dermate hoog is, dat het ongewenst is om daarnaast een geothermisch systeem te ontwikkelen.

Binnen de scope van dit onderzoek kan niet uitgesloten worden dat bij een depletie van minder dan 100 bar, de combinatie van beide systemen seismiciteit zouden kunnen veroorzaken, welke niet te mitigeren is. De verwachting is echter dat een kleine depletie niet of nauwelijks extra risico oplevert, maar omdat het binnen de scope van dit onderzoek niet kwantificeerbaar is, kan geen onderbouwde grenswaarde aangeven worden.

Daarnaast geldt dat een minimale depletie een aanwijzing is voor voortdurende depletie in de tijd. De depletie in het reservoir blok kan toenemen in de tijd als gevolg van een vertragingsfactor tussen het reservoir blok en het Groningen gasveld of als gevolg van een gewijzigde productie strategie van de NAM in het Groningen gasveld. Dus een depletieniveau lager dan de gestelde ondergrenswaarde in het eerste jaar kan gedurende de 30 jaar exploitatie alsnog overschreden worden

4.4 Onderzoeksmogelijkheden naar het depleted scenario

Kan het depleted scenario op een andere wijze gekwantificeerd worden om het risico en de mitigerende mogelijkheden voor dit scenario alsnog vast te stellen?
De scope van een dergelijk onderzoek zou vastgesteld moeten worden in samenwerking met seismiciteits-experts van het Groningen gasveld (TNO). Hierbij spelen de volgende vragen:

- Op welke wijze kan gekomen worden tot een goed onderbouwd theoretische model waarin beide mechanismen een rol spelen (differentiële compactie en geothermische operatie)?;
- Welke scenario's kunnen met dit model worden berekend en welke scenario's leiden tot de worstcases, waarbij het risico door een beheersmaatregel gemitigeerd moet kunnen worden? Kan met deze scenario's een grenswaarde voor depletie worden bepaald?;
- Is het mogelijk beheersmaatregelen te ontwikkelen (bijvoorbeeld TLS en monitoring depletie) die dit risico kunnen mitigeren gedurende 30 jaar exploitatie?

Een dergelijk onderzoek is gecompliceerd en de doorlooptijd zal minimaal een aantal maanden bedragen. Voorafgaand aan het onderzoek is het aan te bevelen de haalbaarheid ervan in te schatten met eenzelfde team van experts.

De ervaringen en monitoring gegevens van de NAM bij de injectie in depleted gasvelden zou een belangrijke bijdrage kunnen leveren aan dit onderzoek (zie 4.2.3). Op basis van jarenlange ervaring blijkt dat op een enkel geval na de injectie in de depleted gasvelden geen significante seismiciteit hebben veroorzaakt.

5

Conclusies en aanbevelingen

5.1 Conclusies

Bij het bepalen van de kans op seismiciteit en de mogelijkheden om de risico's te mitigeren is in het onderzoek onderscheid gemaakt tussen 2 scenario's.

- Non-depleted scenario: in dit scenario is er geen drukdaling in het reservoir blok van het geothermisch systeem als gevolg van de drukdaling in het naastgelegen Groningen gasveld;
- Depleted scenario: in dit scenario is er drukdaling in het reservoir blok omdat de grote breuken tussen het reservoir blok en het Groningen gasveld enigszins doorlatend zijn. De drukdaling in het Groningen gasveld zorgt daardoor ook voor drukdalingen in de aangrenzende reservoirs.

Onze verwachting is dat er niet of nauwelijks beïnvloeding door het Groningen gasveld is (non-depleted).

In het kort kunnen wij de volgende conclusies trekken:

- Non-depleted scenario: de kans op seismiciteit is minimaal en mocht seismiciteit toch optreden, dan kan ruim op tijd worden ingegrepen voordat de seismiciteit gevolgen kan hebben.
- Depleted scenario: in dit scenario is het niet mogelijk uitspraken te doen over de kans op seismiciteit en over hoe die seismiciteit zich in de tijd zou kunnen opbouwen. Met de kwalitatieve benadering, welke binnen dit onderzoek voor het depleted scenario is gehanteerd, is het niet mogelijk om een TLS-systeem te ontwikkelen om het risico op seismiciteit te mitigeren.

In het onderstaande zijn de conclusies verder toegelicht.

5.2 Toelichting conclusies non-depleted scenario

De kans dat seismiciteit optreedt in een non-depleted scenario is klein. Alleen als meerdere ongunstige aannames worden gedaan (denk aan ongunstige aannames voor de operationele inzet van het geothermie systeem en de geologische en geomechanische eigenschappen van het reservoir) kan seismiciteit optreden. De kans dat al deze ongunstige aannames gelijktijdig optreden is klein. Daarnaast geldt ook nog dat bij dergelijke tegenvallende reservoir eigenschappen de operationele inzet van het geothermische doublet naar beneden zal worden bijgesteld. Dat betekent dat de kans dat seismiciteit optreedt in een non-depleted scenario klein is.

Mocht ondanks de kleine kans seismiciteit toch optreden, dan zal dat in eerste instantie niet voelbaar zijn en vervolgens stapsgewijs in sterkte toenemen. Door het inrichten van een monitoring systeem, kan de seismiciteit continu worden gemeten. Als er seismiciteit wordt gemeten en de sterkte daarvan toeneemt, dan kan veilig worden ingegrepen voordat een vooraf gekozen niveau van seismiciteit optreedt. Dit systeem is bekend als een "traffic light system" (TLS) en is wereldwijd erkend als methode om seismiciteit te beheersen.

5.3 Toelichting conclusies en aanbevelingen depleted scenario

Voor dit scenario spelen meerdere mechanismen tegelijk die seismiciteit kunnen veroorzaken: drukverlaging (door de depletie als gevolg van de productie in het Groningen gasveld en door het oppompen van water uit de productieput) en drukverhoging (door injectie van koud water in de injectieput).

Binnen de scope van dit onderzoek is geen kwantificering mogelijk van de effecten van de combinatie van deze mechanismen. Met de kwalitatieve benadering, welke binnen dit onderzoek voor het depleted scenario is gehanteerd, is het niet mogelijk een TLS te ontwerpen dat geschikt is om het risico op seismiciteit te mitigeren.

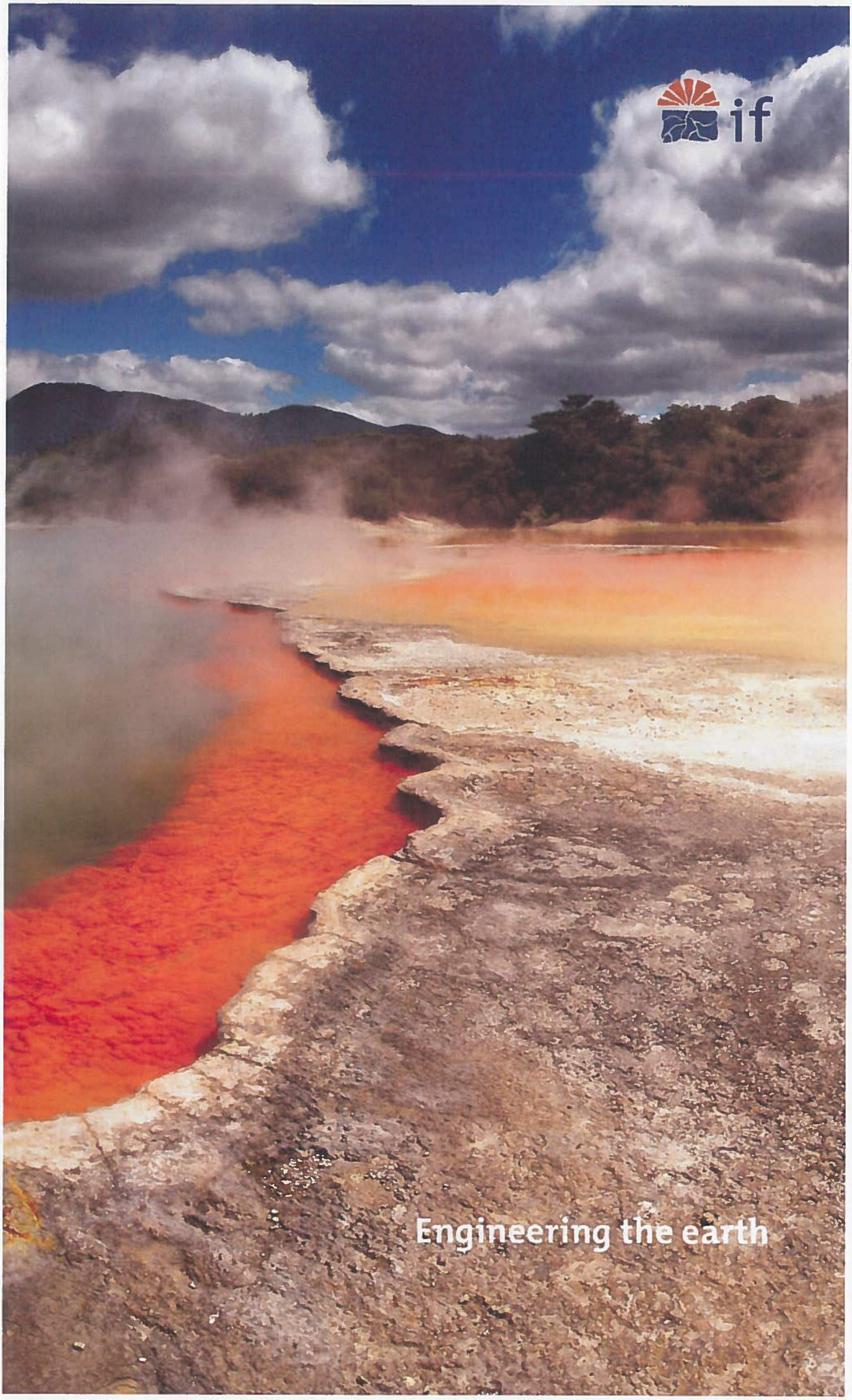
De verwachting is echter dat een kleine depletie niet of nauwelijks extra risico oplevert. Echter, omdat het niet kwantificeerbaar is kan geen onderbouwde maximale depletie aangeven worden. De ervaringen van de NAM onderbouwen de verwachting dat de kans op seismiciteit bij injectie in depleted reservoirs klein is.

Een regulier TLS monitoring systeem geeft ook geen uitsluitsel over de oorzaak van de eventuele seismiciteit: depletie door het Groningen gasveld en/of de geothermische operatie (wie is verantwoordelijk?). Hierbij is van belang dat WarmteStad geen invloed heeft op de depletie als gevolg van de gaswinning.

Een vervolgonderzoek in samenwerking met seismiciteits-experts van het Groningen gasveld en een evaluatie van de NAM ervaringen in de injectie in depleted reservoirs zou meer uitsluitsel kunnen geven. Een dergelijk onderzoek is gecompliceerd en de doorlooptijd zal minimaal een aantal maanden bedragen. Voorafgaand aan het onderzoek is het aan te bevelen de haalbaarheid ervan in te schatten met eenzelfde team van experts.

Bijlage 1

Rapportage reservoirmodellering



Reservoirmodellering

WarmteStad Groningen

if

Engineering the earth

Reservoirmodellering

WarmteStad Groningen

Reservoirmodellering

WarmteStad Groningen

Opdrachtgever **Warmtestad**
Griffeweg 99
Postbus 1
9723 DV GRONINGEN
T 050 367 8746 | E .@WarmteStad.nl
Contactpersoon: de heer

Adviseur **IF Technology bv**
Velperweg 37
Postbus 605
6800 AP ARNHEM
T 026 3535 555 | E @iftechnology.nl
Contactpersoon: de heer B.M. Pittens

Colofon

Auteur:	**de heer**
Versie:	Definitief 1.0
Gecontroleerd door:	de heer
Vrijgegeven door:	de heer

Paraaf:

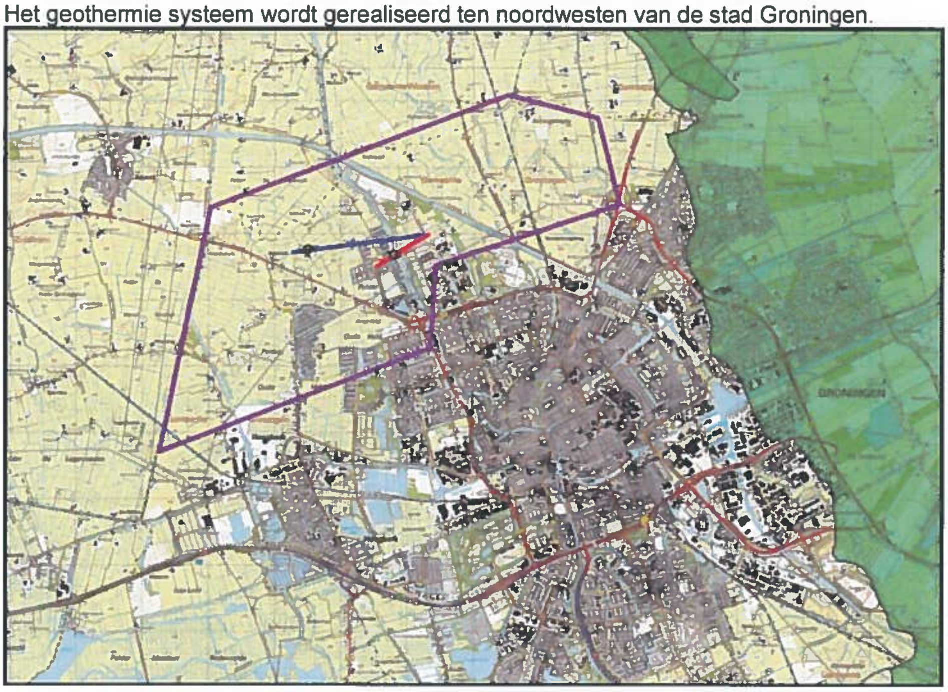
Inhoudsopgave

1

Inleiding

Algemeen
In opdracht van WarmteStad hebben IF Technology en Q-con een onderzoek gedaan naar de risico's op seismiciteit door geothermie in Groningen. Een onderdeel van dit onderzoek was een reservoirmodellering. Dit onderdeel is nader uitgewerkt in het onderliggende rapport.

Onderzoek naar seismiciteit door geothermie in Groningen
Het geothermie systeem wordt gerealiseerd ten noordwesten van de stad Groningen.



Figuur 1
Gebied van de opsporingsvergunning (paars omlijnd) en de beoogde boortrajecten van de producer (rode lijn) en injector (blauwe lijn). Het groene gebied oostelijk van de stad is het Groningen gasveld.

Dit geothermie systeem zou warmte moeten gaan winnen uit de Slochteren Formatie. Uit de Slochteren Formatie wordt in verschillende gasvelden in de omgeving ook aardgas gewonnen. Als gevolg van de gaswinning zijn in de regio vele aardbevingen opgetreden, vooral in het gebied van het Groningen gasveld. Belangrijke vragen voor het beoogde geothermie systeem zijn dan ook:

1) Of er aardbevingen veroorzaakt zouden kunnen worden.
2) Hoe sterk die eventuele aardbevingen dan zouden kunnen zijn.
3) In hoeverre eventuele aardbevingen te voorkomen of te beperken zijn.

Om deze vragen te kunnen beantwoorden is een reservoirmodel gemaakt, waarmee de maximaal te verwachten effecten van het geothermie systeem zijn berekend. Het voorliggende rapport geeft een beschrijving van het reservoirmodel en de uitkomsten daarvan. De vertaling van de resultaten naar de kans op aardbevingen, de sterkte daarvan en de mogelijkheden om deze te voorkomen of te beperken zijn beschreven in een separaat rapport van Q-Con.

2

Reservoirmodellering

2.1 Modelgebied

De belangrijkste informatie die is gebruikt voor het opstellen van het reservoirmodel is:

- Geothermal Energy in Groningen - Geological Investigation (Groot Geologisch Onderzoek Groningen) (Panterra, 2014).
- Advies aanvraag Garantieregeling AARDO4001 Aardwarmte ZernikeGeo (TNO, 2015).
- Reservoirmodel Slochteren Formatie van de Rijks Universiteit Groningen (RUG) (2015).
- Regionale kartering van de diepe ondergrond (v2 DGM-diep voor de breuken en v4 DGM-diep voor dieptes en diktes) voor de gebieden buiten het modelgebied van het model van de RUG

Daarnaast is gebruik gemaakt van een aantal geologische studies voor het Groningen Gasveld (TNO, 2013; NAM, 2013; NAM, 2015; Van Thienen-Visser en Breunese, 2015; NAM, 2016).

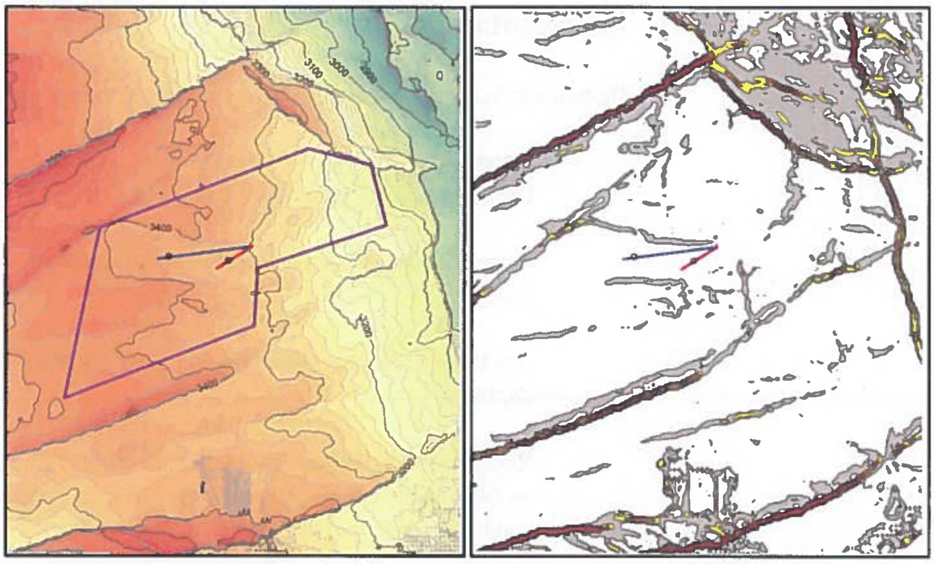
2.1.1 Begrenzing in horizontale richting

Om de grootte van het modelgebied te kunnen bepalen is in eerste instantie gebruik gemaakt van het reservoirmodel van de Rijks Universiteit Groningen (RUG). Het model van de RUG is gebaseerd op gegevens van bestaande boringen en 3D-seismiek. Het model van de RUG is door ons gecontroleerd en als betrouwbaar beoordeeld. Figuur 2 toont de diepte van de top van de Slochteren Formatie zoals die in het model van de RUG is opgenomen. Tevens is voor de top van de Slochteren Formatie het "hellingspercentage" in beeld gebracht. In deze "hellingskaart" zijn duidelijk de plaatsen te zien waar de diepte van de top van het reservoir sterk verandert. Op deze plaatsen bevinden zich breuken, waarlangs verschuivingen zijn opgetreden. De meest felgekleurde lijnen tonen de locaties van de breuken met het grootste (verticale) verzet.

Figuur 2

Links:
Diepte van de top van de Slochteren Formatie [m].

Rechts:
"Hellingspercentage" van het diepteniveau van de top van de Slochteren Formatie.



In bijlage 1 is een aantal dwarsdoorsneden opgenomen, waarin de diepte van de top van de Slochteren Formatie in beeld is gebracht. De verticale verplaatsing varieert van enkele tientallen meters (grijze lijnen) tot meer dan 100 meter (rode lijnen). De maximale verticale verplaatsing is ruim 200 m. Als gevolg van de versplaatsing die is opgetreden ter plaatse van deze breuken treedt beïnvloeding van de doorlatendheid van het reservoir op. In de richting loodrecht op de breukzone kan de doorlatendheid sterk zijn verlaagd, terwijl de doorlatendheid evenwijdig aan de breukzone juist sterk verhoogd kan zijn (zie Figuur 3). Ter plaatse van breuken kunnen daardoor barrières aanwezig zijn, die stroming tussen de reservoirblokken aan beide zijden van de breuk verhinderen.

De mate waarin barrières voor stroming ontstaan in breukzones is van vele factoren afhankelijk (b.v. de kleifractie in het breukvalk, de verplaatsing en de druk waarbij die verplaatsing is opgetreden). Over het algemeen zullen bij breuken met een relatief kleine verplaatsing minder stromingsbarrières ontstaan dan bij breuken met een relatief grote verplaatsing. De kans op de aanwezigheid van stromingsbarrières is dan ook het grootst bij de breuken waar de grootste verplaatsing is opgetreden.

Figuur 3
In een breukzone is sprake van een verhoogde concentratie aan breukjes/barsten in het gesteente, waardoor de doorlatendheid evenwijdig aan het breukvlak verhoogd is. Loodrecht kan de doorlatendheid echter juist sterk verlaagd zijn. De breukzone is tevens een zone waar het gesteente verzwakt is. Nieuwe verschuivingen kunnen daardoor veel makkelijker optreden ter plaatse van bestaande breuken dan op plaatsen waar nog geen breuken aanwezig zijn.

Bron: IEAGHG, 2015.

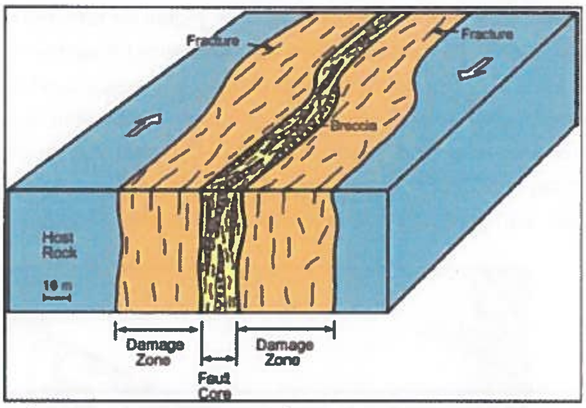


Figure 1 Schematic representation of a fault zone comprised of a fault core and damage zones in a strike-slip fault.

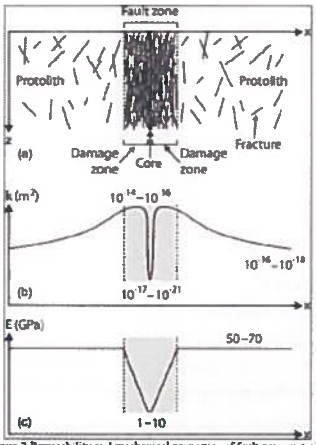


Figure 2 Permeability and mechanical properties of fault zone material.

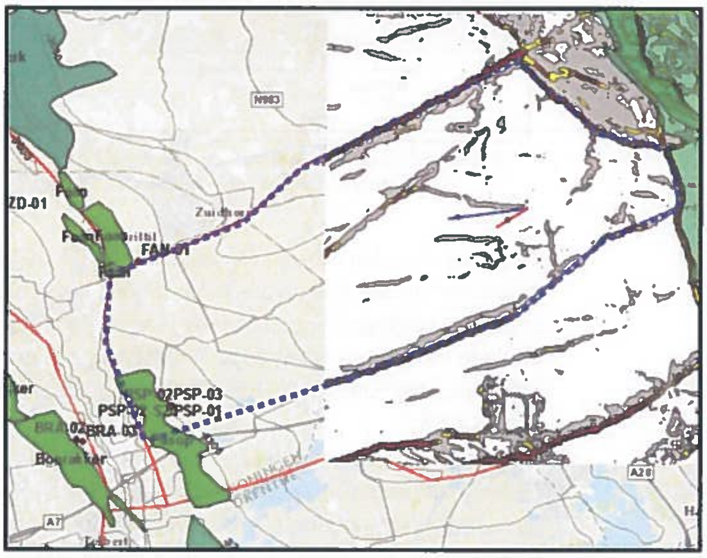
Volgens het meest recente winningsplan (NAM, 2016) is het duidelijk dat sprake is van drukcommunicatie tussen alle delen binnen het Groningen Gasveld, maar hinderen de breuken wel de stroming tussen de verschillende reservoirblokken. De belangrijkste breuken rond het reservoir blok waarin het geothermisch systeem beoogd is, worden in het meest recente model van de NAM als ondoorlatend beschouwd (zie Figuur 4, blauwe geblokte lijn).

Bij het meer westelijk gelegen Pasop gasveld, is bij een relatief beperkte gaswinning een grote drukdaling opgetreden. De meest waarschijnlijke verklaring is dat hier gas is gewonnen uit een relatief klein compartiment, dat begrensd is door ondoorlatende of slecht doorlatende breuken.

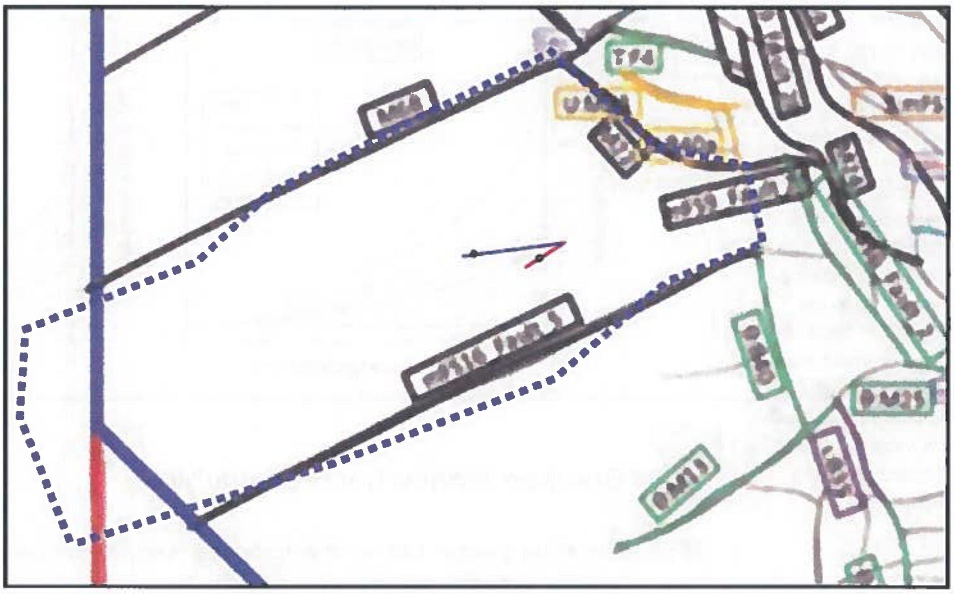
Verder is een aantal drukmetingen in de Slochteren Formatie beschikbaar in de omgeving van het Groningen gasveld (zie Figuur 11). Uit deze metingen blijkt dat er ten tijde van de metingen niet (of nauwelijks) sprake was van drukdalingen, terwijl er op dat moment al wel sprake was van een aanzienlijke drukdaling in het Groningen Gasveld (tussen de 100 en 200 bar). Ook dit wijst op de aanwezigheid van slecht doorlatende of ondoorlatende breuken.

Op basis van bovenstaande informatie is voor het reservoirmodel aangenomen dat de breuken met de grootste verticale verplaatsing ondoorlatend zijn. Deze breuken vormen de begrenzing van het reservoirmodel. Aangezien de effecten van het geothermie systeem kleiner zullen zijn als de breuken wel (enigszins) doorlatend zijn, wordt dit als een worst-case benadering beschouwd. Omdat voor het meest westelijk gelegen gedeelte van het reservoirmodel de detailinformatie ontbreekt (valt buiten het modelgebied van de RUG), is voor dit gedeelte van het gebied gebruik gemaakt van de gegevens uit de regionale kartering van TNO (v2 DGMdiep voor de breuken en v4 DGM-diep voor dieptes en diktes). De gekozen grens van het reservoirmodel is weergegeven in Figuur 4.

Figuur 4
Grens van het reservoirmodel (blauwe geblokte lijn). Rechts op de achtergrond de kaart met het "hellingspercentage", gebaseerd op het model van de RUG en links de regionale kartering van TNO (rode lijnen zijn de regionale breuken en zwarte lijnen de dieptecontouren van de top van de Slochteren Formatie).



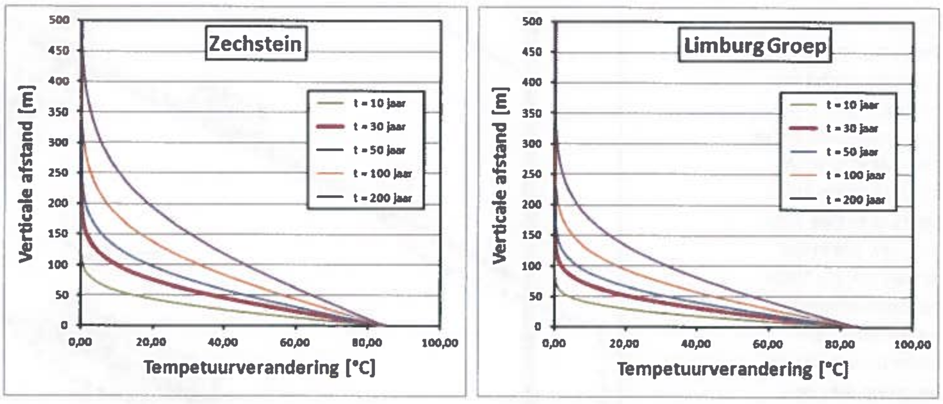
Ter controle is de begrenzing van het reservoirmodel vergeleken met breukenmodel van de NAM uit het recentelijk beschikbaar gekomen winningsplan voor het Groningen Gasveld (NAM, 2016). Uit blijkt dat de gekozen begrenzing van het reservoirmodel goed overeen komt met het breukenmodel van de NAM.



Figuur 5
Begrenzing van het reservoirmodel met als ondergrond de kaart met breuken uit het meest recente model van de NAM. De zwarte lijnen zijn breuken die in het model van de NAM als ondoorlatend zijn opgenomen. De dikke blauwe lijn is de grens van de breuken kaart van de NAM.
Bron: Winningsplan Groningen Gasveld, 2016.

2.1.2 Begrenzing in verticale richting

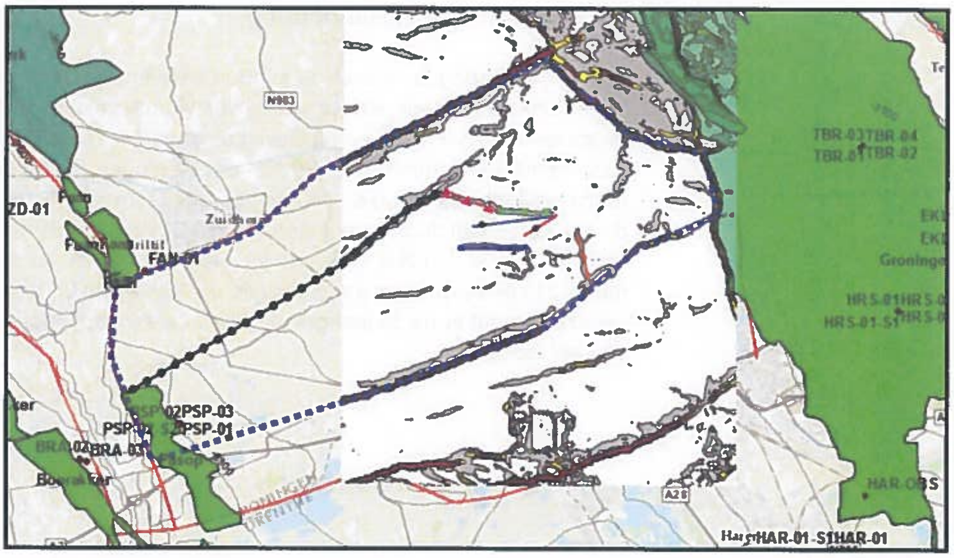
Om de begrenzing in verticale te kunnen bepalen zijn berekeningen uitgevoerd aan de temperatuurveranderingen als gevolg van warmtegeleiding. Hierbij is aangenomen dat de temperatuur in het reservoir plotseling daalt van de initiele reservoir temperatuur (120 °C) naar de infiltratietemperatuur (35 °C). Berekeningen zijn uitgevoerd voor de bovengelegen formatie (Zechstein zout) en de ondergelegen formatie (schalie van de Limburg Groep). Uit de resultaten van de berekeningen (Figuur 6) volgt dat de invloed op de temp na 30 jaar niet verder reikt dan 200 m van de top en de basis van het reservoir. Voor het reservoir model zijn de bovenzijde en onderzijde op 250 m van de top en de bases van het reservoir gekozen, zodat er na 30 jaar geen invloed zal zijn ter hoogte van de boven- en onderzijde van het model.



Figuur 6
Berekende temperatuurafname als gevolg van warmtegeleiding uitgezet tegen de verticale afstand tot het reservoir na een plotselinge temperatuurdaling van 85 °C in het reservoir. Links de berekeningen voor een steenzout formatie (Zechstein) en rechts voor een schalie (Limburg Group).

2.2 Breuken binnen het modelgebied

Binnen de grenzen van het reservoirmodel is een aantal breuken aanwezig met een kleinere verticale verplaatsing (zie Figuur 7).



Figuur 7
Modelgrenzen en 5 breuken binnen het modelgebied die in het reservoirmodel zijn opgenomen.

De waarnemingen van de NAM geven aan dat sprake is van drukcommunicatie tussen alle delen van het Groningen Gasveld. Binnen het Groningen Gasveld is volgens het beschikbare kaartmateriaal van de NAM een netwerk van kleinere breuken aanwezig (NAM, 2016). De waargenomen drukcommunicatie is alleen te verklaren als de kleinere breuken niet volledig ondoorlatend zijn. Hiervoor zijn verschillende mogelijkheden:

1) De kleinere breuken zijn overal enigszins doorlatend;
2) Een deel van de kleinere breuken is doorlatend en de anderen zijn ondoorlatend.
3) De breuken zijn plaatselijk doorlatend en voor het overige deel ondoorlatend.

Voor de doorlatendheid van de kleinere breuken zijn dan ook verschillende aannames mogelijk. Om een idee te krijgen van de invloed van verschillende aannames op de uitkomsten, zijn hiervoor meerdere scenario´s doorgerekend:

1) Alle breuken binnen het modelgebied zijn ondoorlatend. Dit scenario wordt als onwaarschijnlijk beschouwd, maar is niet volledig uitgesloten.
2) De breuk aan de westzijde (lijn met zwarte bolletjes in Figuur 7) is doorlatend en de overige breuken zijn volledig ondoorlatend. Dit wordt als realistisch ongunstig scenario beschouwd.
3) Alle breuken zijn enigszins doorlatend, waarbij voor de permeabiliteit van de betreffende cellen in het model vermenigvuldigingsfactoren zijn gebruikt variërend van 0,001% (vrijwel ondoorlatend) tot 10% (redelijk doorlatend). Ook dit wordt als het meest realistische scenario gezien. Het is echter niet duidelijk welk van de vermenigvuldigingsfactoren nu precies het meest realistische beeld oplevert.
4) De doorlatendheid van de breuken is gelijk aan de doorlatendheid van het reservoir. Aangezien de grotere breuken de stroming tussen verschillende reservoirblokken hinderen of blokkeren, is de verwachting dat de kleinere breuken ook een verlaagde doorlatendheid hebben. Dit scenario lijkt daarom minder waarschijnlijk, maar is niet uit te sluiten.

2.3 Eigenschappen van de modellagen

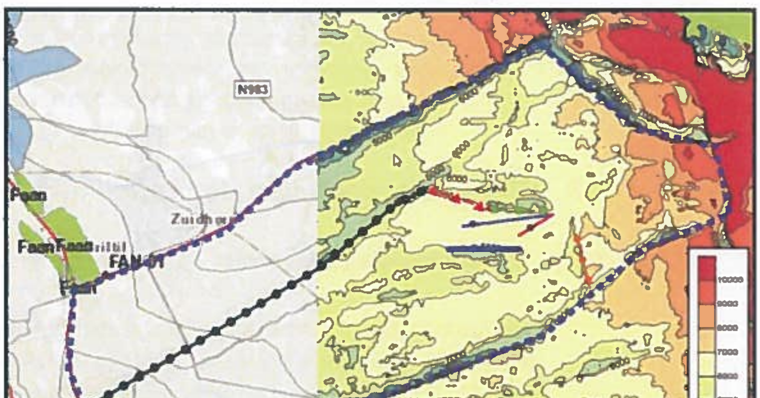
2.3.1 Transmissiviteit reservoir

De eigenschappen van het reservoir zijn voor het overgrote deel gebaseerd op de rapporten van Panterra (Panterra, 2014) en TNO (TNO, 2015) en het reservoirmodel van de RUG. Door verschillende gegevens te combineren is een kaart gemaakt met de te verwachten transmissiviteit (dit is de gemiddelde permeabiliteit van het reservoir vermenigvuldigd met de dikte van het reservoir: hoe hoger de transmissiviteit, hoe makkelijker het water door het reservoir kan stromen) berekend:

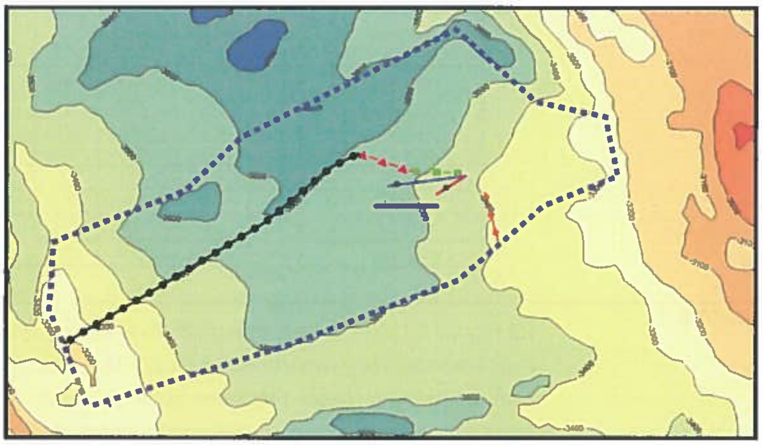
- De diepte van de top en de basis van de Slochteren Formatie zijn afkomstig uit het reservoirmodel van de RUG (het verschil geeft de dikte van de Slochteren Formatie);
- De dikte van de slecht doorlatende kleirijke laag aan de top van de Slochteren Formatie (Ten Boer Member) is berekend aan de hand van de gegevens uit het rapport van Panterra (dikte Slochteren Formatie – dikte Ten Boer Member = effectieve dikte van het te gebruiken reservoir);
- De relaties tussen (1) de diepte van het midden van het reservoir en de gemiddelde porositeit en (2) de gemiddelde porositeit en de gemiddelde permeabiliteit uit het rapport van TNO zijn gebruikt om de te verwachten gemiddelde permeabiliteit van het reservoir te schatten.

Figuur 8 toont de berekende transmissiviteit voor het gebied waarvan de gegevens uit het model van de RUG beschikbaar zijn. Hieruit blijkt dat de te verwachten transmissiviteit in de omgeving van de beoogde ondergrondse putlocaties redelijk constant is (tussen 6 en 7 Dm). Doordat het reservoir bij de oostelijke randen van het gekozen modelgebied minder diep ligt (wat leidt tot een hogere permeabiliteit), is de transmissiviteit hier duidelijk hoger. Omdat het reservoir ook in het meest westelijke deel van het gekozen modelgebied minder diep ligt (zie Figuur 9), wordt ook daar een hogere transmissiviteit verwacht.

Figuur 8
Te verwachten transmissiviteit van het reservoir [mDm].



Figuur 9
Diepte [m] van de top van de Slochteren Formatie volgens v4 DGMdiep.



In het reservoirmodel is aangenomen dat de transmissiviteit over het gehele gebied gelijk is aan de transmissiviteit ter plaatse van het geothermie systeem. Aangezien de effecten vooral zullen optreden in de directe omgeving van de putten is dit een goede benadering voor het berekenen van de effecten van het geothermie systeem. Omdat de gemiddelde transmissiviteit in het modelgebied hoger is dan ter plaatse van het geothermie systeem, zullen de berekende effecten wat groter zijn, dan in werkelijkheid (worst-case benadering).

Om te voorkomen dat de effecten van het geothermie systeem worden onderschat is in het reservoirmodel uitgegaan van de P90 waarde van de transmissiviteit uit de Doubletcalc berekeningen van TNO (4,5 Dm).

Transmissiviteit sublagen

In het rapport van Panterra (2014) is het reservoir onderverdeeld in een aantal sublagen en zijn de eigenschappen van de verschillende sublagen ingeschat. In het rapport van TNO is aangegeven dat deze opdeling van het reservoir in sublagen van belang is om mee te nemen in de reservoirmodellering. In het reservoirmodel is het reservoir daarom opgedeeld in een aantal sublagen. De zeven lagen uit het rapport van Panterra zijn in het reservoirmodel teruggebracht naar drie lagen (Figuur 10). Hierbij is als criterium aangehouden dat de permeabiliteit van de samen te voegen lagen vergelijkbaar moet zijn.

Figuur 10
Eigenschappen van de deellagen die in het onderzoek van Panterra (2014) zijn onderscheiden. De gekleurde blokken geven aan welke deellagen zijn samengevoegd tot één modellaag in het reservoirmodel.
K = permeabiliteit.
T = Transmissiviteit.

Table 6.5 Arithmetic field averages per zone for all analysed wells as described in Section 6.2.2 and for the total Slochteren Formation (ROSL total). A cut-off of PHIE ≥ 10% was applied to discriminate net sand from gross interval thickness.

Zone Name	Gross [m]	Net Sand [m]	N/G [%]	PHIT [%]	PHIE [%]	K_{P90} — K_{P50} — K_{P10} [mD]	T_{P90} — T_{P50} — T_{P10} [mDm]
RO-7-SLU	28.5	27.5	96.4	18.9	17.2	1 – 5 – 18	34 – 130 – 492
RO-6-SLU	27.1	25.3	93.5	18.7	17.2	19 – 61 – 194	482 – 1538 – 4909
RO-5-SLL	36.7	33.8	92.1	17.9	16.6	19 – 59 – 190	628 – 2006 – 6404
RO-4-SLL	43.2	42.8	99.2	19.6	18.5	21 – 70 – 229	907 – 2980 – 9795
RO-3-SLL	25.6	23.5	91.7	18	17.1	17 – 57 – 187	407 – 1337 – 4393
RO-2-SLL	33	30	90.9	18.4	17.5	5 – 18 – 70	140 – 544 – 2111
RO-1-SLL	25.1	13.1	52	15.5	14.9	5 – 16 – 52	63 – 207 – 681
ROSL total	219.1	195.9	89.4	18.5	17.3	14 — 45 — 147	2661 — 8742 — 28786

Uit Figuur 10 blijkt dat het overgrote deel van de totale transmissiviteit aanwezig is in de middelste deellaag (waarin RO-3-SLL, RO-4-SLL, RO-5-SLL en RO-6- SLU zijn samengevoegd). Tabel 1 toont een overzicht van de meest relevante gegevens over de transmissiviteit van de drie deellagen van het reservoirmodel. Op basis hiervan is de volgende verdeling aangehouden:

Bovenste deellaag: 1,5% van de totale P90 transmissiviteit = 0,06 Dm
Middelste deellaag: 90,5% van de totale P90 transmissiviteit = 4,07 Dm
Onderste deellaag: 8,0% van de totale P90 transmissiviteit = 0,36 Dm

Tabel 1
Samenvatting van de beschikbare informatie over de transmissiviteit van de verschillende deellagen in het reservoirmodel. De gegevens zijn gebaseerd op de informatie uit het rapport van Panterra (2014).

		P90 Transmissiviteit	P50 Transmissiviteit
Data Panterra (gemiddelde)	Bovenste deellaag	0,03 Dm (1,3%)	0,13 Dm (1,5%)
	Middelste deellaag	2,42 Dm (91,1%)	7,86 Dm (89,9%)
	Onderste deellaag	0,20 Dm (7,6%)	0,75 Dm (8,6%)
SAU-01 (dichtstbij-zijnde put)	Bovenste deellaag	0,02 Dm (1,5%)	0,08 Dm (1,7%)
	Middelste deellaag	1,21 Dm (90,7%)	3,91 Dm (89,9%)
	Onderste deellaag	0,10 Dm (7,8%)	0,37 Dm (8,4%)

2.3.2 Dikte reservoir

Dikte reservoir

Voor de dikte van het reservoir is uitgegaan van de minimale waarde uit het rapport van Panterra (2014), namelijk 240 meter. Deze minimale waarde is bevestigd door TNO. Door deze minimale waarde aan te houden, zal de koude bel (die ontstaat door het infiltreren van het afgekoelde water) zich sneller verspreiden in het reservoir en zal het invloedsgebied na een bepaalde tijd zich verder uitstrekken in horizontale richting. De kans op beïnvloeding bij breuken is daardoor groter, zodat sprake is van een worst-case benadering.

Dikte deellagen

Op basis van de data uit het rapport van Panterra (2014) is voor de locatie van de putten bepaald welk aandeel van de totale dikte bij de verschillende deellagen hoort. Door dit percentage vervolgens toe te passen op de totale aangehouden dikte, is de dikte van de deellagen in het model bepaald (waarden in meest rechtse kolom).

Tabel 2 Informatie over het aandeel van de verschillende deellagen op de totale dikte van het reservoir en aangehouden diktes in het reservoirmodel.

	Verkregen via interpolatie	Gemiddelde van putten in de omgeving	SAU-01	Gebruikt in reservoirmodel	
Bovenste deellaag	16%	13%	24%	18%	40 m
Middelste deellaag	58%	61%	53%	57%	140 m
Onderste deellaag	27%	26%	22%	25%	60 m

2.3.3 Overige eigenschappen

Porositeit

Volgens het onderzoek van TNO ligt de porositeit van het reservoir tussen 13 en 18%. In het reservoirmodel is ervoor gekozen om uit te gaan van de minimale waarde van 13%. Dit betekent dat de thermische effecten zich in het model relatief snel zullen verbreiden, waardoor het thermisch invloedsgebied na 30 jaar relatief groot zal zijn (worst-case benadering).

Bergingscoëfficiënt

De bergingscoëfficiënt van het reservoir bepaalt hoe snel de drukveranderingen in het reservoir reageren op de onttrekking en infiltratie door het geothermie systeem. Hoe lager de bergingscoëfficiënt, hoe sneller de drukveranderingen zich zullen verspreiden. De bergingscoëfficiënt (S) kan als volgt worden berekend:

$$S = \rho g D(\alpha + n\beta)$$

, waarin ρ de dichtheid van het water is, g de valversnelling (9,81 m/s^2), D de dikte van het reservoir, α de samendrukbaarheid van het poreuze gesteente, n de porositeit en β de samendrukbaarheid van water. In het model is voor α een waarde van $3{,}5 \cdot 10^{-10}$ gebruikt (Horne, 1990).

Thermische eigenschappen

De warmtecapaciteit van het reservoir wordt bepaald door de porositeit van het reservoir en de warmtecapaciteiten van het water en het gesteente (de korrels). In het reservoirmodel is de warmtecapaciteit van het gesteente opgegeven.

De warmtegeleidingcoëfficiënt van het reservoir is geschat op basis van de porositeit (Revil, 2000) en nog iets naar beneden bijgesteld omdat de zandsteen ook een laag percentage klei bevat.

Tabel 3 geeft een overzicht van de aangehouden warmtecapaciteiten, warmtegeleidingcoëfficiënten en de overige eigenschappen van de modellagen.

Tabel 3
Overzicht van de aangehouden eigenschappen van de lagen in het reservoirmodel.

Modellaag	Diepte	Permeabiliteit	Porositeit	Warmtecapaciteit korrelskelet	Warmtegeleidings-coëfficiënt
	[m]	[mD]	[%]	[MJ/(m³ °C)]	[W/(m °C)]
Zechstein	3175 - 3355	0,001	8	1,9	3,2
Ten Boer	3355 - 3425	0,001	8	2,3	2,1
RO-7	3425 - 3465	1,5	13	2,0	4,5
RO-3-6	3465 - 3605	29	13	2,0	4,5
RO-1-2	3605 - 3665	6	8	2,0	4,5
Limburg Groep	3665 - 3915	0,001	8	2,3	2,1

Temperatuur

In overeenstemming met de verwachtingen van Panterra en TNO is voor het reservoirmodel uitgegaan van een gemiddelde reservoir temperatuur van 120 °C.

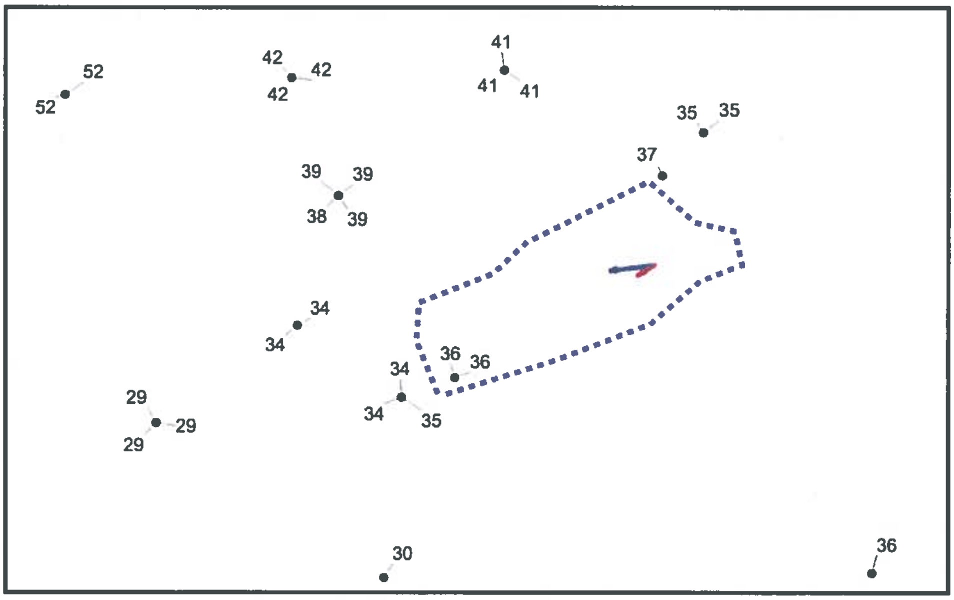
Zoutgehalte

Voor het zoutgehalte van het water in het reservoir is 250 gram per liter aangehouden (Panterra, 2014 en TNO, 2015).

Druk in het reservoir

Op basis van de database met drukmetingen die beschikbaar zijn op het Nederlands Olie en Gas Portaal (NLOG) is een kaart gemaakt van de overdruk in het reservoir (voorafgaande aan eventuele winning van gas of olie uit de betreffende putten). Hierbij zijn alleen de drukmetingen gebruikt die als betrouwbaar zijn aangemerkt. Het vermoeden bestaat dat er op dit moment niet of nauwelijks sprake is van drukdaling ten opzichte van de oorspronkelijke situatie (zie hoofdrapport). In het reservoirmodel is daarom uitgegaan van een overdruk van 37 bar. Als de werkelijke druk anders is, dan heeft dat geen gevolgen voor de uitkomsten van het reservoir model: de berekende veranderingen van de drukken en temperaturen blijven gelijk.

Figuur 11 Gemeten overdrukken [bar] in de omgeving. Het modelgebied is weergegeven met de blauwe geblokte lijn.



2.4 Geothermie systeem

Voor de berekeningen aan het geothermie systeem zijn de volgende uitgangspunten gehanteerd:

- voor de ondergrondse locaties van de putten is uitgegaan van de locaties uit het detail ontwerp (WEP, 2014);
- het maximale debiet van het systeem is 200 m^3/uur;
- elk jaar maakt het systeem 8.000 vollasturen (dat betekent dat het systeem in het model nagenoeg het gehele jaar op volle capaciteit draait);
- het systeem is gedurende 30 jaar in bedrijf;
- de temperatuur van het geïnfiltreerde water is 35 °C.

3 Resultaten reservoirmodellering

3.1 Validatie software

De berekeningen zijn uitgevoerd met het softwarepakket HSTWin3D (Kipp, 1998). Voordeel van HSTWin3D is dat dit softwarepakket relatief eenvoudig is, waardoor snel kan worden gewerkt. Nadeel is dat dit de mogelijkheden van dit softwarepakket minder uitgebreid zijn dan van andere softwarepakketten. Om er zeker van te zijn dat de resultaten van HSTWin3D overeen komen met de resultaten van andere, meer uitgebreide softwarepakketten is als eerste stap een validatie uitgevoerd door de resultaten van HSTWin3D te vergelijken met de resultaten van het softwarepakket Petrasim (Thunderhead Engineering, 2015). Beide softwarepakketten zijn gemaakt (en gevalideerd) voor het uitvoeren van berekeningen aan transport van warmte en water in poreuze gesteenten. Als met beide programma's dezelfde situatie wordt doorgerekend, blijken de resultaten inderdaad (vrijwel) overeen te komen.

3.2 Scenario's

De effecten van het geothermie systeem zijn berekend voor een aantal scenario's (zie ook paragraaf 2.2):

Scenario 1) Alle breuken binnen het modelgebied zijn ondoorlatend. Dit scenario wordt als onwaarschijnlijk beschouwd, maar kan niet volledig worden uitgesloten.

Scenario 2) De breuk aan de westzijde (lijn met zwarte bolletjes in Figuur 7) is doorlatend en de overige breuken zijn volledig ondoorlatend. Dit wordt als realistisch ongunstig scenario beschouwd.

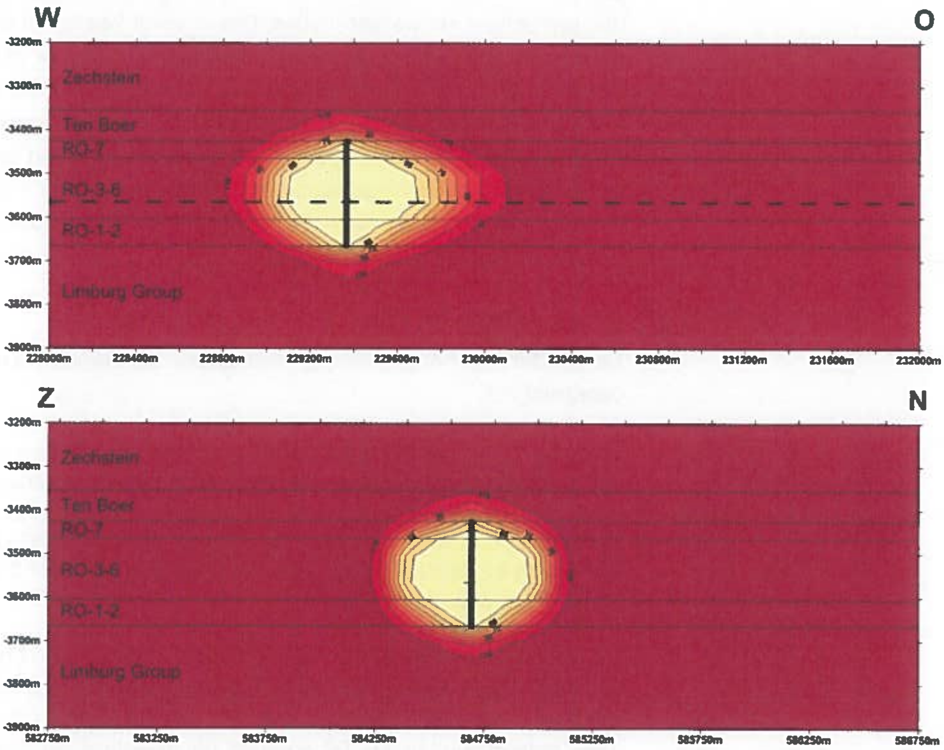
Scenario 3) Alle breuken zijn enigszins doorlatend (of plaatselijk doorlatend en plaatselijk ondoorlatend). Voor de permeabiliteit van de betreffende cellen in het model zijn vermenigvuldigingsfactoren zijn gebruikt variërend van 0,001% (vrijwel ondoorlatend) tot 10% (redelijk doorlatend). Dit wordt als het meest realistische scenario gezien. Het is echter niet duidelijk welk van de vermenigvuldigingsfactoren nu precies het meest realistische beeld oplevert.

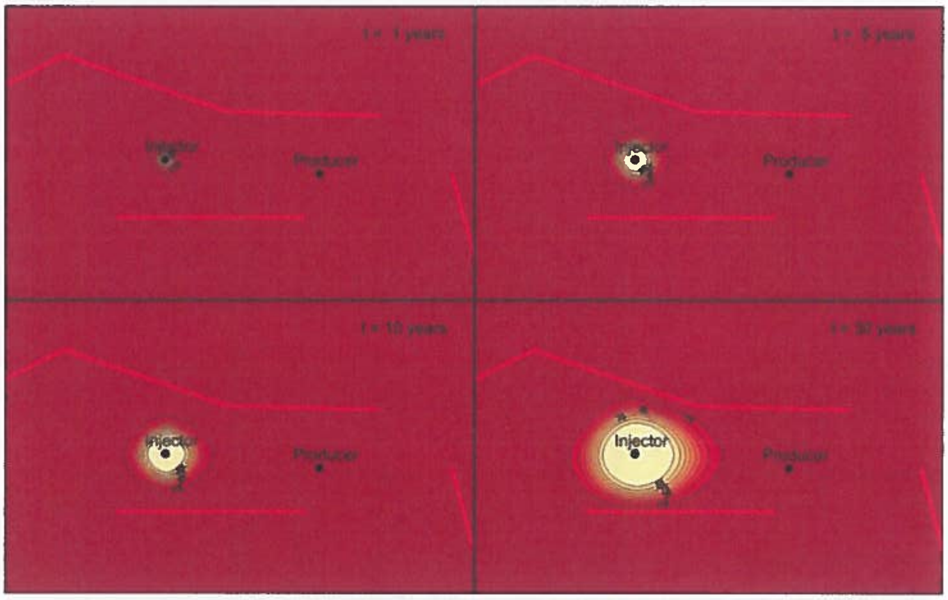
Scenario 4) De doorlatendheid van de breuken is gelijk aan de doorlatendheid van het reservoir. Aangezien de grotere breuken de stroming tussen verschillende reservoirblokken hinderen of blokkeren, is de verwachting dat de kleinere breuken ook een verlaagde doorlatendheid hebben. Dit scenario lijkt daarom minder waarschijnlijk, maar is niet uitgesloten.

3.3 Berekende temperaturen

De voor scenario 1 berekende temperaturen na 30 jaar geothermie zijn weergegeven in Figuur 12 (dwarsdoorsneden) en Figuur 13 (bovenaanzicht).

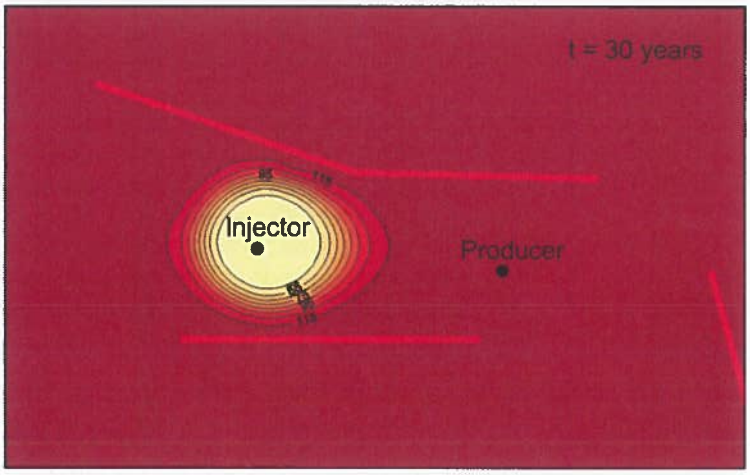
Figuur 12 Berekende temperaturen [°C] voor scenario 1, 30 jaar na het opstarten van het geothermie systeem. De horizontale stippellijn in de bovenste dwarsdoorsnede toont de diepte van het horizontale dwarsdoorsnedes.



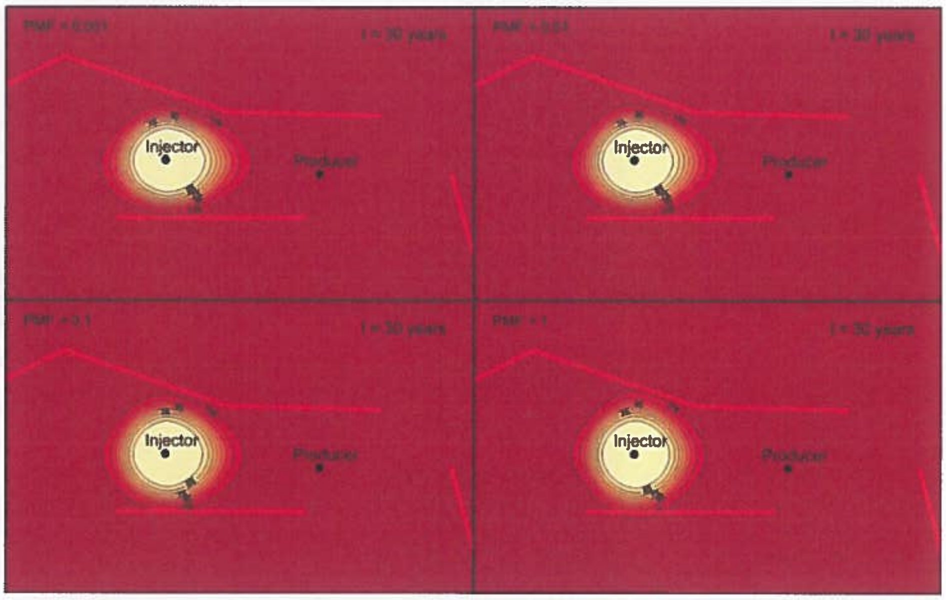


Figuur 13 Bovenaanzicht met de berekende temperaturen [°C] in het midden van het reservoir voor scenario 1. Weergegeven zijn de temperaturen 1, 5, 10 en 30 jaar na opstarten van het geothermie systeem. De initiële temperatuur in het reservoir is 120 °C. Het contourinterval is 5 °C. De buitenste contourlijn toont de begrenzing van het gebied waarbinnen meer dan 5 °C afkoeling is berekend.

De voor scenario 2 berekende temperatuur na 30 jaar (bovenaanzicht) is weergegeven in



Figuur 14 Berekende temperatuur na 30 jaar in het midden van het reservoir voor scenario 2.



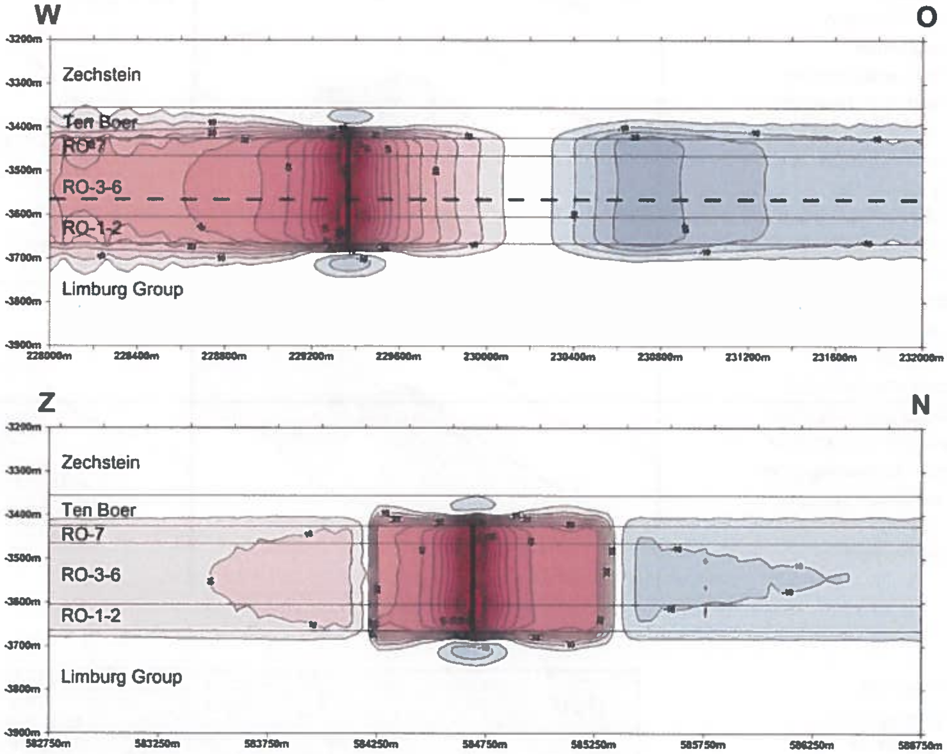
Figuur 15 Berekende temperatuur na 30 jaar in het midden van het reservoir voor de scenario's 3 en 4. PMF staat voor de "Permeability Multiplication Factor" die is gehanteerd voor de cellen waar de breuken doorheen lopen. Bij PMF 0,001 is de permeabiliteit in de betreffende cellen dus 0,1% van de oorspronkelijke permeabiliteit. Bij PMF 1 is de permeabiliteit van de cellen met de breuken gelijk aan die van de overige cellen (scenario 4).

Uit de berekeningen blijkt, dat de temperatuurinvloed in de meeste scenario's niet tot aan de breuken reikt. Alleen in de scenario's met doorlatende (scenario 4) of redelijke doorlatende breuken (scenario 3 met vermenigvuldigingsfactor 10%) is na 30 jaar bij de zuidelijk gelegen breuk een invloed van 5 à 10 °C berekend.

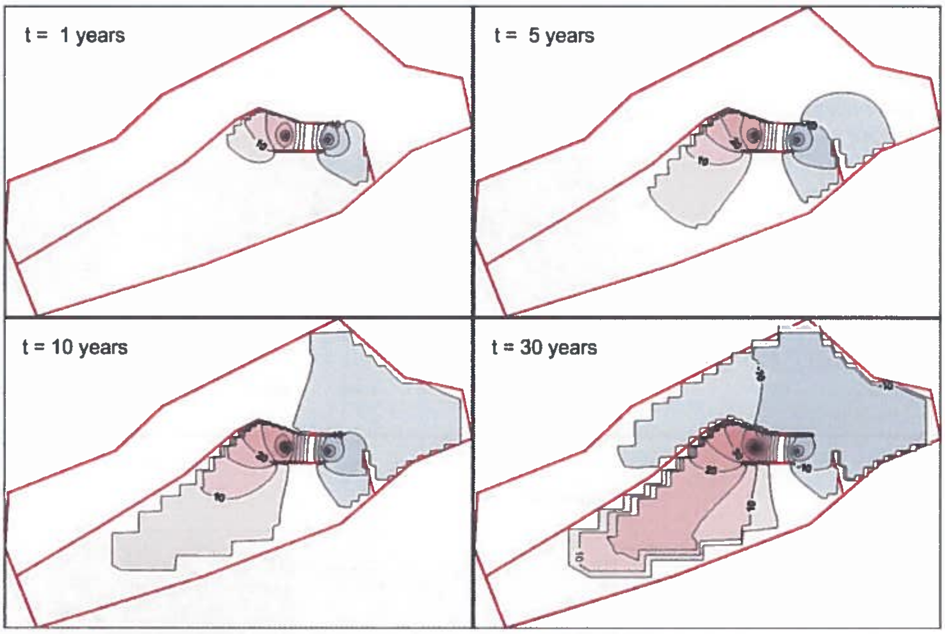
3.4 Berekende drukveranderingen

Figuur 16 toont voor scenario 1 twee dwarsdoorsneden met de berekende drukveranderingen na 30 jaar. In de omgeving van de putten is er niet of nauwelijks variatie in verticale richting in de berekende drukveranderingen: op elke locatie zijn de berekende drukveranderingen over de gehele dikte van het reservoir (vrijwel) gelijk. Op grotere afstanden van de putten neemt de variatie in de berekende drukveranderingen in verticale richting toe.

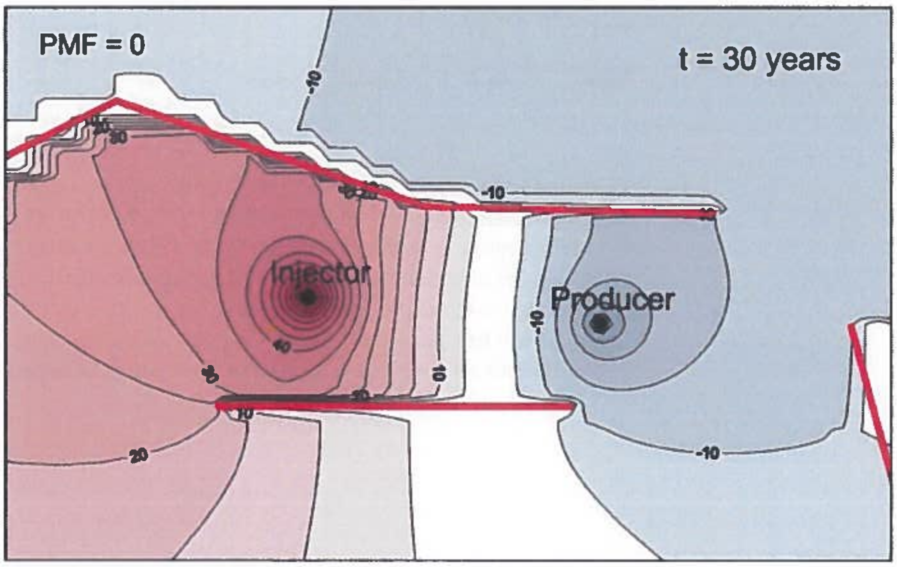
Figuur 16
Berekende drukveranderingen [bar] voor scenario 1, 30 jaar na het opstarten van het geothermie systeem. De horizontale stippellijn in de bovenste dwarsdoorsnede toont de diepte van het horizontale dwarsdoorsneden.



In Figuur 17 zijn voor scenario 1 de berekende drukveranderingen na 1, 5, 10 en 30 jaar geothermie weergegeven in het horizontale vlak, halverwege het reservoir. In verhouding tot de temperatuurveranderingen (zie Figuur 13) verspreiden de drukveranderingen zich veel sneller en strekken deze zich na 30 jaar veel verder uit. Bij de breuken in de omgeving van de putten is er dus veel sneller sprake van invloed op de druk dan op de temperatuur. In Figuur 18 is het gebied in de omgeving van de putten uitvergroot en zijn nogmaals de berekende drukveranderingen na 30 jaar geothermie weergegeven.



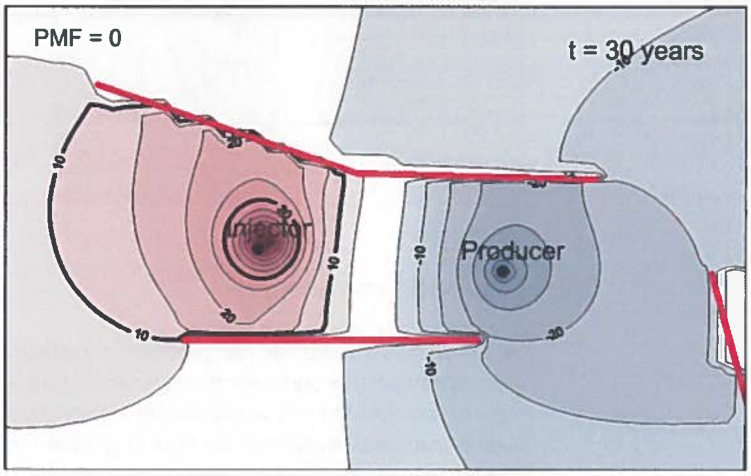
Figuur 17
Voor scenario 1 berekende drukveranderingen [bar] 1, 5, 10 en 30 jaar na het opstarten van het geothermie systeem. Het contourinterval is 5 bar. De buitenste contourlijn toont de begrenzing van het gebied waarbinnen meer dan 5 bar drukverandering is berekend. Negatieve waarden staan voor een drukverlaging en positieve waarden voor de drukverhoging.

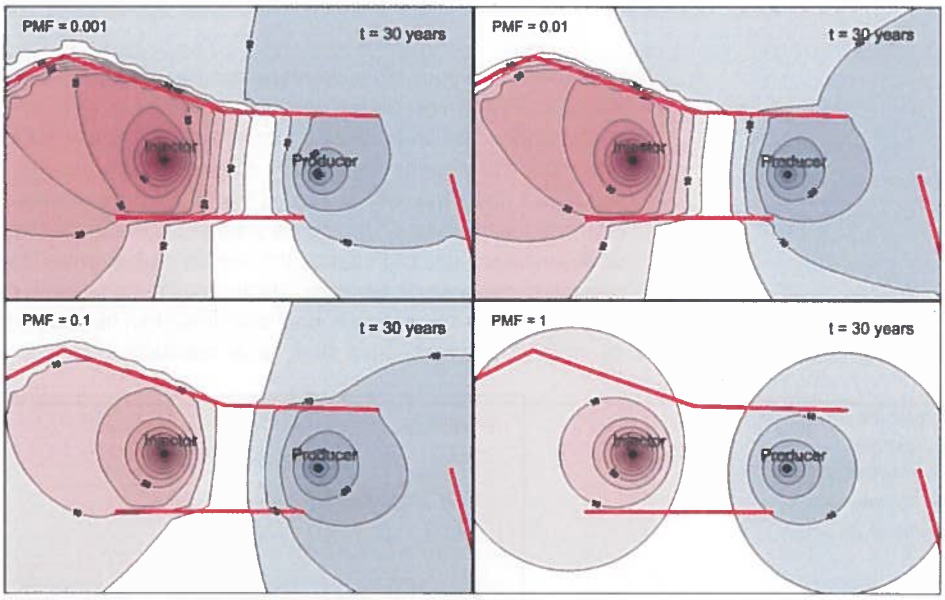


Figuur 18
Voor scenario 1 berekende drukveranderingen [bar] 30 jaar na het opstarten van het geothermie systeem (uitvergroting gebied rondom putten geothermie systeem).

In scenario 2 (Figuur 19) is de breuk aan de westzijde als volledig doorlatend aangenomen, waardoor er een veel betere druk communicatie mogelijk is tussen het gebied ten noorden en ten zuiden van de breuken noordelijk van de putten. Hierdoor nemen de berekende maximale drukveranderingen bij de putten en bij de breuken aanzienlijk af ten opzichte van scenario 1. In de scenario's 3 en 4 (Figuur 20) is de westelijk gelegen breuk wel aanwezig, maar zijn de breuken enigszins doorlatend of geheel doorlatend. Zoals te verwachten, blijkt uit de berekeningen blijkt dat de berekende drukveranderingen afnemen bij toenemende doorlatendheid van de breuken. Als de doorlatendheid van de cellen waarin de breuken aanwezig zijn 0,1% is van de doorlatendheid van het reservoir, dan lijken de resultaten in de omgeving van de putten sterk op de resultaten bij ondoorlatende breuken (scenario 1).

Figuur 19
Berekende drukveranderingen na 30 jaar voor scenario 2.





Figuur 20 Berekende drukveranderingen [bar] na 30 jaar in het midden van het reservoir voor de scenario's 3 en 4. PMF staat voor de "Permeability Multiplication Factor" die is gehanteerd voor de cellen waar de breuken doorheen lopen. Bij PMF 0,001 is de permeabiliteit in de betreffende cellen dus 0,1% van de oorspronkelijke permeabiliteit. Bij PMF 1 is de permeabiliteit van de cellen met de breuken gelijk aan die van de overige cellen (scenario 4).

3.5 Evaluatie resultaten

De berekende invloed van het geothermie systeem is bedoeld als input voor de geomechanische analyse en de "Seismic Hazard Assessment" (SHA). In het kader van de reservoirmodellering zijn verschillende scenario's doorgerekend. Als input voor de geomechanische analyse en de SHA is gekozen voor een worst-case benadering door gebruik te maken van de resultaten van scenario 1. Daarnaast is ook een wat minder ongunstige (meer realistische) benadering gebruikt, door ook de resultaten van scenario 2 door te rekenen.

In het rapport van de geomechanische analyse is een inschatting gemaakt van de stressveranderingen die nodig zijn om de breuken in de omgeving van het geothermie systeem te reactiveren. Daarnaast zijn voor de meest kritische breuk de veroorzaakte stressveranderingen berekend, op basis druk- en temperatuurveranderingen die met het reservoirmodel zijn berekend.

De ontwikkeling van de maximale sterkte van de eventuele seismiciteit die onder worst-case omstandigheden zou kunnen optreden, is door Q-con berekend. Op basis van de resultaten is nagegaan of het mogelijk is om de seismiciteit te beheersen door gebruik te maken van een “Traffic Light System” (TLS) (zie deelrapport Q-con).

Een belangrijke kanttekening bij de berekende effecten is dat deze afhankelijk zijn van de gekozen uitgangspunten. Door de uitgangspunten te wijzigen kunnen daardoor ook de te verwachten effecten worden beïnvloed. Een eenvoudig voorbeeld is dat de druk- en temperatuurveranderingen kunnen worden beperkt door het maximale debiet van het systeem te verlagen. Een andere mogelijkheid om de drukveranderingen in de omgeving van de putten te beperken is door de afstand tussen de putten te verkleinen. De locaties waar de druk- en temperatuurveranderingen optreden kunnen worden beïnvloed door de locaties van de putten te veranderen: bijvoorbeeld door het verwisselen van de producer en de injector. Dit betekent dat er mogelijkheden zijn om het ontwerp aan te passen en daarmee de invloed op de omgeving en de daaraan gekoppelde kans op seismiciteit te beperken.

Tot slot is van belang dat de situatie met betrekking tot de doorlatendheid van de breuken in de omgeving onzeker is en dat deze van invloed is op de kans op seismiciteit. Als de eerste put is aangelegd, dan kan hierover meer zekerheid worden verkregen door een productietest uit te voeren.

Literatuur

Horne (1990). Modern well test analysis - A computer-aided approach..

IEAGHG (2015). Criteria of Fault Geomechanical Stability during a Pressure Build-up. Ref. 2015/04, April. 2015.

Kipp, K.L. (1998). HST3D: A computer code for simulation of heat and solute transport in three-dimensional groundwater flow systems. USGS, Water-Resources Investigation. 1998Report 86-4095.

NAM (2013). Winningsplan Groningen 2013.

NAM (2015). Hazard and Risk Assessment for Induced Seismicity in Groningen. Interim Update November 2015. Report nr. EP201511200172.

NAM (2016). Technical Addendum to the Winningsplan Groningen 2016. Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field. Part I - Summary & Production.

Panterra (2014). Geothermal Energy in Groningen - Geological Investigation (Groot Geologisch Onderzoek Groningen). Panterra G1111.

Thunderhead Engineering (2015). User manual Petrasim 2015.

TNO (2013). Toetsing van de bodemdalingsprognoses en seismische hazard ten gevolge van gaswinning van het Groningen gasveld. Rapportnr. TNO 2013 R11953.

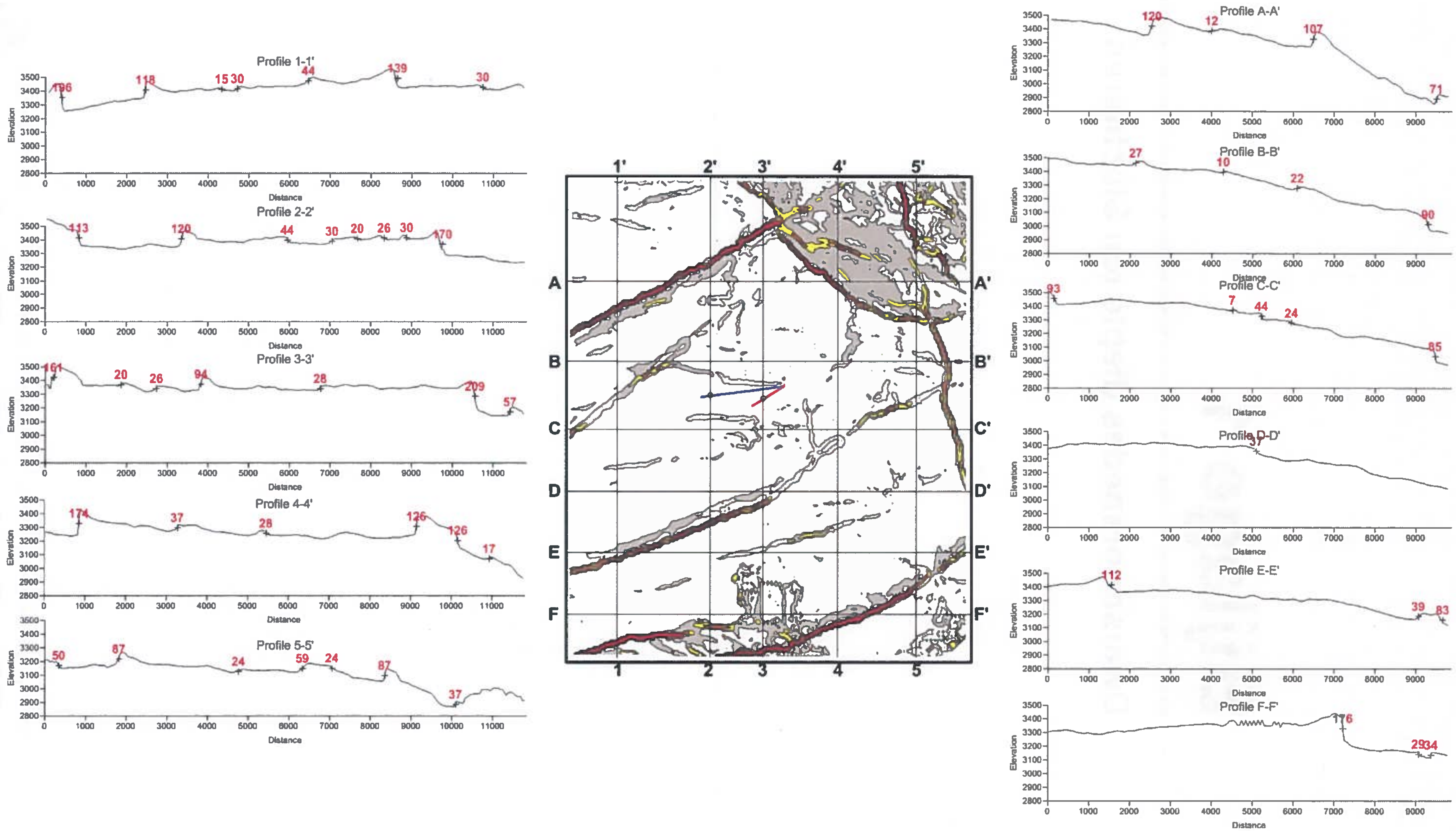
TNO (2015). Advies aanvraag Garantieregeling AARD04001 Aardwarmte ZernikeGeo. Referentie AGE 15-10.008.

Van Thienen-Visser and Breunese (2015). Induced seismicity of the Groningen gas field: History and recent developments.

Well Engineering Partners (2014). Geothermal Project Groningen - GRN-GT-01 & GRN-GT-02 Detailed Design. Version 2.1, 27-10-2014.

Bijlage 1

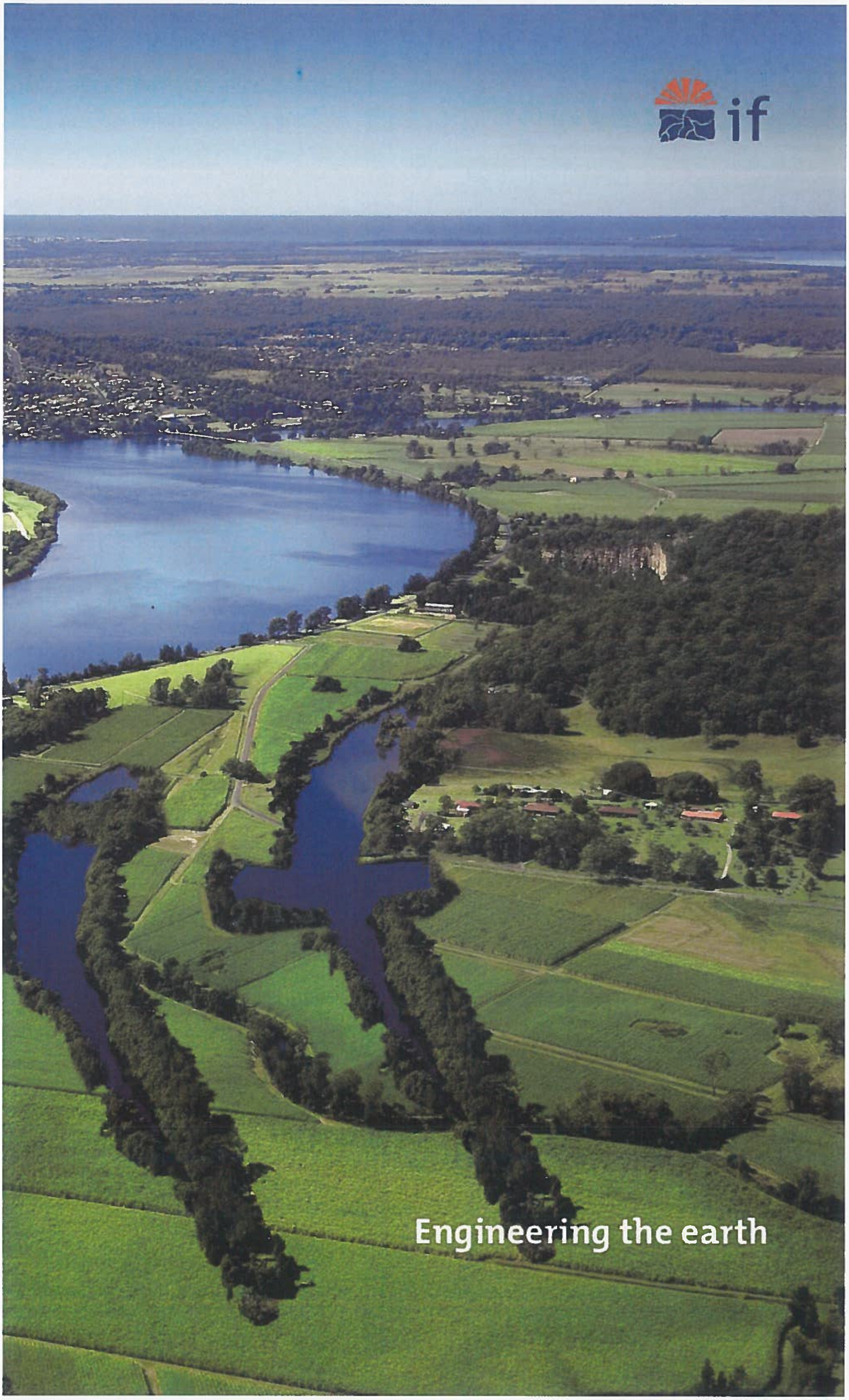
Dwarsdoorsnedes diepte top Slochteren



Dwarsdoorsnedes, waarop de diepte van de top van de Slochteren Formatie in beeld is gebracht. Voor de belangrijkste breuken is het verticale verzet in meters weergegeven in de dwarsprofielen (rode getallen). Bij de rode lijnen is sprake van een verzet van minimaal 100 meter. Bij de oranje lijnen is dat minimaal 80 meter en bij de grijze lijnen gaat het om enkele tientallen meters.

Bijlage 2

Geomechanische Evaluatie



Geomechanische Evaluatie

Geothermie WarmteStad Groningen

Engineering the earth

Geomechanische Evaluatie

Geothermie WarmteStad Groningen

Geomechanische Evaluatie

Geothermie WarmteStad Groningen

Opdrachtgever **WarmteStad**
Griffeweg 99
Postbus 1
9723 DV GRONINGEN
T 050 367 8746 | E @WarmteStad.nl
Contactpersoon: de heer

Adviseur **IF Technology bv**
Velperweg 37
Postbus 605
6800 AP ARNHEM
T 026 3535 555| E @iftechnology.nl
Contactpersoon: de heer

Colofon

Auteur:	**de heer**
Versie:	concept 1.0
Gecontroleerd door:	de heer
Vrijgegeven door:	de heer

Paraaf:

Geomechanische evaluatie

Inhoudsopgave

1

Stress situatie en breuk oriëntatie

1.1 Initiële stress situatie

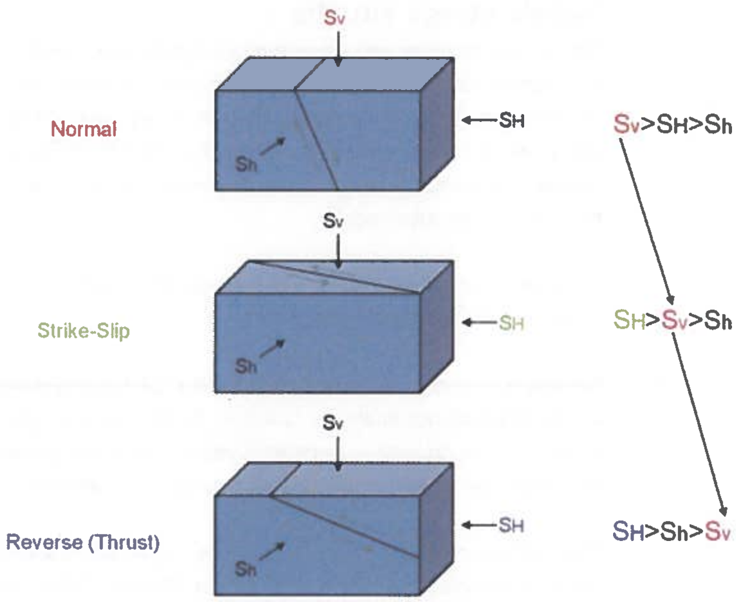
Om te bepalen of er een risico bestaat dat aanwezige breuken gereactiveerd worden door de effecten van het geothermische systeem is het van belang om de initiële stresssituatie in de ondergrond rondom de projectlocatie te bepalen. Hierbij wordt onderscheid gemaakt in drie verschillende stressen: Sv, SHmax en Shmin. Belangrijk is om op te merken dat de initiële stress situatie alleen bepaald kan worden voor de situatie dat er geen depletie van het reservoir is opgetreden.

Sv is de stress in verticale richting en wordt bepaald door het gewicht van de lagen die zich boven het reservoir bevinden.

SHmax is de maximale horizontale stress. De richting wordt bepaald aan de hand van borehole break-out analyses (Zoback, 2008). Indien er geen metingen aanwezig zijn, moeten om de grootte te bepalen diverse aannames gedaan worden. Hierdoor kan alleen een minimale en een maximale waarde bepaald worden (Zoback, 2008).

Shmin is de minimale horizontale stress. Algemeen aangenomen wordt dat deze loodrecht op de maximale horizontale stress staat (Zoback, 2008). De grootte wordt bepaald aan de hand van empirische relaties of aan de hand van leak-off tests.

De onderlinge grootte van de stress componenten bepaalt wat voor soort breuken in het gebied aanwezig zijn. In Figuur 1 is dit schematisch weergegeven.



Figuur 1 Schematische weergaven van relatie tussen stress componenten en breuk-regime.

1.2 Richting van het regionale stressveld

Op basis van een borehole break-out analyse in de boring NOR-45 is bepaald dat de richting van de maximale horizontale stress 335 (+/-10) NW bedraagt. Deze richting komt goed overeen met andere in Noord-Oost Nederland uitgevoerde borehole break-out analyses (Frikken, 1996; NAM, 2013; Rondeel H. E., Everaars J. S. L., 1993).

1.3 Magnitudes initieel aanwezige stress componenten

Sv is bepaald aan de hand van density logs uit omliggende olie en gas boringen (zie Tabel 1). Omdat de diepte van deze olie en gas boringen niet overeenkomen met de diepte van het reservoir ter plaatse van de projectlocatie, is Sv omgerekend naar een gemiddelde verticale stress gradiënt. Deze verticale stress gradiënt is vervolgens gebruikt om de verticale stress op de diepte van het reservoir bij de projectlocatie te berekenen. Bij het bepalen van de gradiënt zijn alleen olie en gas boringen gebruikt die qua geologisch opbouw vergelijkbaar zijn met de geologische opbouw op de projectlocatie. De berekende gemiddelde verticale stress gradiënt bedraagt 23,2 MPa/km. Bij een reservoirdiepte van 3.450 m resulteert dit in een Sv van 80,0 MPa.

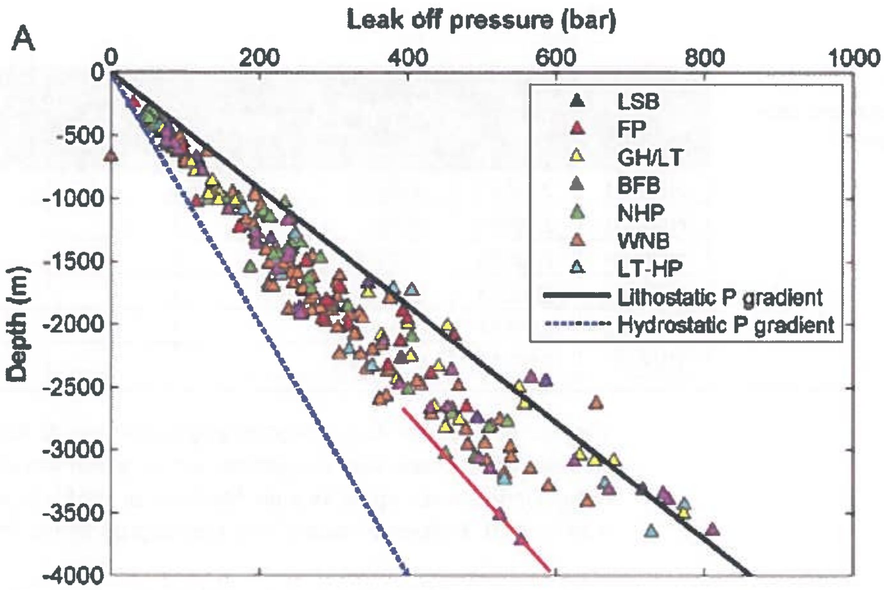
Tabel 1
Overzicht gebruikte boringen.

Well	X-RD	Y-RD	Break-out	Vp	Vs	density	Depth Slochteren [mTVDss]
HRS-01	239787	582633		x		x	2922-3096
NOR-31	224877	567927		x	x	x	2650-2804
NOR-04	223053	569855	x	x		x	2667-2828
NOR-01	226213	565591		x		x	2888-2953
SAU-01	231687	589103		x		x	3228-3490
BRA-01	219718	578926		x		x	2890-3094

Voor het bepalen van Shmin is gebruikt gemaakt van de relatie van Eaton (Eaton, 1969) en van leak-off test data. Voor het gebruik van de relatie van Eaton is een Poisson's ratio nodig. Op basis van Vp en Vs data (Mavko et al., 2011) is een Poisson's ratio berekend van 0,24 +/- 0,01. Bij deze Poisson's ratio bedraagt de Shmin 51,8 MPa.

In Figuur 2 is een overzicht van leak-off data weergegeven. Dit figuur is integraal overgenomen uit een publicatie van van Wees et al. (Van Wees et al., 2014). De leak-off data geeft aan bij welke druk het reservoir bezwijkt. Een regressie lijn door de datapunten geeft de frac gradiënt. Op basis van de regressielijn door de datapunten ter hoogte van het reservoir kan de minimale Shmin bepaald worden. De frac gradiënt ter hoogte van het reservoir bedraagt (rode lijn in het figuur) 15 MPa/km. Bij een diepte van 3.450 m bedraagt Shmin 52,5 MPa. Deze waarde komt redelijk overeen met de waarde berekend op basis van de relatie van Eaton. Voor de berekeningen is daarom een Shmin van 52,0 MPa gehanteerd.

Figuur 2
Leak-off test data. (van Wees et al., 2014) Rode lijn is frac gradiënt ter hoogte van het reservoir.



De SHmax is bepaald met een relatie die beschreven wordt in Zoback (Zoback, 2008). Uit deze relatie volg dat de maximale waarde van Shmax voor een normal faulting regime ongeveer 78 MPa is. Deze berekende waarde komt goed overeen met de bewering van Frikken (Mulders, F.M.M, 2003) dat Sv~SHmax. In het technische addendum van het Winningsplan van Groningen 2013 (NAM, 2013) staat dat SHmax ongeveer 10% hoger is dan Shmin. Dit betekent dat SHmax rond de 57 MPa zou zijn. Dit is een grote afwijking ten opzichte van de berekende SHmax van 78 MPa. Dit kan goed verklaard worden doordat de ene waarde de ondergrens is, en de andere waarde de bovengrens. Om het effect van SHmax inzichtelijk te maken zullen de berekeningen in deze bijlage met beide waarden uitgevoerd worden. Opgemerkt moet worden dat verwacht wordt dat de lage waarde meer representatief is, aangezien deze op en aantal indirecte metingen gebaseerd is (NAM, 2013).

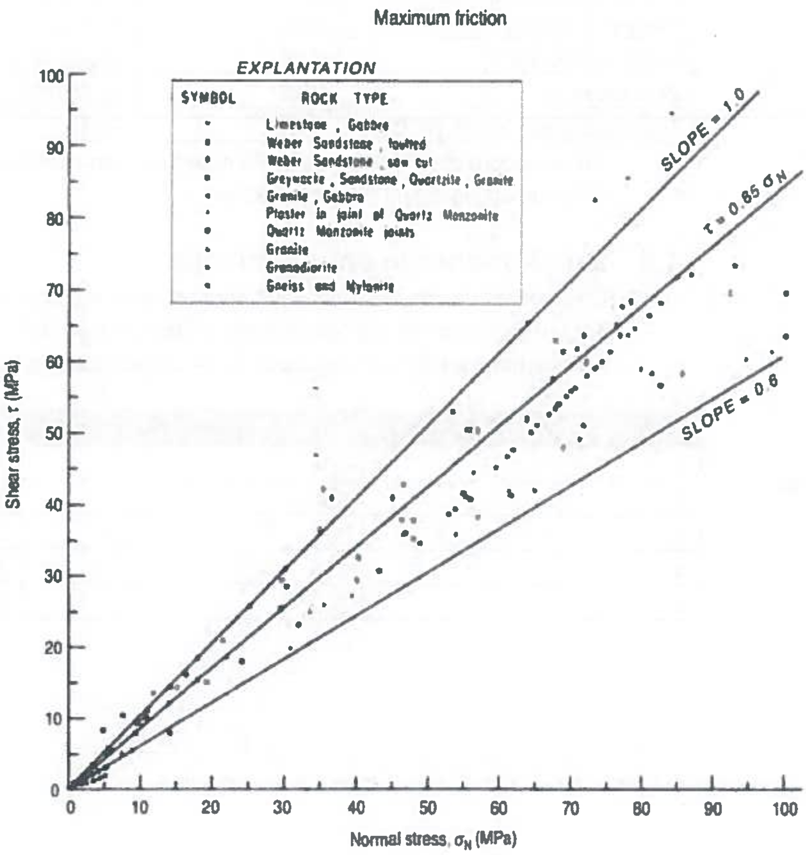
1.4 Young's modulus en frictie coëfficiënt

Een andere belangrijke parameter voor de geomechanische berekeningen is de Young's modulus. In het addendum op het Winningsplan van Groningen (NAM, 2013) staat een relatie tussen de porositeit en de Young's modulus. Op basis van deze relatie wordt een

Young's modulus van 15 GPa (13% porositeit) berekend, met een onzekerheid van ongeveer 5 GPa.

Voordat een breuk gereactiveerd kan worden moet er een bepaalde interne wrijving overwonnen worden. Dit wordt de frictie coëfficiënt genoemd. Als er geen data beschikbaar is, dan is het gebruikelijk om 0,6 aan te houden (Zoback, 2008). Uit metingen blijkt dat dit een conservatieve aanname is (zie Figuur 3).

Figuur 3
Frictie coëfficiënt.



Tabel 2 Samenvatting geomechanische parameters.

Paramater	Gehanteerde waarde	Gehanteerde onzekerheid
Richting maximale horizontale stress [°]	335 NW	+/- 10
Sv [MPa]	81,2	Geen onzekerheid meegenomen
SHmax [MPa]	57,0 en 78,0	Beide waardes zullen worden gebruikt
Shmin [MPa]	52,0	alleen worst case inschatting gebruikt
Young's modulus [GPa]	15,0	+/- 5
Poisson's ratio [-]	0,24	+/- 0,01
Frictie coëfficiënt [-]	0,60	alleen worst case inschatting gebruikt
Pore pressure	38,6[1]	+/- 0,5 MPa
Thermische exp. coeff. [1/°C]	$1*10^{-5}$	Geen.

[1]Reservoirdruk 35,0 MPa + 3,6 MPa overdruk (non-depleted).
[2]Waarde afkomstig uit (Zoback, 2008).

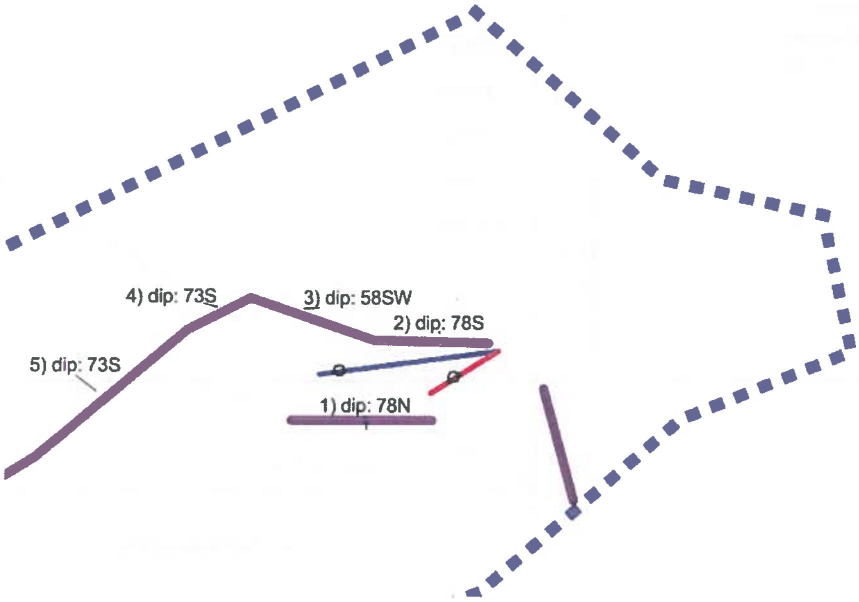
1.5 Breukoriëntatie en -reactivatie

De stabiliteit van de breuken wordt bepaald door hun oriëntatie (strike) in het stressveld een door de hellingshoek ten opzichte van de horizontaal (dip). Deze parameters zijn bepaald voor de breuken die zich het dichts bij de projectlocatie bevinden(zie Tabel 3 en Figuur 4).

Tabel 3 Data breuksegmenten.

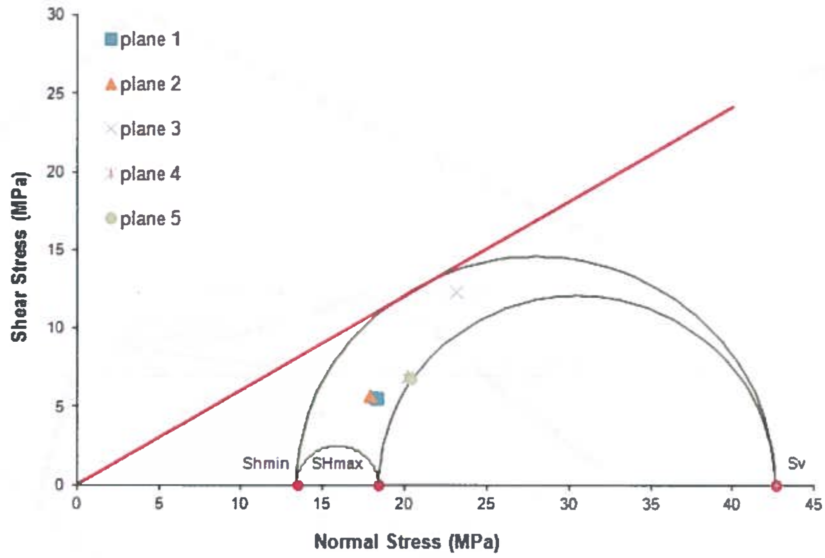
Breuksegment	Strike [°]	Dip en richting [°]
1	90	78N
2	95	78S
3	110	58SW
4	255	73S
5	230	73S

Figuur 4
Locatie breuksegmenten.

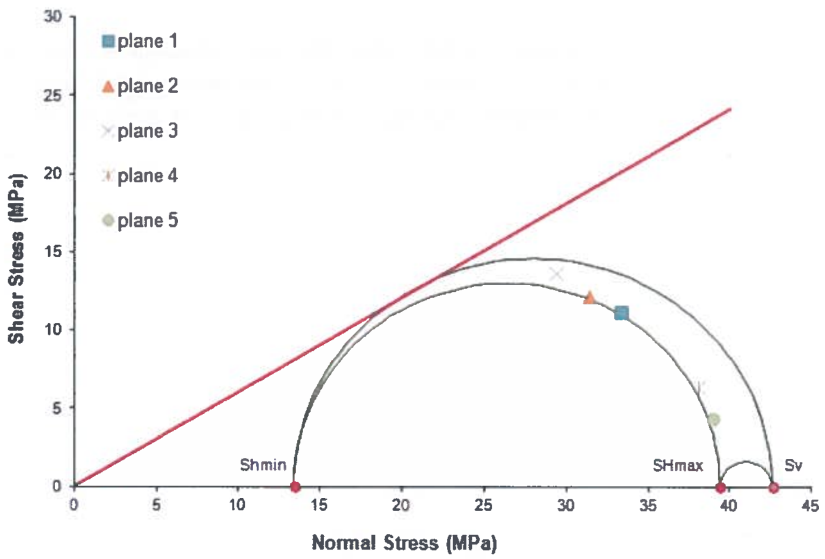


De stressverandering die nodig is om een breuk te reactiveren kan berekend worden met het Mohr-Coulomb criterium. In onderstaande twee figuren (Figuur 5 en Figuur 6) is dit voor twee situaties uitgewerkt. In beide figuren is uitgegaan van een poriedruk van 38,6 MPa.

Figuur 5
Mohr-Coulomb criterium voor een SHmax van 57 MPa.



Figuur 6
Mohr-Coulomb criterium voor een SHmax van 78 MPa.



In Tabel 4 staat de berekende reactivatie stress voor de verschillende breuksegmenten. Uit de tabel blijkt dat breuk segment 3 het meest kritisch gestrest is. Van de twee doorgerekende situaties is de situatie met een en SHmax van 57 MPa het meest kritisch. Zoals reeds opgemerkt is dit ook de meest aannemelijke situatie.

Tabel 4
Reactivatie stress.

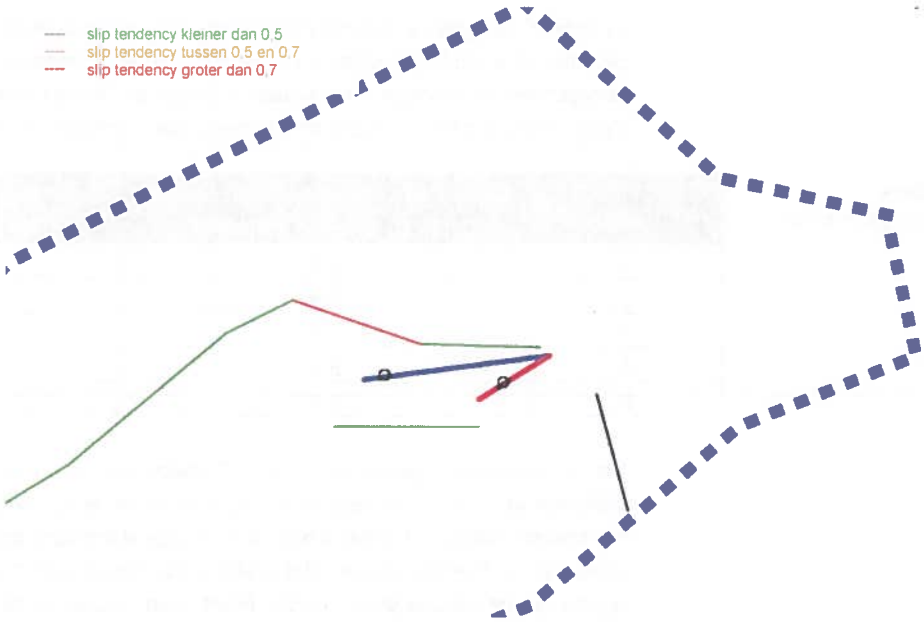
Breuksegment	Benodigde stress voor reactivatie [MPa], SHmax: 57 [MPa]	Benodigde stress voor reactivatie [MPa], SHmax: 78 [MPa]
1	5,8	11,2
2	5,4	8,8
3	1,9	5,4
4	5,5	19,0
5	5,3	16,5

Van de parameters genoemd in Tabel 2 spelen met name de overdruk in het reservoir, de oriëntatie van het stress veld, en de dip van de breuk een belangrijke rol. Een dip van 60° is het meest kritisch. Uit Tabel 4 blijkt dat het meest kritische breuksegment (nr 3) een dip van bijna 60° heeft en dat de benodigde stress voor reactivatie 1,9 MPa is. Het verhogen van de dip van dit breuksegment tot 60° heeft geen invloed op de benodigde stress voor breuk reactivatie.

Indien de poriedruk met 0,5 MPa verhoogd wordt en de stressveld oriëntatie wordt gewijzigd naar 325°, neemt de benodigde stress voor breuk reactivatie af tot 1,2 MPa. De poriedruk verhoging heeft de meeste invloed. In de berekeningen is voor Shmin en de frictie coëfficiënt een minimale waarde aangehouden. Dit betekent dat in werkelijkheid een hogere stressverandering benodigd is om de breuk te reactiveren dan is berekend. Een verhoging van Shmin naar 53,0 MPa (was 52,0 MPa) en een van de frictie coëfficiënt naar 0,65 (was 0,6) verhoogt de breuk reactivatie stress naar 3 MPa.

Een andere manier om te bepalen hoe kritisch breuken gestresst zijn is om de slip tendency van de breuk te berekenen (Neves et al., 2009). Hoe hoger de slip tendency hoe makkelijker de breuk gereactiveerd kan worden. In Figuur 7 zijn de berekende waarden voor de slip tendency weergegeven. Uit dit figuur blijkt dat breuk segment 3 wederom het meest kritisch is.

Figuur 7
Slip tendency breuken.



2

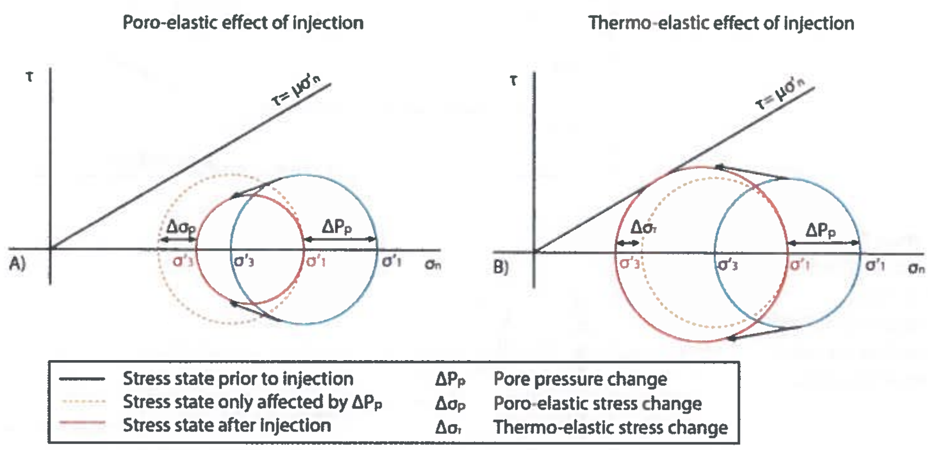
Poro- en thermo-elastische analyse

2.1 Effect van koud water infiltratie

Door de infiltratie van koud water treedt krimp van het gesteente op en daardoor verandert de ondergrondse stress situatie. In Figuur 8 is schematisch weergegeven wat er met de Mohr cirkel gebeurd op het moment dat koud water geïnfiltreerd wordt. De volgende processen kunnen onderscheiden worden (TNO, 2014):

1. Door de drukverhoging als gevolg van de infiltratie schuift de Mohr cirkel in zijn geheel naar links. De cirkel komt hierdoor dichter bij het failure criterium te liggen.
2. Door de temperatuur verlaging, wordt Shmin kleiner, waardoor de cirkel groter wordt. Ook hierdoor komt de cirkel dichter bij failure.
3. Door de verhoging van de poriedruk neemt het volume toe, waardoor de Shmin toeneemt, en de cirkel kleiner wordt. De cirkel komt daardoor verder van het failure criterium te liggen.

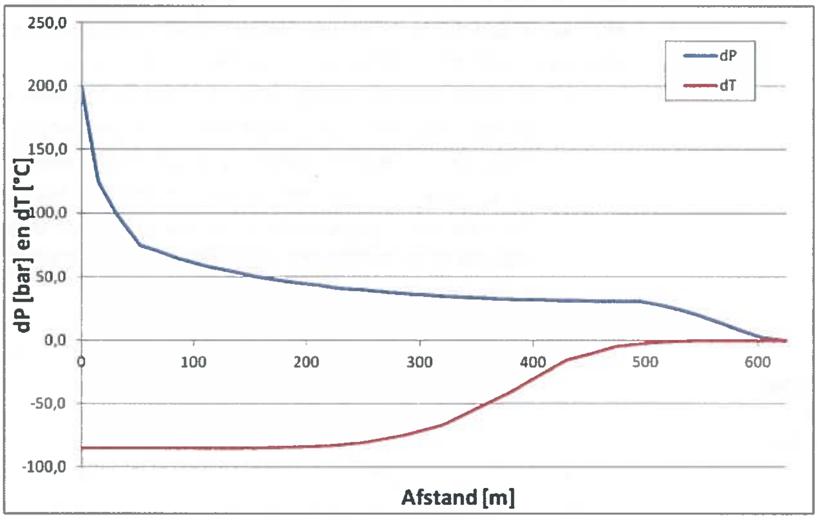
Figuur 8 Schematische effect van koud water infiltratie op de Mohr cirkel.



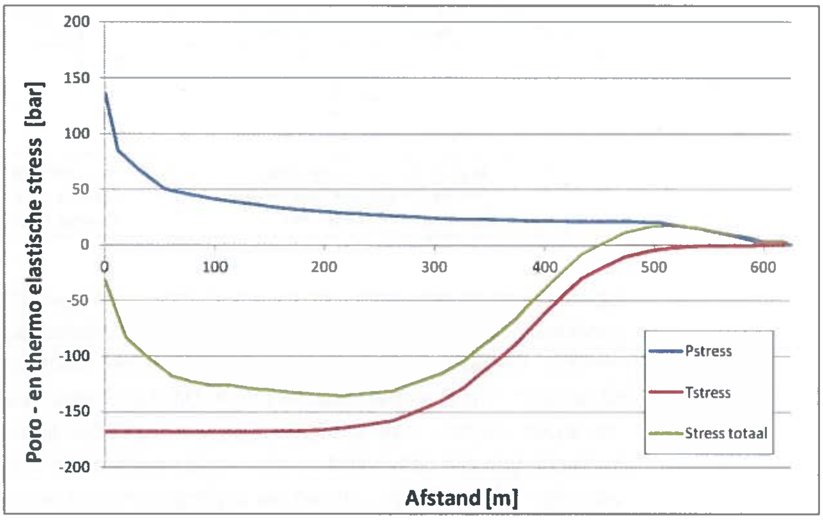
Op basis van de resultaten van de reservoirberekeningen zijn de poro- thermo-elastische berekeningen voor 2 scenario's uitgewerkt: 1) Gesloten breuken en 2) Deels gesloten breuken. De berekeningen zijn uitgevoerd voor een profiellijn die loopt vanaf de infiltratieput tot loodrecht op te meest kritische breuk. Dit is de kortste afstand tot de breuk en geeft de maximale effecten. In de profiellijn is de breuk gelegen op circa 550 m afstand. De berekeningen zijn gebaseerd op de vergelijkingen beschreven in (TNO, 2015, 2014). De waardes uit Tabel 2 zijn gebruikt als uitgangspunt voor de berekeningen.

In Figuur 9 en Figuur 10 zijn de resultaten van het "gesloten breuk" scenario weergegeven (situatie na 30 jaar).

Figuur 9
Berekende druk- en temperatuur veranderingen voor het "gesloten breuk" scenario.



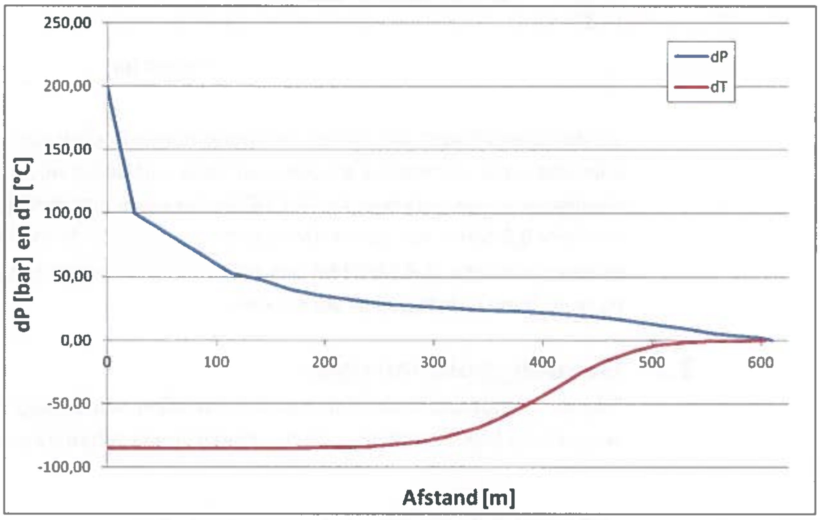
Figuur 10
poro- en thermo-elastische stressverandering voor het "gesloten breuk" scenario.



Uit Figuur 9 en Figuur 10 is af te lezen dat de poriedrukverhoging bij de breuk ongeveer 3 MPa bedraagt, het gecombineerde poro- thermo-elastische effect geeft een positief effect van 1,6 MPa. Dit betekent dat er een netto stressverandering van 1,4 MPa bij de breuk optreedt. Volgens het Mohr-Coulomb criterium is de reactivatie stress van het meest kritische breuksegment 1,9 MPa. Alleen bij worst-case aannames (reactivatie stress is dan 1,2 MPa) zou er dan reactivatie kunnen optreden.

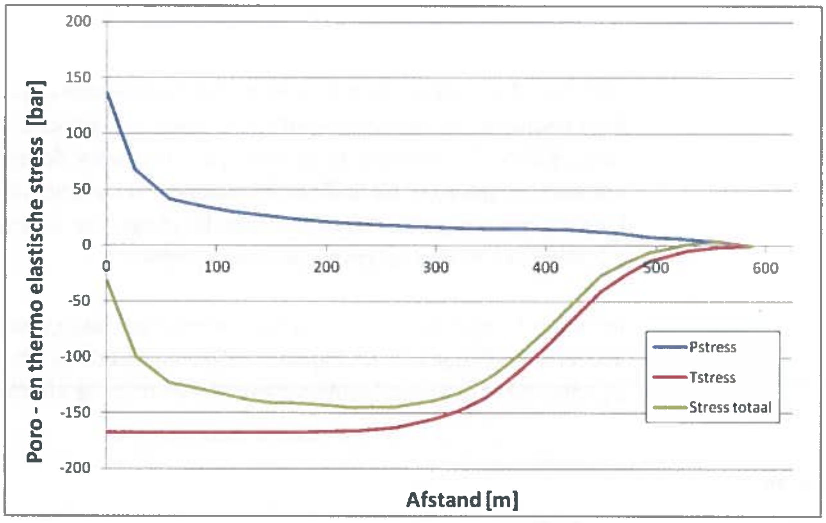
In Figuur 11 en Figuur 12 zijn de berekeningsresultaten voor het "deels gesloten breuk" scenario weergegeven. Uit Figuur 11 blijkt dat de drukveranderingen die optreden kleiner zijn dan in het gesloten breukscenario. De thermische effecten zijn min-of-meer gelijk.

Figuur 11
Berekende druk- en temperatuur veranderingen voor het "deels gesloten breuk" scenario.



Uit Figuur 12 blijkt dat er in dit scenario bijna geen effecten bij de breuk optreden.

Figuur 12
poro- en thermo-elastische verandering voor het "deels gesloten breuk" scenario.



Uit de berekeningen blijk dat er een poriedrukverhoging van circa 1 MPa bij de meest kritische breuk optreedt. Een deel van deze verhoging wordt gecompenseerd door de poro-elastische stress verandering (0,1 MPa). De netto stressverandering bij de breuk bedraagt hierdoor 0,9 MPa. Aangezien deze netto stressverandering kleiner is dan de verwachtte reactivatie stress (1,9 MPa) en ook kleiner dan de worst-case waarde (1,2 MPa). Er is daarom geen reactivatie te verwachten.

2.2 Gevoeligheidsanalyse

Thermo-elastische stress kan berekend worden met behulp van eq. 1 (TNO, 2015). Uit de vergelijking blijkt dat de thermische stress lineair afhankelijk is van alle parameters.

Figuur 13
Overgenomen uit (TNO, 2015)

$$\Delta\sigma_{thermal} = \alpha \cdot \frac{E}{(1-v)} \cdot \left(T_{init\_res} - T_{cooling}\right) \quad \text{eq. 1}$$

where:

α thermal expansion coefficient
E Young's modulus
v Poisson's ratio
T_{init_res} initial temperature of the reservoir
$T_{cooling}$ new temperature caused by injection of the cold fluid.

De spreiding in de Poisson's ratio heeft gezien de geringe spreiding in de onzekerheid geen significant effect op de berekeningsresultaten. Een verhoging van de Young's modulus resulteert in een hogere thermische stress. De ingeschatte hoogste waarde van de Young's modulus resulteert is een verhoging van de thermische stress met 30%.

Uit onderstaande relatie blijkt dat de poro-elastische stress, naast de drukverandering, alleen afhankelijk is van de Poisson's ratio. De onzekerheid in deze relatie is hierdoor niet groot.

Figuur 14 Overgenomen uit (TNO, 2015)

$$\sigma_{poro} = \frac{1-2v}{1-v} \cdot \left(P_f - P_{in}\right) = C \cdot \left(P_f - P_{initial}\right) \quad \text{eq. 6}$$

where:

$\sigma_{h,min}$ minimum horizontal stress

σ_{poro} poro-elastic stress

$\sigma_{th,tan}$ tangential component of the thermal stress

C constant (based on Poisson ratio ν)

2.3 Discussie en conclusie

De poriedruk heeft een grote invloed op de positie van de Mohr-cirkel en heeft ook invloed op de poro-elastische stress. De invloed van het geothermie systeem op de poriedruk wordt bepaald door de dikte en de permeabiliteit (is transmissiviteit) van het reservoir. De permeabiliteit kent een grote onzekerheid. Alle berekeningen zijn uitgevoerd met een zeer lage waarde van de transmissiviteit (P90: 90% kans dat de werkelijke transmissiviteit hoger is). De berekeningsresultaten geven hierdoor waarschijnlijk een overschatting van de werkelijk optredende effecten.

Uit metingen (Pepin et al., 2004) blijkt dat de werkelijk optredende thermo-elastische stress veranderingen in de prakrijk een stuk kleiner zijn dan op basis van de theoretische relatie berekend wordt. Pepin komt op basis van metingen met een thermische beïnvloeding van 0,3 bar/ °C, terwijl een beïnvloeding van 2 bar/°C berekend wordt. De methode van (Perkins and Gonzalez, 1985) kan worden gebruikt om hiervoor deels te corrigeren. Door de correctie methode toe te passen nemen de berekende thermo-elastische stress veranderingen met ongeveer 20% af.

Report title:	SHA Geothermal Project Groningen
Author(s):	
Report date:	31st May 2016
Project:	Warmtestad
Prepared for:	IF Technology
Version:	160531
Archive No.:	IF001

Contents

1 SUMMARY

A seismic hazard analysis is conducted for the planned geothermal system in the Groningen-2 concession, located in close proximity to the Groningen gas field. The physics of induced seismicity is well understood and, based on physical models, a deterministic approach is pursued. Subsurface parameter constellations are subject to uncertainties which are addressed by introducing different hazard scenarios.

First, we describe the physical mechanisms of induced seismicity with a focus on geothermal reservoirs. Characteristic features of reservoir seismicity are outlined that serve as a basis for risk mitigation based on a traffic light system (TLS).

For the seismic hazard we distinguish between contributions driven by (1) geothermal activities and (2) depletion of the nearby Groningen gas field. The hazard scenario related to geothermal activity is based on the assumption of negligible stress interference from the depleting Groningen gas field ('non depleted case'). A quantitative hazard assessment is performed for this scenario. Numerical simulations of stress perturbations related to operating the geothermal system are performed to estimate the maximum magnitude of induced reservoir events.

Numerical simulation results indicate that the occurrence of noticeable seismicity on the mapped faults is unlikely if hydro-geological conditions are as expected. For the extreme case of a compartmentalized reservoir, implying almost impermeable faults on a large scale, a potential maximum magnitude of M_w=3.2 for reservoir seismicity is estimated. In the hypothetical extreme case of an unknown, critically stressed fault in the immediate vicinity of the injection well, the maximum event magnitude may exceed the level of M_w=3.5. A risk mitigation scheme based on a TLS in combination with seismic monitoring is developed to constrain the seismic hazard to acceptable levels even in these hypothetical cases.

Hazard scenarios associated with the ongoing depletion of the Groningen gas field are strongly depending on future gas production patterns. Reservoir depletion in the gas field is a non-stationary process and associated induced seismicity cannot be reliably predicted for the 30 year's lifetime of a geothermal facility. Therefore, we restrict our hazard assessment to a qualitative discussion of the dominating effects.

2 THEORETICAL ASPECTS OF INDUCED SEISMICITY

2.1 Physical Mechanisms of Induced Seismicity

The phenomenon of man-made seismicity is known from different energy technologies such as mining, oil and gas exploitation, water impoundment and from geothermal reservoirs (National Research Council (NRC), 2012). The physical mechanisms underlying the induced seismicity are controlled by stress changes in the subsurface caused by anthropogenic activities.

If stress changes act on a pre-existing fracture or similar zone of weakness, seismicity may occur on the fracture if the shear stress exceeds the fracture strength. Let τ and σ_n denote the shear and normal stress resolved on a fracture plane, p_{fl} the *in situ* fluid pressure, μ the coefficient of friction and c_0 cohesion, then shear slippage occurs on the fracture if (e.g. Zoback, 2007):

Equation 1: $$\tau > \mu \cdot (\sigma_n - P_{fl}) + c_0$$

Stress perturbations can be described by Coulomb stress changes ΔCS, which can be defined as (Scholz, 2002):

Equation 2: $$\Delta CS = \Delta\tau - \mu \cdot (\Delta\sigma_n - \Delta p_{fl}),$$

with $\Delta\tau$, $\Delta\sigma_n$, and Δp_{fl} denoting changes of shear-stress, normal-stress and fluid pressure, respectively. Positive ΔCS values increase the tendency to failure of a fracture.

The occurrence of perceptible induced seismicity requires several conditions:

1. Shear-stresses need to be resolved on an existing shearing plane in the subsurface, e.g. a critically stressed fault.
2. The shearing plane needs to be mechanically strong enough to support high shear-stresses, implying a significant strength of the associated rocks. Seismic energy is only released if the hardness of the rocks is sufficiently large to allow for an almost instantaneous failure. Sedimentary rocks usually exhibit a smaller strength compared to crystalline rock (e.g. Abdullah, 2006). This could explain why (noticeable) seismicity caused by geothermal operations typically occurs in the crystalline rock (e.g. Evans et al., 2011).
3. The dimensions of the critically stressed fault need to be large enough to host a perceptible earthquake (see the following section).

2.2 Earthquake Strength

The strength of an induced earthquake is controlled by the dimension of the shearing plane on which the earthquake occurs:

Equation 3: $M_0 = G \cdot A \cdot d,$

where M_0 is the seismic moment, *G* denotes shearing modulus, *A* is the area of the shearing plane, and d is the average slip occurring on the shearing plane. Simple mechanical considerations reveal that the shear slip displacement *d* cannot become arbitrary large, but is limited by (1) the capacity of the surrounding rock to absorb deformation, and (2) by the amount of shear stress driving the failure process. Therefore, the dominating parameter controlling the strength of an induced event is the area *A* of the associated shearing plane.

Several empirical relationships exist to convert seismic moment to earthquake magnitude. Following Hanks & Kanamori (1979), we use

Equation 4: $M_w = 2/3 \cdot \log(M_0) - 6.1$

for the determination of the moment magnitude M_w.

As an example, the source dimensions of an earthquake with magnitude $M_w=2$ ($M_w=3$) are in the order of 0.02 km^2 (0.2 km^2).

2.3 Mechanisms of Geothermal Reservoir Seismicity

Different physical mechanisms may induce seismicity in geothermal reservoirs according to section 2.1. These include elevated pore pressure due to water injection, thermally induced stresses (thermal reservoir compaction) and stresses associated with water-level drawdown.

In situ pore pressure increase may be caused by hydraulic stimulation operations as well as by fluid circulation prior to reaching quasi-stationary hydraulic conditions. For the geothermal concept under consideration, no (large scale) hydraulic stimulations are considered and the focus of the current study is on hydraulic overpressure associated with fluid circulation.

There exist only few documented cases of induced seismicity interpreted as being caused by overpressures from mass balanced geothermal circulations. These include the geothermal system at Unterhaching (Germany), where a maximum magnitude of $M_L=2.4$ occurred (Megies & Wassermann, 2014) as well as the geothermal system at Landau (Germany) with a maximum event magnitude of $M_L=2.7$ (Bönnemann et al., 2010). In both systems, noticeable seismicity occurred after several years of operating the geothermal system.

Typical observations of geothermal reservoir seismicity include:

- The Kaiser-Effect, implying that induced seismicity occurs only at those locations in a reservoir, where previously experienced *in situ* fluid pressures are exceeded (e.g. Baisch et al., 2009). The Kaiser-Effect follows directly from the Mohr-Coulomb failure criterion (Baisch & Harjes, 2003).
- A systematic (temporal) increase of the maximum magnitude of the induced seismicity (Figure 1). This characteristic forms the basis for implementing a 'Traffic Light System' for risk mitigation (Bommer et al., 2006).
- The occurrence of seismic activity after stopping fluid injection/circulation (post-injection seismicity, 'trailing effect'), with the largest magnitude event frequently

occurring after shut-in (Figure 2; Baisch et al., 2006; 2010). The largest trailing effect was observed after the stimulation of the DHM geothermal reservoir at Basel (Switzerland). Here, a post-injection magnitude increase of 0.5 M_w magnitude units has been observed.

The second process that could lead to induced seismicity in a doublet system is the thermal contraction of reservoir rock causing stress perturbations on nearby faults. In general, it is difficult to unambiguously attribute observed seismicity to thermal contraction. Therefore, no empirical data base exists for this type of seismicity which can only be addressed by physical models.

3 GEOTHERMAL PROJECT GRONINGEN

3.1 Location

The proposed geothermal facility in the Groningen-2 concession area is located in the North of the town of Groningen (Figure 3). Towards the East, the concession area extends close to the boundary of the Groningen gas field.

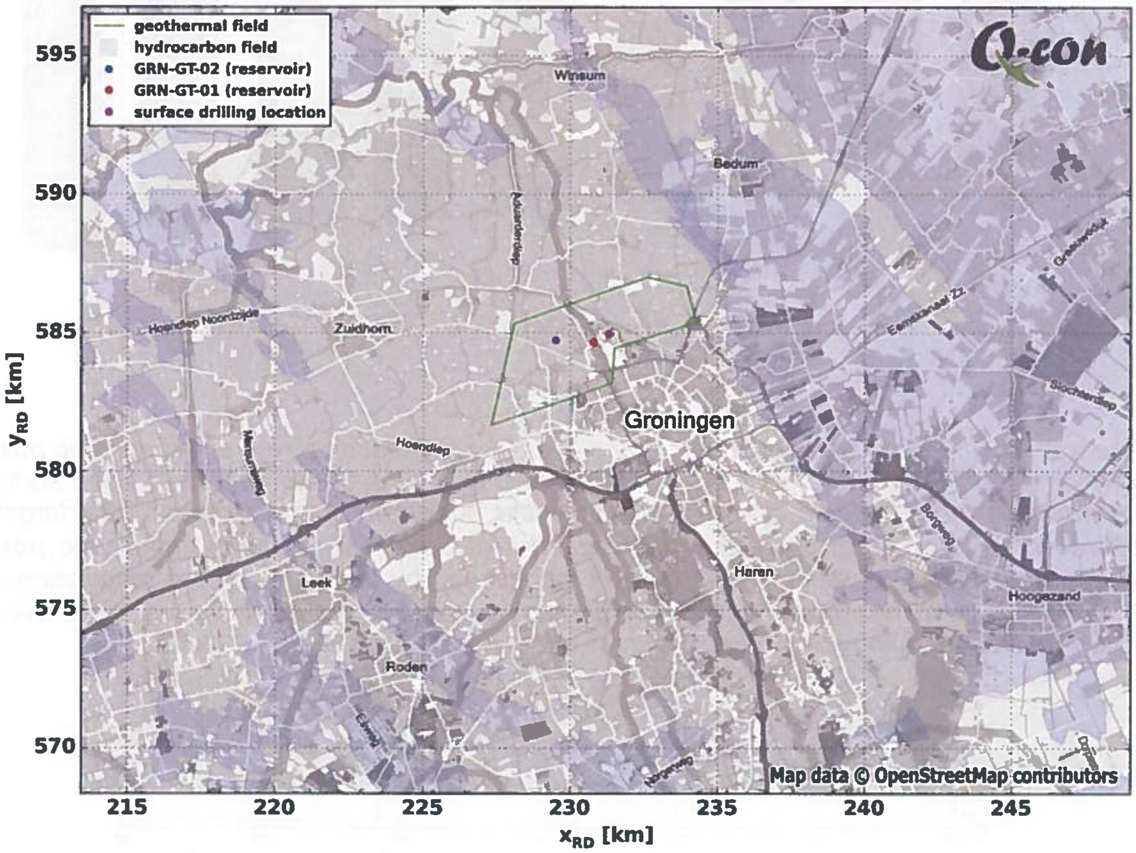


Figure 3: Outline of the geothermal field (Gronigen-2 concession) in the North of the town of Groningen (green). Locations of the planned production (GRN-GT-01) and injection well (GRN-GT-02) intersections with the top reservoir are shown. Adjacent gas fields are outlined by blue patches with the large Groningen gas field towards the East. RD coordinates in km.

3.2 System Design

The geothermal facility is supposed to supply heating for approximately 3,000 houses. The planned geothermal system consists of a doublet targeting the Permian Slochteren formation as the main aquifer. This is the same formation from which gas is produced in the Groningen field. The reservoir horizon is expected at a depth between 3.2-3.5 km. Spacing between production and re-injection well is designed to be 1.3 km at reservoir level. The doublet shall be operated in a mass-balanced circulation mode with cooled water being re-injected into the same reservoir formation. No extended reservoir stimulation operations are foreseen. Production temperature from the Slochteren formation is estimated at 120 °C. A circulation rate of at least 200 m^3/hrs and re-injection temperature of 35 °C is envisaged (PanTerra, 2014).

3.3 Background Seismicity

Natural seismicity in the Netherlands is mainly restricted to the South of the country, where faults are active (Dost & Haak, 2007). Accordingly, there has been no known natural seismicity at the geothermal site (KNMI seismic catalogue as of March, 2016).

In comparison, a large number of induced events related to gas production have been registered in the vicinity of the geothermal concession (Figure 5). These are related to gas production from the Groningen field towards the East of the planned geothermal site.

Seismicity in the north-eastern part of the Netherlands has been monitored by KNMI since 1996 with an accelerometer station network (17 stations in 2004, Dost et al., 2004). Upgrading of the network started in 2014 with accelerometers installed at some 70 locations (NAM, 2015; Figure 5). The estimated magnitude of completeness of the 1996 network is determined as M_L=1.5 assuming $M_L \approx M_w$ (NAM, 2015), although this assumption is currently reviewed by KNMI (B. Dost, pers. comm. Feb. 2016). Hypocenter location uncertainties are provided by KNMI on a generic, event-independent basis with ±500 m uncertainty in lateral directions and ±1000 m vertically. For Groningen seismicity, earthquakes are routinely located assuming a fixed depth of 3,000 m. Only after the recent upgrade of the network, hypocentral depth is estimated from the data. However, catalogued earthquake data referred to in the current study is generally based on a fixed depth assumption.

Figure 5 shows the seismicity distribution in the vicinity of the geothermal concession. Seismicity is most pronounced in the center of the Groningen gas field, where also the largest magnitude M_w=3.6 earthquake occurred (Huizinge earthquake, Dost & Kraaijpoel, 2013). Seismicity has migrated also in the western direction beyond the Groningen gas field. Some of these events are quite close (within 1.5 km) to the geothermal concession. Other fields towards the West of the geothermal concession show little or no seismicity at all.

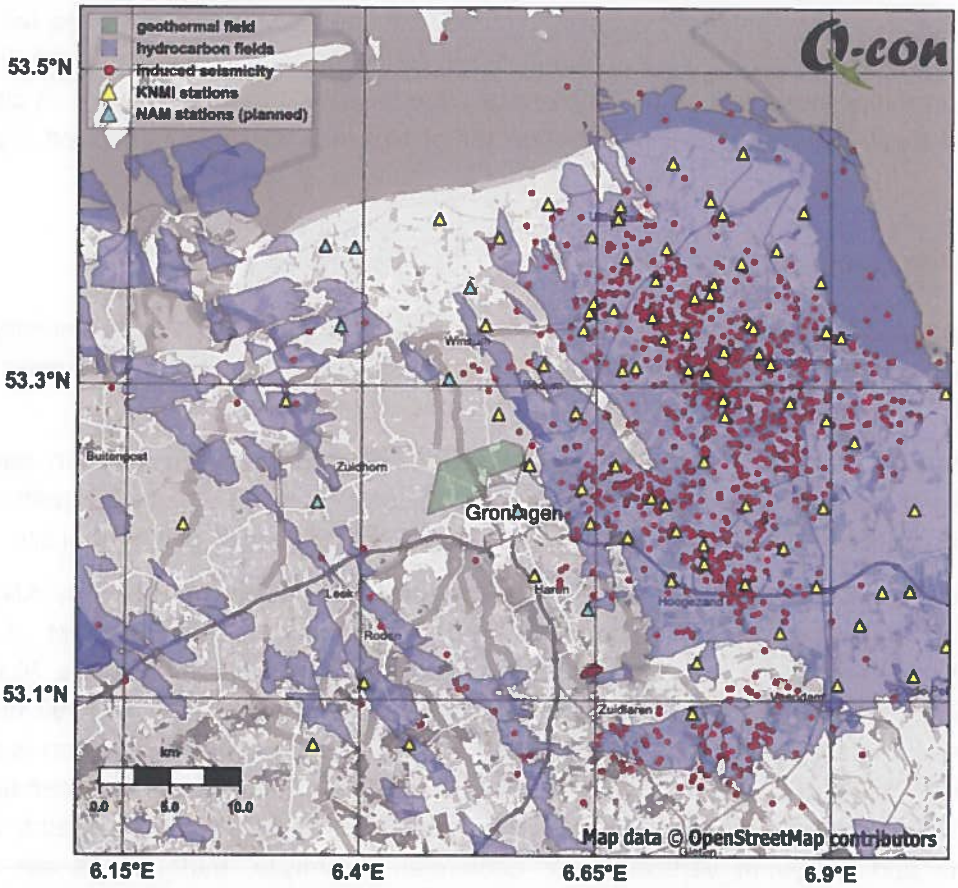


Figure 4: Induced seismicity (red dots) related to hydrocarbon fields (blue patches) in the vicinity of the geothermal concession (green patch). KNMI catalogue of induced seismic events as of March 2016. The largest seismic activity is related to the Groningen field towards the East of the planned geothermal site. Yellow triangles denote the KNMI station network. Light blue triangles denote planned locations of the NAM stations. Only the location of the nearest settlement is known for these stations. The stations have been positioned at the center of the respective settlement for displaying purposes. Data for NAM stations kindly provided by E. Kuperus, Shell (March 2016).

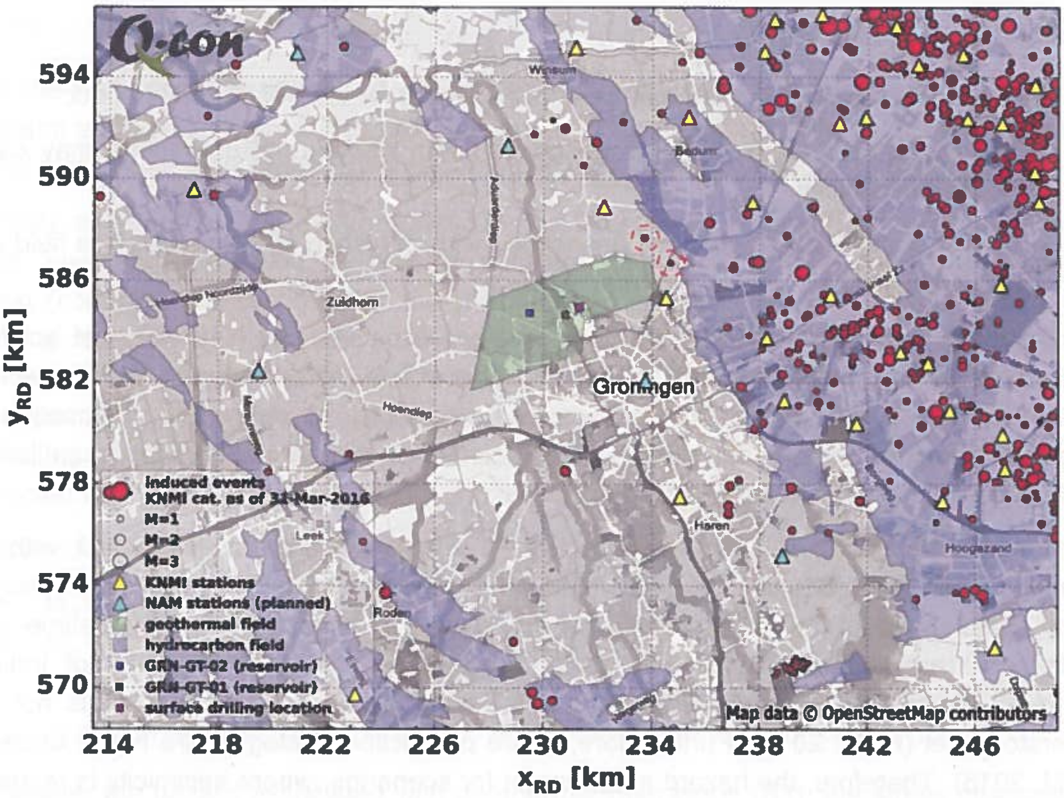


Figure 5: A close up view of Figure 4 demonstrates the migration of gas-production related seismicity towards the eastern rim of the geothermal concession. Dashed red circles denote location uncertainty in lateral direction for events closest to the geothermal concession. RD-coordinates in km.

For seismicity induced by fluid injections into the geothermal reservoir at Soultz-sous-Forêts, Baria et al. (2004) estimate a triggering threshold value of 3 MPa, which is consistent with numerical simulations of hydraulic overpressures in other EGS reservoirs (e.g. Cooper Basin, Baisch et al., 2015). A global lower bound value for a triggering threshold, however, does not exist as the lower bound value is location and time-dependent and can become arbitrarily small during the nucleation process of tectonic earthquakes. In principle, stress perturbations, such as dynamic stresses associated with passing waves from natural earthquakes place a lower limit to the triggering threshold. These stress perturbations can be as large as 1 MPa (Hill, 2008), but are depending on geometrical details of the receiver fault and therefore do not define a strict lower limit.

In the current study we assume a lower triggering threshold of 1 MPa which we consider to be conservative, in particular given the lack of natural seismic activity in the area. For comparison, TNO (van Eijs, 2006, table 2) has estimated a minimum depletion of 112 bar required for producing stress perturbations that are sufficiently large to induce reservoir seismicity in gas producing fields.

The trailing effect describes the occurrence of seismic activity after fluid injection (stimulation, circulation, well testing) has been terminated (section 2.3). As the largest magnitudes frequently occur after shut-in, the potential increase of event magnitudes must be accounted for when defining the TLS thresholds. After shut-In, further mitigation measures for reducing maximum magnitudes will be limited.

The magnitude increase of reservoir seismicity after shut-in depends on the level of previous maximum magnitudes. For the magnitude range considered in this study, the additional increase by 0.5 magnitude units (M_w) observed in the Basel project (section 2.3) can be taken as an indicative value. This is the largest magnitude increase during shut-in that has been observed so far in geothermal stimulation operations and is considered conservative in the context of seismic risk mitigation.

4.5 Induced Seismicity Associated with Gas Production

The gas production in the Groningen field has resulted in significant reservoir seismicity. Induced seismic events up to magnitude M_w=3.6 occurred in the past, causing non-structural material damage (NAM, 2015). Almost 1,000 induced events with magnitudes have been associated with the Groningen gas reservoir (KNMI catalogue as of March 2016), some located outside the boundaries of the Groningen field. Depletion of the gas reservoir, causing differential compaction, has been identified as the causative factor for reservoir seismicity (e.g. *Bourne et al., 2014*).

The seismic risk associated with gas production in Groningen has been investigated in extensive studies by NAM and others (e.g. NAM 2013, NAM 2015). Results from the NAM studies cannot be applied in the current context for several reasons, though. First, the NAM studies do not extend over the geothermal concession area. Second, seismic risk determined in these studies refers to the cumulative impact of seismicity occurring anywhere in the Groningen gas field. A seismic risk evaluated for a given location includes contributions from seismicity occurring underneath this location but also from larger magnitude events occurring at other, more distant locations (Figure 6). However, only the seismic risk associated with the given location is relevant in the context of the geothermal system.

Both of the above factors could in principle be obtained from the NAM risk assessment. The risk assessment, however, follows an evidence based approach, i.e. is based on previous experience. Risk forecasts are only calibrated for the immediate future and the forecasting capabilities over the lifetime of the geothermal system (~30 years) are limited.

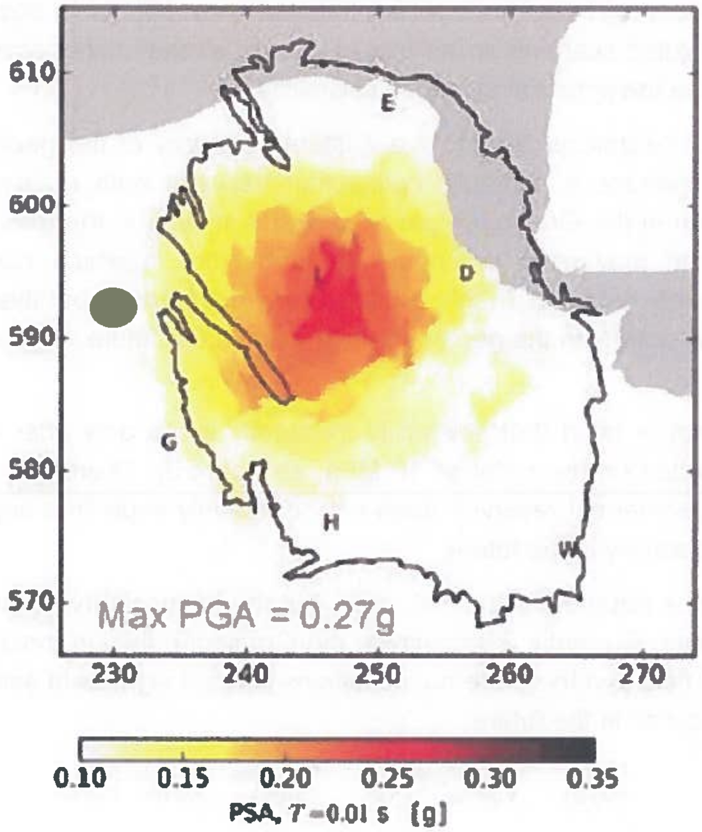


Figure 6: Example hazard map for a specific production scenario (33 bcm/year) for the time interval 1-2016 until 1-2021 as given in NAM study (NAM, 2015). Map shows spectral acceleration for 0.01s period The location of the Geothermal concession area is overlain in green.

The deformation process in the gas reservoir may cause stress interference with the geothermal reservoir. Two interference mechanisms need to be considered in the context of the current study:

- poro-elastic stresses resulting from compaction in the Groningen gas reservoir,
- (partial) depletion inside the geothermal reservoir.

Poro-elastic stresses are reflected by a subsidence pattern extending beyond the gas field into the geothermal concession. The associated stress perturbations, however, do not result in differential compaction but in a spatially continuous stress change. To first order, this does not result in an increase of Coulomb stress changes. Hence, this mechanism is not further considered here.

A (partial) depletion of the geothermal reservoir occurs if hydraulic connectivity has been established with the gas reservoir. Whether such a connection exists is unclear at this stage. Depletion may result in differential compaction and significant distortions of the local stress conditions, undermining our previous assumption that no critically stressed structures exist close to the geothermal reservoir. A stress threshold, as defined in section 4.4 cannot be estimated in a depleted scenario. In an extreme case, already minor stress perturbations in the subsurface have the potential to induce seismicity.

The occurrence of seismicity close to the eastern boundary of the geothermal concession (Figure 5) might indicate a hydraulic connection between both reservoirs. The time lag between production in the Groningen gas field and depletion in the geothermal reservoir is unknown. Depletion may even lag many years behind, in which case the geothermal reservoir is only partly depleted. In this scenario it cannot be ruled out that ongoing depletion may cause seismic activity in the geothermal reservoir in the future, even without geothermal activities.

It needs to be kept in mind that seismicity frequently starts only after a certain depletion threshold is exceeded (in the order of 10 MPa, section 4.3). Therefore, the current lack of seismicity in the geothermal reservoir does not necessarily imply that ongoing depletion will not cause seismic activity in the future.

The main concern is not the seismic risk itself, but the impossibility to quantify the risk over the coming 30 years. Currently, seismicity in the Groningen field is most pronounced in the central part of the field and there are no indications yet that significant seismicity will occur at the geothermal location in the future.

5 HAZARD SCENARIOS

The hazard related to geothermal activities (S1, non-depleted reservoir) is covered in sections 5.1 and 5.2 in a quantitative approach. The hazard with respect to interference from the adjacent gas field (S2, partially or fully depleted reservoir) is dealt with in a generic approach in section 5.3.

5.1 Non-Depleted Case

In order to quantify stress perturbations related to geothermal operations, simulations based on a numerical reservoir model have been conducted. Expected reservoir parameter and a circulation rate of 200 m^3/hrs served as input parameters for the simulation runs.

Initially, fluid pressure changes and the resulting effect on fault criticality are considered (see section 2.1). There exists large uncertainty with respect to the geomechanical parameters of the faults. Assuming a non-depleted reservoir, the faults at the outer boundaries of the numerical model must be impermeable to avoid hydraulic connectivity with adjacent, depleted gas reservoirs. The hydro-mechanical parameter of the remaining faults within the geothermal reservoir, however, may vary between the extreme cases of impermeable and conductive. To account for this uncertainty, three different scenarios are considered: In the 'open fault' scenario (OF), faults are assigned the same properties as the reservoir. In the 'closed fault' scenario (CF), faults are impermeable. The 'partly closed fault' scenario (PCF) considers the previous closed fault scenario where fault structures are discontinuous and/or slightly permeable.

The pressure distribution in the geothermal reservoir after 30 years of continuous circulation has been computed for the different scenarios. The resulting distribution for the OF-scenario is shown in Figure 7 and for the CF-scenario in Figure 8.

Considering a threshold of at least 1 MPa for reservoir seismicity (section 4.4), permeable faults result in a low seismic hazard as the threshold value has not been exceeded anywhere on the mapped faults (Figure 7). This is also true when assuming higher fault permeabilities which further reduce the overall pressure level.

Decreasing permeabilities on the faults, however, leads to compartmentalization and an increasing pressure level. In the extreme case of impermeable faults, large segments of the faults in the vicinity of the doublet are exposed to an overpressure above 3 MPa (Figure 8).

At this point it should be noted that an extreme pressure distribution as depicted in Figure 8 only occurs if a compartmentalization of the geothermal reservoir due to impermeable faults exists. Such a compartmentalization confines the increased fluid pressure levels around the injection well. There is no possibility of pressure leveling because of restricted flow paths. To demonstrate this, the PCF-scenario has been simulated (Figure 9). The compartmentalization barriers are now partly permeable resulting in a significantly smaller level of overpressure on the faults.

levels on the other fault segments. Here, overpressures in the order of 4 MPa are obtained

Based on the fault area subjected to a certain pressure level ('triggering threshold'), the temporal evolution of the maximum earthquake strength was calculated (Figure 10). Strength of seismicity increases with time and allows for sufficient reaction time in the order of days before reaching critical levels (see section 6.1).

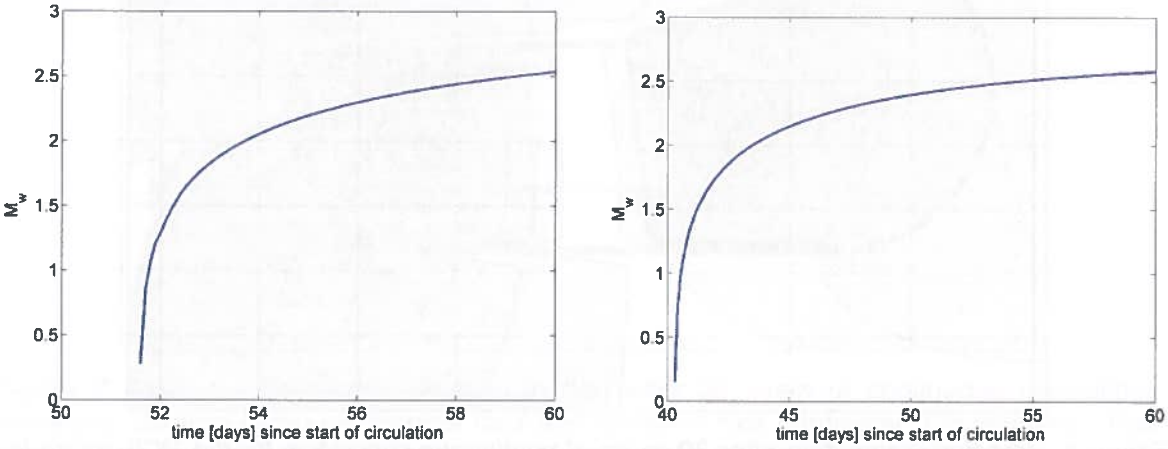


Figure 10: Increase of potential reservoir seismicity strength with time on northern (left) and southern (right) fault close to injector. Magnitude values are based on patch sizes on the faults exposed to overpressures above 1 MPa and a corresponding stress drop of 1 MPa.

Another potential source for reservoir seismicity is related to stress perturbations caused by contraction of the reservoir rock. When circulating fluid, the cold injected fluid causes a volumetric cooling of the reservoir rock that originates at the injection point and increases in size over time. The corresponding cooling pattern has been computed for 30 years of circulation and is depicted in Figure 11. The faults closest to the injection well are not exposed to significant temperature changes within the time frame considered here.

In previous hazard studies, the cumulative stress impact of a contracting geothermal reservoir was numerically simulated to estimate Coulomb stress changes on natural faults in the far-field (e.g. Baisch et al., 2009 SERIANEX). It was demonstrated that stresses change slowly over the lifetime of the geothermal system. For the current fault geometry we did not explicitly simulate the evolution of thermal contraction stresses. Due to the fault kink, the maximum magnitude for an event occurring in the reservoir is limited to the level of M_w=3.2 and the gradual buildup of contraction related stresses is independent of the fault geometry. Therefore, the TLS defined in the chapter 6 is considered an effective mitigation measure.

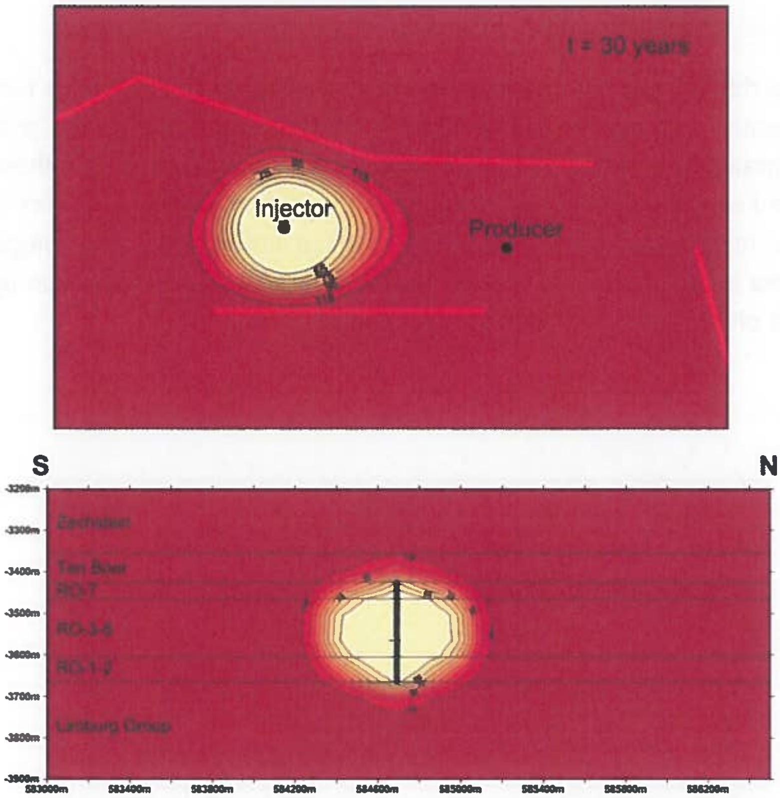


Figure 11: Cooled reservoir rock around the injection well after 30 years of circulation. The lower image displays an North-South depth section, the upper image a plane view of the cooling pattern, including the fault trajectories at reservoir level.

5.2 Non-Depleted Case - Hidden Fault

This hazard scenario presumes the existence of a seismogenic structure (fault) in the vicinity of the injection well that has not been mapped ('hidden fault'). In a hypothetical extreme case, geothermal fluid is directly injected into a seismogenic fault. In this case, the strength of the induced seismicity tends to scale with the injected volume. In principle, the maximum possible earthquake magnitude can be estimated from generic, numerical models (e.g. Baisch et al, 2010). Without calibration, the forecasting capabilities of such an approach, however, are limited.

Experience with injection directly into a critically stressed fault exists from the geothermal project at St. Gallen. There, a well was drilled into a seismically active fault patch, which hosted two natural earthquakes over the last 30 years (Diehl et al., 2013). During injection operations into the geothermal well, a magnitude M_w=3.5 earthquake was induced.

We consider this data example to define the extreme limit of a seismicity response when injecting into a critically stressed fault. For the North of the Netherlands, however, the existence of such a critically stressed fault is considered unlikely.

5.3 False Association

A severe project risk is given when seismicity caused by gas production is falsely associated with the geothermal reservoir. A prerequisite to discriminate against gas production related seismicity is a spatial separation of the sources causing the seismicity. If these sources (and hence the related seismic event locations) have converged spatially (as described in section 4.5), the risk of false association is inevitable. More importantly, risk mitigation measures cannot take effect in this scenario. These have been defined for one source (geothermal) but do not affect the other, gas production related source.

6 MITIGATION MEASURES

Risk mitigation in the context of reservoir seismicity is achieved by defining a Traffic Light System (TLS) of which seismic monitoring is an essential part (Bommer, 2006). A TLS is built upon the characteristic increase of the strength of reservoir seismicity with time (section 2.3). This facilitates operational reaction schemes to avoid a potential escalation of reservoir seismicity.

For the reasons outlined in 4.5, it has to be noted that mitigation measures described here apply only to the non-depleted scenario (sections 5.1 and 5.2). In case of a (partially) depleted reservoir, risk mitigation based on a TLS may not necessarily work.

Different requirements for the seismic monitoring exist for the different project phases. The 'critical' phase includes the drilling of the wells and the time frame, where non-steady state stress conditions prevail in the geothermal reservoir. Especially in the initial phase, the largest Coulomb stress changes occur and the reservoir is tested for its seismicity response for the first time. A quick response time is necessary, at least with the start of fluid injection operations, to initiate timely reaction measures, like termination of the current operation. In this phase, a real time monitoring is required.

Once steady-state conditions set in, less stringent requirements can be defined[2]. The time frame for reaction measures can be extended as the strength of potential reservoir seismicity in this phase increases over a larger time scale. Primary causes of reservoir seismicity may be stress perturbations on faults caused by either thermal contraction or increased fluid pressures at the outer rim of the reservoir. Response time in this phase may be defined depending on whether reservoir seismicity has occurred and the scale and activity rate of events.

Potential TLS response time based on experience from other geothermal projects are given in Table 1. Drilling through a fault is considered potentially critical. However, fluid losses during drilling have, to our knowledge, not caused significant reservoir seismicity so far. A response time of one day is thus appropriate. A response within a day is also suggested during circulation in the quasi-stationary phase if reservoir seismicity has occurred that exhibits a tendency of increasing scale and rate. Otherwise, a next business day response is sufficient.

[2] The time at which the system becomes quasi-stationary may be determined more precisely after initial reservoir parameter results have been obtained after drilling.

operation	TLS response time
drilling into fault	24 h
testing, injection	real-time
circulation, initial phase	real-time
circulation, quasi stationary (minute or no reservoir seismicity)	72 h
circulation, quasi stationary (reservoir seismicity)	24 h

Table 1: Response time for the TLS.

6.1 Traffic Light System (TLS)

Although the previous analysis demonstrates that the seismic hazard associated with the geothermal operations is low, a TLS will be implemented as a control and protective measure.

Geothermal operations will be aborted if the strength of induced seismicity exceeds a pre-defined threshold value. The basis for the TLS is the systematic increase of earthquake strength with the duration of (re-)injection operations (compare chapter 2). The operation of the TLS requires seismic real-time monitoring according to the specifications given in section 6.3. A limiting factor for operating a TLS is the 'trailing effect' (section 2.3), which needs to be considered when defining TLS threshold values. Based on previous experience, we estimate that a post-operational increase of the earthquake magnitude of 0.5 M_w magnitude units is the upper limit of what could be expected.

The proposed TLS considers the threshold values of M_w=1.4 for the lowest level of perceptibility and M_w=2.5 for the lowest level at which material damage at sensitive buildings is considered possible (section 4.2). To avoid potential damage, the threshold for the termination of operation criterion ('red') considers a conservative value for a maximum trailing effect of ΔM_w=0.5 (section 2.3). The threshold for a higher alertness status ('yellow') is chosen such that the TLS is in 'yellow'-mode in case seismicity reaches the estimated level of perceptibility. Here, we conservatively assume the same trailing effect as for the damage level.

The flow chart in Table 2 summarizes the TLS. To account for hypocenter location errors, the TLS applies to all earthquakes within an epicentral distance of 3 km from the injection point.

TLS Status			
Definition	$M_w < 0.9$	$0.9 <= M_w < 2.0$	$M_w \geq 2.0$
Actions	regular operations	– higher alert level – no increase of injection rate – report to regulator	– stop operations – immediately report to regulator – expert panel convenes

Table 2: TLS design. See text for details.

6.2 Expert Panel

It is recommended to establish an Expert Panel for managing 'unforeseeable events', in particular if a TLS event has occurred. The Expert Panel should include representatives from

- SodM,
- the project developer WarmteStad B.V.,
- KNMI,
- and NAM.

6.3 Seismic Monitoring Network

The sensitivity and localization accuracy of a seismic observation network is basically determined by the number of monitoring stations and their spatial distribution as well as the type of instruments used. For a monitoring network to comply with the requirements stipulated by the proposed traffic light system (section 6.1), the following recommendations are given:

- A minimum number of 5 stations should be operated. An optimized station geometry depends on the number of stations included in the network and can be modelled as part of the network design. Nominal 2σ epicenter location errors should be at the level of 500 m or less throughout the region of interest (i.e. covering 2 km radius around the injection well as well as the closest faults).
- The location of the stations should exhibit a comparatively low level of background noise. The detection threshold for reservoir earthquakes should be approx. M_w=0.
- To facilitate the detection of secondary seismic waves, 3-component seismometers should be utilized.
- The eigenfrequency of the seismometers should be ≤1 Hz.
- The instrumental registration should be based upon an absolute time base (GPS synchronization). The sampling frequency should be at least 100 Hz.
- Data should be recorded time continuously on a 24 bit acquisition system.
- Real-time data access is required.

These requirements are only partly fulfilled by the existing KNMI station network (see Figure 5). In particular, the KNMI network does not have sufficient coverage to adequately determine locations of seismicity originating in the geothermal reservoir. Also the required detection threshold cannot be achieved at the geothermal site with the existing network. An additional limitation is given by station outages due to technical issues. Station uptime cannot be guaranteed by KNMI (B. Dost, pers. com. March 2016). Further stations planned to be installed by NAM (Figure 5) increase the station coverage near the geothermal site. Due to the current uncertainties regarding station locations and time line for installation, these stations cannot be considered at this stage, however.

Taking these factors into account, we recommend installing a designated local seismic network at the site. Data of the existing KNMI/NAM stations might be integrated whenever it appears necessary, but the basic station network should be operated independently by WarmteStad.

An example for a local network configuration is shown in Figure 12 and Figure 13. The configuration has been determined by desktop analysis only and should not be considered as a final recommendation.

The characteristics of the network demonstrate a sufficiently low detection threshold (M_w =0) centered at the injection well GT-02 (Figure 12). Also the modelled horizontal location accuracy (Figure 13) in this region is adequate for discriminating against seismicity in the Groningen gas field.

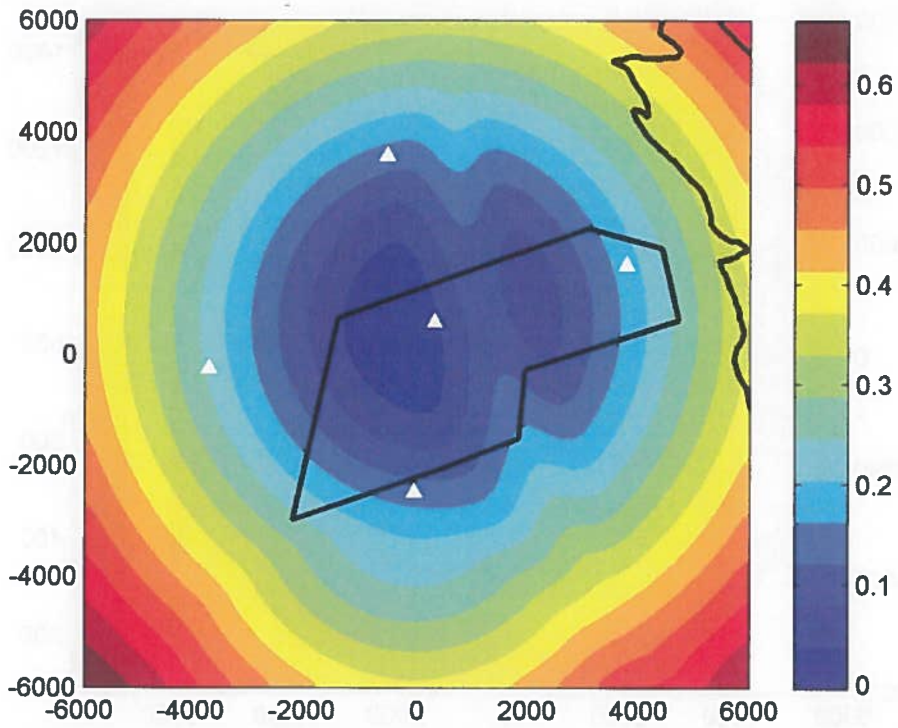


Figure 12: Simulated detection threshold for a possible station network geometry (white triangles). Color scale denotes moment magnitudes Mw. The data is based on conservative noise estimates at the station locations and a weak soil assumption (vs30<=200m/s). Event depth is assumed at 3.5 km. Black polygon in the center outlines geothermal concession Groningen-2, coordinates in m relative to intersection of GT-02 with Top-Slochteren.

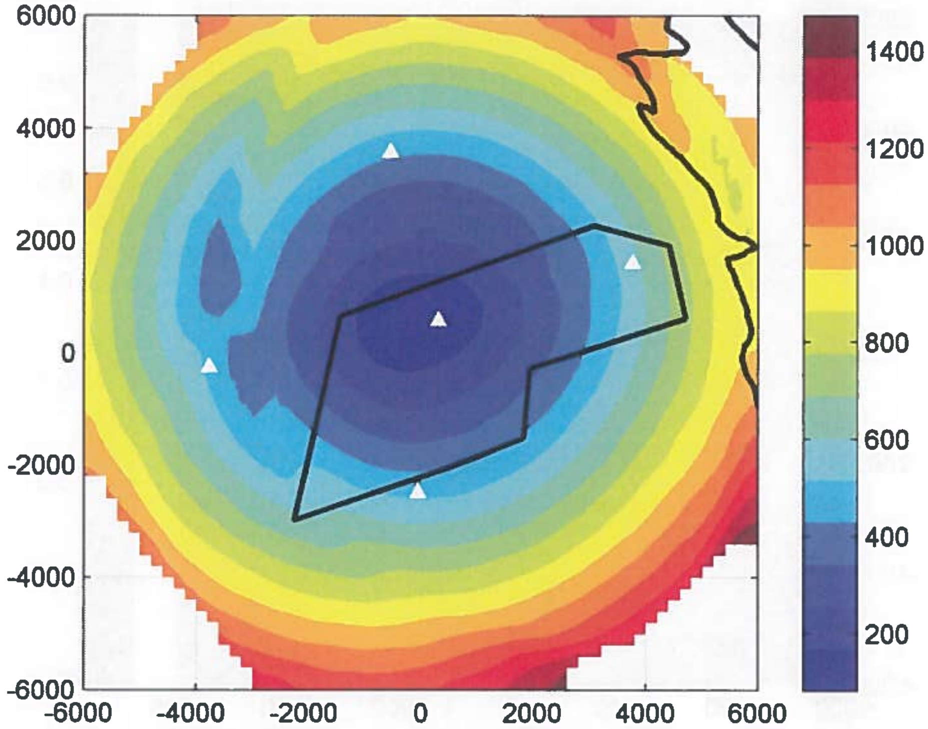


Figure 13: Simulated location error in the horizontal direction (2σ) of reservoir events in m for proposed potential station network geometry (white triangles) according to color scale. The data is based on conservative noise estimates at the station locations and a weak soil assumption (vs30<=200m/s). Event depth is assumed at 3.5 km. Black polygon in the center outlines geothermal concession Groningen-2, coordinates in m relative to intersection of GT-02 with Top-Slochteren.

REFERENCES

Abdullah, R. A., 2006. A study on stress-strain behaviour of granite and sandstone using closed-circuit servo-controlled testing machine, Master thesis, Universiti Teknologi Malaysia.

Baisch, S., and H.-P.Harjes, 2003. A model for fluid injection induced seismicity at the KTB. *Geophys. Jour. Int.*, **152**, 160-170.

Baisch, S., Weidler, R., Vörös, R., and R. Jung, 2006. A conceptual model for post-injection seismicity at Soultz-sous-Forêts. *Geothermal Resources Council*, Trans., Vol. 30, 601-606.

Baisch, S., Carbon, D., Dannwolf, U., Delacou, B., Devaux, M., Dunand, F., Jung, R., Koller, M., Martin, C., Sartori, M., Secanell, R., and R. Vörös, 2009. Deep Heat Mining Basel - Seismic Risk Analysis. *SERIANEX study prepared for the Departement für Wirtschaft, Soziales und Umwelt des Kantons Basel-Stadt, Amt für Umwelt und Energie*, 553 pages.

Baisch, S., Vörös, R., Rothert, E., Stang, H., Jung, R., and R. Schellschmidt, 2010. A numerical model for fluid injection induced seismicity at Soultz-sous-Forêts. *International Journal of Rock Mechanics and Mining Sciences 47, 405-413 DOI 10.1016/j.ijrmms.2009.10.001*

Baisch, S., Rothert, E., Stang, H., Vörös, R., Koch, C., and A. McMahon, 2015. Continued geothermal reservoir stimulation experiments in the Cooper Basin (Australia). *Bull. Seism. Soc. Amer.*, **105**, 198-209.

Baria, R., Michelet, S., Baumgärtner, J., Byer, B., Gerard, A., Nicholls, J., Hettkamp, T., Teza, D., Soma, N. Asanuma, H., Garnish, J., and T. 2004. Microseismic monitoring of the world's largest potential HDR reservoir. Proceedings, 29th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28, 2004.

Bönnemann, C., Schmidt, B., Ritter, J., Gestermann, N., Plenefisch, T. and U. Wegler, 2010. Das seismische Ereignis bei Landau. Abschlussbericht der Expertengruppe „Seismisches Risiko bei hydrothermaler Geothermie, 54 Seiten.

Bommer, J. J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., Marroquin, G., and J. Rivas, 2006. Control of hazard due to seismicity induced by a hot fractured rock geothermal project. *Eng. Geol.*, **83**, 287-306.

Warmtestad - Seismic Risk Analysis Zernike Geothermal project

Proposal for

WarmteStad BV
Griffeweg 99
9723 DV Groningen
The Netherlands

1 INTRODUCTION

SGS Horizon B.V. (SGSH) was requested by WarmteStad BV to prepare a proposal for the Seismic Risk Analysis Zernike Geothermal project

"Warmtestad," a joint venture between the municipality of Groningen and the Groningen water company, has been setup to investigate whether a geothermal system can be installed close to the city of Groningen to supply households with energy/hot water.

A cold water injection well and a production well are envisaged to be drilled. The target would be an aquifer in the permeable Slochteren formation. The area is downdip and located a number of kilometres West of the Groningen gasfield.

The city council has asked for supporting technical documentation, which would explain that the risk of induced seismicity/earthquakes is limited. If there is a (small) risk of seismicity, a traffic light system (TLS) should be devised (monitoring system and forward action plans).

A consultant Qcon/IF has performed a simple geomechanical study, under the assumption that the aquifer is undepleted. Modeling work has indicated that seismic risk is limited in such a case (to be reviewed by SGS).

Based on the discussions with experts in the industry (TNO), on the 20th of July 2016 it has been agreed that simulations will have to be performed assuming that the reservoir is (partly) depleted. TNO has suggested there is a high chance that the aquifer has been depleted by production from the Groningen gasfield (depleted by some 250 bar). The degree of depletion is currently unknown at the Zernike block. There are a number of (minor) NW/SE striking faults between the Zernike block and the Groningen field.

These boundary faults can be open, sand-sand juxtaposition or closed via clay smearing. However the Groningen field is heavily depleted and at a differential pressure over the fault, of say 50 bar, the fault could already start to "sweat."

Depletion can change the stresses at the fault, such that it becomes critically stressed. In the area where water production takes place, there will be a pressure sink which could cause faults nearby to slide. Additionally thermal stresses due to cold water injection could initiate sliding of these critically stressed faults.

Main intra Zernike block faults are mainly NE/SW oriented and tend not to be critically stressed in an undepleted case. The NW/SE faults separating the Zernike block from Groningen may be the first faults to become critically stressed. This is dependent on the principal stresses in the underground, among others.

There has currently been no real seismicity in the area, except over the Groningen gasfield.

The objective of the study is to determine the risk of inducing major seismic events in the Zernike area in a situation where the aquifer is (partly) depleted. A traffic light system will be devised with the aim of monitoring the operation and a forward action plan will be developed in case significant seismic events have been initiated or are imminent.

Based on SGS's understanding of Warmtestad's requirements, please find below the proposed scope of work, selected key staff members, and proposed budget.

1.1 SGS TRACK RECORD

Track record

SGS has an extensive knowledge of the subsurface of the Netherlands, including the province of Groningen. Our involvement in numerous projects has contributed to our regional and technical knowledge applicable to the current study, including:

- A very similar study was performed, regarding induced seismicity during cold water injection in a depleted gas field in the North of the Netherlands. A paper for the Society of Petroleum Engineers was published, regarding this project:Paper reference:"*Inducing Earthquake By Injecting Water In A Gas Field: Water-weakening Effect,*" **SPE 166430**, September 2013, Axel Bois and Niek Dousi.
- In-depth knowledge of the Groningen gas field through our involvement in an independent review study (audit) of subsurface static and dynamic models in 2013 and 2015. The project involved the evaluation of the technical quality of the modelling work carried out by the client and its appropriateness for the preparation of production forecasts. SGS is aware of the technical method applied by NAM on how to calibrate the subsurface fluid simulation model by the subsidence calculations. This knowledge may be applied to estimate the depletion in the Zernike block.
- Expertise in estimation of the risk of induced seismicity and the associated maximum magnitude applied to a client project involving the calculation of elastic parameters of the Vlieland and Rotliegend reservoirs and their overburden in the Vikega field.
- Curistec, the SGS associate company, has been involved in numerous geomechanical finite element simulations for oil and gas fields and for gas storage projects, many of them including the problematic of fault reactivation. Moreover, Curistec has been involved in seismicity prediction for the Lacq and Rousse fields, in South-West of France.
- Strong familiarity with subsidence and compaction issues in relation to hydrocarbon production applied to assisting our clients with the performance of a 3D compaction and subsidence study for the Zuidwal and Harlingen Chalk gas fields.
- Thorough background in static and dynamic modeling through involvement in numerous projects with clients in The Netherlands and abroad, including an underground gas storage modelling study for the Bergermeer gas field.

Furthermore, several of our staff members have experience working on geothermal projects with previous employers or Ph.D. studies, including specific expertise on microseismic interpretation, numerical simulation of geothermal flow rate and heat transfer, modelling of temperature and viscosity changes in the reservoir and resource estimation of geothermal heat potential.

2 PROPOSED SCOPE OF WORK

The scope of work is divided into 5 steps. Each of these steps has been priced separately:

1. Estimate range of depletion in the Zernike block
   1. Base the analysis on NAM aquifer pressure data and subsidence measurements above the Zernike block.
   2. Review Qcon geomechanics model. Review inputs such as Young's modulus, Poisson's ratio, Biot's coefficient, Coefficient of thermal dilation, fault friction angle.
   3. Run similar model assuming pressure depletion, if needed.
   4. If depletion is considered to be minimal and the Qcon-model is deemed suitable after the review, the project scope will, in agreement with Warmestad, be changed. If the change of stress is very small at the fault, then it can be assumed that the induced seismic events are minimal. Subsequent phases

may not have to be executed. Budget is likely to be reduced.

2. If depletion is significant and first pass geomechanical modelling work indicates stress changes may be significant, perform geomechanical modelling and determine the potential slip of critically stressed faults
   1. Review and Enhance (if needed) existing geological- and fluid flow model
      1. Review inputs such as porosity, permeability, water viscosity and water compressibility, temperature gradient, well model, rock heat capacities.
      2. Review implementation of geological features such as top structure and fault throws and orientations, sedimentary layers.
      3. Review modelling assumptions.
      4. Run reservoir simulation model to obtain 3D pressure and temperature predictions.
   2. Assess stresses using a 2D finite element geomechanical model
      1. Generate a 2D finite element model perpendicular to the critically stressed faults.
      2. Run model to obtain stress and fault slip predictions.
   3. For a range of degree of depletion and injection rate scenarios, the degree of fault sliding, if any, will be calculated
      1. A matrix will be created linking fault slip (and eventually earthquake magnitude) to depletion and injection rate, for a number of discrete timesteps.
3. Based on the results from the geomechanical model, estimates of the magnitude of potential future seismic events will be made
   1. Determine size of fault plane, ie. section of fault that is stressed.
   2. Apply empirical relationship to determine magnitude and frequency of seismic events based on fault sliding parameters.
   3. Estimate PGV/PGA based on geomechanical model by modelling or correlations.
4. For each depletion/flowrate scenario, a TLS system will be devised. It is envisaged that the following ingredients will be incorporated in the plan, to be further matured during the project:
   1. Similar TLS systems will be studied, such as the one for the Bergermeer underground gas storage.
   2. The TLS system may involve monitoring the frequency of the seismic events over time. Consider the location and number of potential geophones.
   3. TLS system may involve reduction in flowrates.
   4. The "SBR-A" directive may be incorporated. "Oscillation" speed at surface should not exceed ~3mm/s (PGA 0.008-0.036g).
5. The technical work will be documented in a comprehensive report (in English), with a summary which can be understood by non-technical personnel (in Dutch, if desired).

It is the understanding of SGS that the majority of the project should be finalized by the 1st of October. Key results should be presented to the city council around this date.

Considerations

- SGS understands that the existing static and dynamic models were prepared in Petrel RE and cover six potential layers in the Slochteren formation with modelled reservoir parameters based on the Groningen gas reservoir characteristics. A meeting with RUG representatives will be held to ensure that SGS staff will have a comprehensive understanding of previous work completed.
- Depletion may continue during future gas production in the Groningen field. This effect will be taken into account in the dynamic and geomechanical modelling process, if significant. A rough estimate of future depletion will be made.
- Both thermal stresses and stresses induced by pressure variations will be incorporated in the geomechanical modelling work.

Scope limitations

- It has been assumed that the reservoir simulation model developed by RUG, which can predict future pressures and temperatures, can be used in the evaluation, with limited modifications.
- The existing Qcon geomechanical model developed will be critically reviewed in phase 1. If decided after phase 1, a new geomechanical model will be developed, as a 2D finite element model, perpendicular to the critically stressed faults. If a second 2D model or a 3D model would have to be built, this would lead to an addendum to the project scope and budget.
- No seismic processing or seismic interpretation will be conducted as part of this study. It is expected that WarmteStad will request approval from NAM to be able to utilize 3D seismic and fault interpretation data.

Fig. 2.1

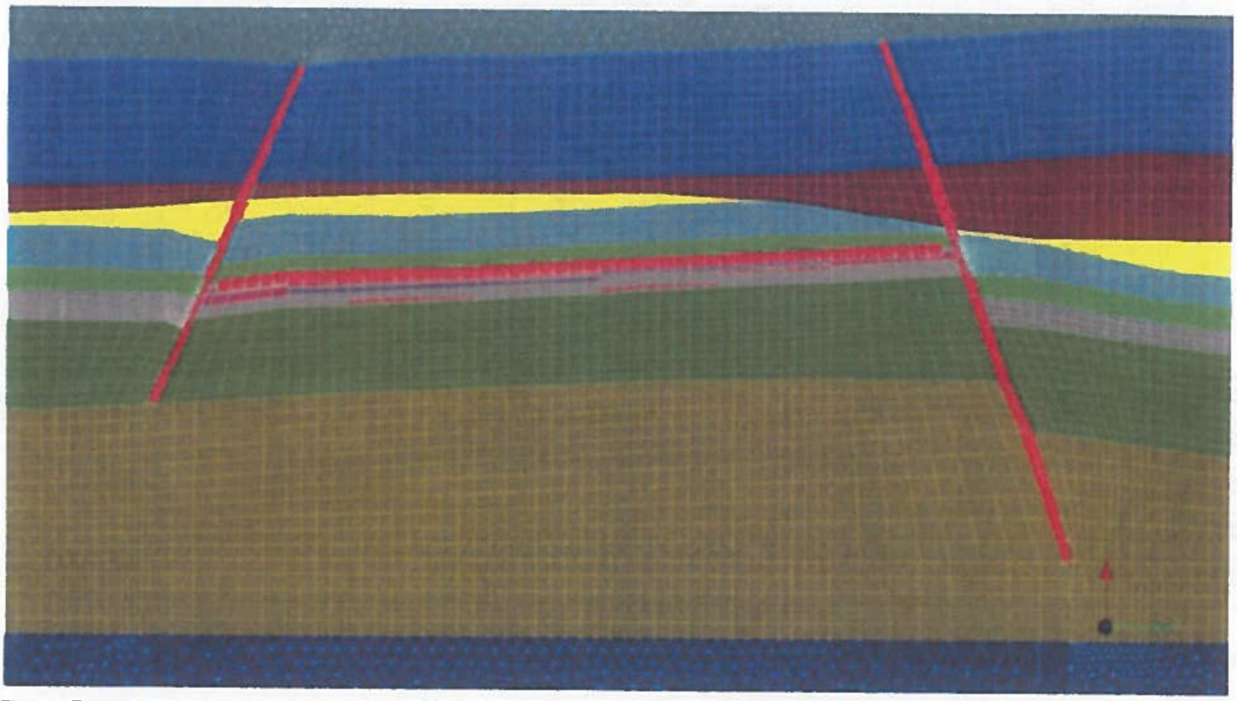


Fig. 2.1 Example 2D grid of a geomechanic model

2.1 DATA REQUIREMENTS

To complete the proposed scope of work, SGS understands that the following data will be made available by WarmteStad before **August the 2nd 2016** to be able to meet the End of September deadline:

- 3D static model in Petrel, including fault surfaces.
- 3D dynamic model in Petrel.
- Qcon geomechanics model.
- Documentation on the static and dynamic modelling work performed (if available).
- Datapack provided to Qcon/IF on commencement of the initial stages of the project.
- Datapack received from Qcon/IF on finalization of the initial stages of the project.
- NAM pressure measurements in aquifer
- Subsidence measurements taken above Zernike block

The expected timeline as listed in the project schedule section below is based on the assumption that all the necessary data has been delivered to SGS by August 2nd 2016 and that at this date all the contractual

4. Slide pack summarizing work performed.
5. Final written report (in English, with Executive Summary in Dutch, if desired) .

Following the completion of the draft report, WarmteStad is invited to provide comments and a request for changes to the SGS project manager within two weeks (10 business days) following delivery. If no comments or communications are received from WarmteStad within this time period, SGS will automatically consider the deliverables as accepted, submit the final report and close-out the project.

3 PROPOSED TEAM

3.1 PROJECT MANAGER

PROJECT MANAGER

will be the Project Manager for this study. He will coordinate the day-to-day technical work in the Project Team. He will:

- Manage the budget, timing and resources of the project.
- Manage all communication between SGS and Warmtestad.
- Be responsible for quality assurance and control (QAQC) of the project work.

holds an MSc in Petroleum Engineering from Delft University of Technology. He has written his MSc thesis at NAM (JV Shell&Exxon) in the Netherlands, where he investigated and modelled gas well liquid loading. After his study in 2005, he joined SGS, and is currently a Senior Reservoir Engineer. He has taken part in a number of integrated field development studies, analysing oil and gas assets in the North Sea, Continental Europe, North & West Africa and Russia, among others. He carried out activities for a various clients such as Majors, small/mid-size operators and non-operators. His main tasks consisted of classical reservoir engineering analyses, history matching and production forecasting by means of reservoir simulation. As from 2011 he has been project manager of various reservoir studies for clients in the Netherlands, UK, Italy, Algeria, Ecuador, Tunisia, Algeria, Cameroon and Russia. During his working period with SGS, Niek has also participated in - and led various reserves evaluations, using SPE-PRMS. He also gained experience with Underground Gas Storage developments and Geomechanical studies. In 2008, 2009, 2014 and 2015 he has been part of data room review teams evaluating various UK, Italian, Polish and Nigerian assets.

Niek will coordinate the SGS team composed of experienced staff, selected on criteria of suitability of technical skills and availability, as listed below.

3.2 KEY STAFF

Key staff are listed below

holds an engineering degree from the School of Mines of Nancy (France) and a PhD in geomechanics from Sherbrooke University (Canada). Axel-Pierre is involved in petroleum geomechanics since the mid-nineties. He first worked for Simecsol consulting company in Paris (1994), before becoming an independent consultant in 2000 and creating CurisTec in 2009. He has been involved in various projects all over the world, America (Bolivia, Canada, USA, Venezuela), Europe (France, Italy, Netherlands, Norway, UK), Africa (Algeria, Angola , Cameroon, Congo, Egypt, Gabon, Ivory Coast, Nigeria, Soudan, Uganda), and Asia (Brunei, China, Kazakhstan, Kuwait, Oman, Qatar, UAE). His main skills are in the fields of geomechanics (in situ state of stress, formation property evaluation, wellbore stability, hydraulic fracturing, reservoir mechanical behaviour, field modelling at geological scale, Drill cuttings re-injection), well integrity (cement sheath integrity, casing for Advanced Studies he gained experience in the acquisition, processing, and analysis of magnetotelluric data. Merijn joined SGS in 2013 where he worked in multiple field production and development studies in Nigeria and Algeria. In addition, he is one of the lead geologists in SGS research and development studies on unconventional shale resources. His activities focus on determining the mechanical behaviour of shale using innovative techniques, i.e. QEMSCAN, nanoindentation, for reservoir quality assessment. During a secondment to Sirius Exploration Geochemistry, based in the US, Merijn gained extensive experience in basin modeling.

holds an engineering degree in petroleum geology from Russian State Geological Prospecting University n.a. Sergo Ordzhonikidze in Moscow (2012) and an engineering degree in Earth sciences from Polytechnic Paris – University of Pierre and Marie Curie in Paris (2014). She works since 2014 within CURISTEC as an engineer in geomechanics. She is involved in all geomechanical studies to determine mechanical properties and state of stress at wellbore scale. In this framework, she builds different 1D MEMs and studies wellbore stability. These projects require generally the analysis of in-situ tests measurements, regional geology, and field and wells histories. She is also involved in different projects for compaction and subsidence evaluation. These projects require laboratory mechanical tests analysis and their interpretation in order to determine the parameters of the models used for computations. She has worked on various projects all over the world, Africa (Cameroon, Gabon, Ivory Coast), Europe (France, UK), America (Venezuela), Middle East (UAE).

3.3 QAQC

SGSH enforces thorough internal QAQC standards and procedures, which will be applied in the course this project. QAQC is ensured by peer reviews at significant project milestones, which will be conducted by our experienced subject matter experts. For the current project, the following staff will carry out the QAQC:

holds an MSc in Physics from Utrecht University. He joined Shell in 1989 and worked as Reservoir Engineer in the Netherlands and the UK. He continued his career in 1997 with Wintershall in the Netherlands, focusing on production optimisation and reservoir management of gas fields in the Southern North Sea, both in hands-on and supervisory roles. His 20+ years of experience with an operator also includes exploration well testing and prospect evaluation, field development planning, gas network modelling, reservoir modelling, asset evaluation, unitisation issues, field reserves determination and company reserves coordination. In these roles he gained ample project coordination experience and a high level of understanding of technical, commercial and business aspects of small and large gas fields in the offshore environment. Maarten joined SGS Horizon in 2012 and has been project manager for integrated static and dynamic reservoir modelling studies on oil and gas fields in Nigeria, Egypt, Croatia, the Netherlands, and Italy. He has also been involved in data rooms, asset evaluations, reserves evaluations (PRMS) and technical peer reviews.

holds an MSc in Geology from Free University Berlin. He joined Deminex in Essen, Germany, in 1980 as a staff geologist and worked for the company - which was 1997 acquired by VEBA Oil & Gas and in 2002 by Petro-Canada – on assignments in Norway, The Netherlands, UK, Syria and in Libya. He has more than 30 years of experience as an exploration geologist and development geologist in various regions and reservoirs i.e. North Sea chalk, North Africa and Middle East carbonate fields, Trinidad offshore turbidites, Norwegian North Sea, Russia and Far East clastics. Andreas has a profound expertise in carbonate reservoir characterization, static and dynamic 3D reservoir modelling and the planning of vertical and horizontal oil and gas wells. During the early 1990s he was heavily involved in the development and management of digital E&P databases. In 2010 Andreas joined SGS Horizon as Geosciences Manager and Geology team leader. As head of the Innovations & Special Studies group he coordinates SGS's new technologies for the mineralogical, geochemical and geomechanical characterization of conventional and unconventional reservoirs.

4 LOCATION

SGSH operates globally from its office in Voorburg (The Hague area), the Netherlands. The office is fully equipped with all necessary hard and software to run complete integrated projects. It is assumed that the bulk of the services outlined in this proposal will be executed from our office in Voorburg and the Curistec office in Lyon. Meetings at client's office may be organized, in agreement with the client as appropriate and required by the development of the study.

Regular telephone conferences may be scheduled to ensure good communication and alignment between client and SGSH teams involved in the project.

Bijlage 3

IF Technology
Velperweg 37
6824 BE Arnhem
Postbus 605
6800 AP Arnhem
T 026 35 35 555
F 026 35 35 599
E info@iftechnology.nl
I www.iftechnology.nl

Rabobank 38.39.42.047
IBAN NL60 RABO 0383 9420 47
KvK Arnhem 09065422
BTW nr. NL801045599B01

WarmteStad BV
Attn:
Griffeweg 99
9723 DV GRONINGEN

Sent per e-mail: @groningen.nl

Date	July 29th 2016
Reference	65308/BP/20160729
Your reference	---
Subject	**Offer Geomechanical Study and TLS Design for the Depleted Scenario - Geothermie WarmteStad Groningen**
Handled by:	
Checked by:	

Dear [redacted]

Hereby you will find our offer for a Geomechanical Study and TLS design for the depleted scenario in the WarmteStad geothermal project.

1. Background

IF Technology BV and Q-con GmbH performed a seismic hazard assessment study (SHA) for the geothermal project "WarmteStad Groningen".
As a main conclusion, the study revealed that the seismic hazard resulting from geothermal operations is small and manageable, whereas another source of seismic hazard stems from stress changes associated with gas production from the nearby NAM field. The latter source of seismicity is strongly depending on (yet unknown) future production patterns in the gas field and on the hydraulic coupling between the geothermal and the gas reservoir. The study concluded that the hazard associated with gas production may not necessarily be very large, but is extremely difficult to assess quantitatively. Furthermore, geothermal mitigation measures such as stopping geothermal production will have no impact on the seismicity caused by gas production.
Based on these conclusions, WarmteStad asked TNO for technical advice. A TNO workshop was held during which the general situation was discussed. Aspects for seismic hazard assessment in a (partially) depleted geothermal reservoir were discussed and it was concluded that it should be possible to design a traffic light system (TLS) even for this specific situation.

July 29th 2016

WarmteStad has asked IF and Q-con for a work proposal addressing the following key questions:

I. Can a geothermal system be operated safely in a depleted situation?
II. Can a TLS be designed for the depleted situation?

The degree of depletion in the geothermal reservoir is unknown, but expectations changed recently (e.g. the NAM static model predicts 0-50 bar depletion). Therefore, WarmteStad puts more emphasis on scenarios with small depletion levels and will not continue geothermal activities if (after drilling the 1st well) the depletion is found to be larger 100 bar.

2. Work Proposal

This work proposal addresses the two key questions formulated above using geomechanical modelling. The study is performed in four stages. After stage 2 and stage 3 it will be discussed with WarmteStad whether or not the study shall be continued.

Stage 1:Identification of relevant processes for induced seismicity in a depleted reserv[redacted]

Based on the scientific literature, the relevant physical processes will be summarized:
During geothermal circulation, the hydraulic fluid pressure is decreased at the production well and increased at the injection well. In a typical geothermal scenario, only the pressure increase caused by the injection well is relevant for the induced seismicity. In contrast, pressure depletion in a gas reservoir can also induce seismicity. When operating a geothermal system in a depleted reservoir, seismicity may therefore be induced by hydraulic overpressures (originating at the injection well) as well as by pressure drawdown (originating at the production well).

Relevant observations of induced seismicity in depleted reservoirs will be presented: It is acknowledged that no direct field analogues exist (in The Netherlands or abroad), where a geothermal doublet was operated in a (significantly) depleted reservoir.
Therefore, seismicity observations from neighboring technologies are considered. These include gas storage in depleted reservoirs as well as production induced seismicity. Focus of data examples is The Netherlands.

<u>Deliverables:</u>

- Formulation of the relevant physical mechanisms for induced seismicity in a depleted scenario. This serves as the basis for stage 3.
- Overview of induced seismicity observed in depleted reservoirs with a focus on re-injection. These observations set the framework for the expected seismicity.

Stage 2: Defining Depletion Scenarios

Available data/information that is considered relevant for the depletion level in the geothermal reservoir is reviewed. This includes

- hydraulic pressure observations made in nearby wells,
- the NAM static model (if available)
- TNO study relating observed subsidence to reservoir depletion.

We will check in a pragmatic way, which depletion scenarios could be likely to occur in the geothermal reservoir block. This will be a simplified evaluation, based on existing information and expert judgement. No modeling or (sophisticated) prediction models will be used. This approach has been discussed with WarmteStad.

This short evaluation will be done in 5 days (timeline is two weeks). We expect input from NAM/Warmtestad (even if it is holyday season). As we understand, Sander Visser is already gaining the NAM information we asked for. Within this timeline and the available information during these two weeks, IF will report the most likely and less likely depletion scenarios. Depletion scenarios need to be consistent with observations and should reasonably cover the possible range of current reservoir depletion.

An important issue is the prognosis of the gas production in the Groningen gas field in future and therefore the prognosis of the depletion in the Groningen gas field itself. For the near future the production plan is known and will be followed in this study. However prognosis for a longer period of time will be discussed with WarmteStad intensively. Together with WarmteStad it will be decided, which starting point for the calculations should be made.

<u>Deliverables:</u>

- Three depletion scenarios (based on information available) including the current depletion level and a prognosis about the depletion over the next 30 years.
- Recommendations for measurements after drilling the first well to define the state of the reservoir and stresses.

We did not calculate any meetings with NAM or others in this stage, though it could be of extra value. If meetings are to be arranged in this short timeline, we will discuss this with Warmtestad. Cost will be charged based on real costs (see Chapter 4)

Go/nogo:

The deliverables of stages 1 and 2 are required to define the scenarios for the geomechanical modeling and to check if the proposed set-up of the geomechanical model can be applied or needs to be changed.

The outcome of these stages could be negative, for example: the scenario analysis results in "extreme" outcomes like that is it very likely that >80bar depletion is expected in the coming 15 years, or that the numerical model parameters cannot be reasonably constrained. The results will be discussed with WarmteStad and WarmteStad will give a formal "go" or "no-go" for the next project stage.

Stage 3: Geomechanical Modelling

It is acknowledged that numerical simulations of compaction induced seismicity are extremely challenging regarding the computational effort. Therefore, approximations and simplifications cannot be avoided.

Previous attempts for simulating compaction induced slip in a scenario applicable to the Groningen reservoir were restricted to generic 2D models (e.g. the most recent NAM study by 2015).

A particular challenge for this type of simulator is the specific geometry, where a seismogenic (receiver) fault is embedded into the compacting volume. For the current scenario, this can be avoided when considering that the depletion caused by geothermal activities changes at much higher rates than the depletion caused by NAM production. Therefore, the influence from the NAM field can be implemented as a starting condition (constant over the geothermal field). The comparatively fast acting stress impact from the geothermal depletion can be simulated by approximating the depleted region around the production well by (semianalytic) Okada elements.

With this strategy, the existing reservoir model (IF Technology) will be implemented into a new numerical modelling environment, where the simulated hydraulic pressure can be combined with

a. a simulator for compaction induced stresses (Okada elements),
b. and a quasi-dynamic simulator for induced seismicity (slider-block approach).

The simulators are not strictly coupled, i.e. seismic deformation does not change the fluid pressure (although it does change the stress state in the system).

The numerical model configuration is used to simulate stress changes on the faults and seismicity resulting from compaction due to geothermal pressure drawdown as well as from pressure increase associated with re-injection.

The numerical model is used to

- simulated induced seismicity in the 3 depletion scenarios,
- perform a sensitivity study to investigate to what extent seismicity characteristics (spatio-temporal and magnitude evolution with time) are depending on parameter assumptions.

<u>Deliverables:</u>

- Seismicity characteristics (spatio-temporal and magnitude evolution with time) for the depletion scenarios.
- Assessment of the possibility that a damage relevant earthquake can be induced without smaller magnitude precursors.

Go/nogo:
The deliverables of stage 3 are needed to define the response times and layout of a TLS. The outcome of stage 3 could be negative, for example: a TLS cannot be implemented as required response times are too short, or larger magnitude events could occur without precursors.
Based on stage 3 results, the general technical and financial feasibility of a TLS will be assessed and discussed with WarmteStad. WarmteStad will give a formal "go" or "no-go" for the next project stage.

Stage 4: Definition of a TLS for the depleted case
Based on the previous results, a traffic light system (TLS) is designed. Depending on the outcome of stage 3, the proposed TLS mitigation measures may not only depend on magnitude/vibration threshold values, but also on further seismicity characteristics.

Deliverables:

- TLS design to allow safe operation of the geothermal system in scenarios of different degree of depletion.

3. IF and Q-con

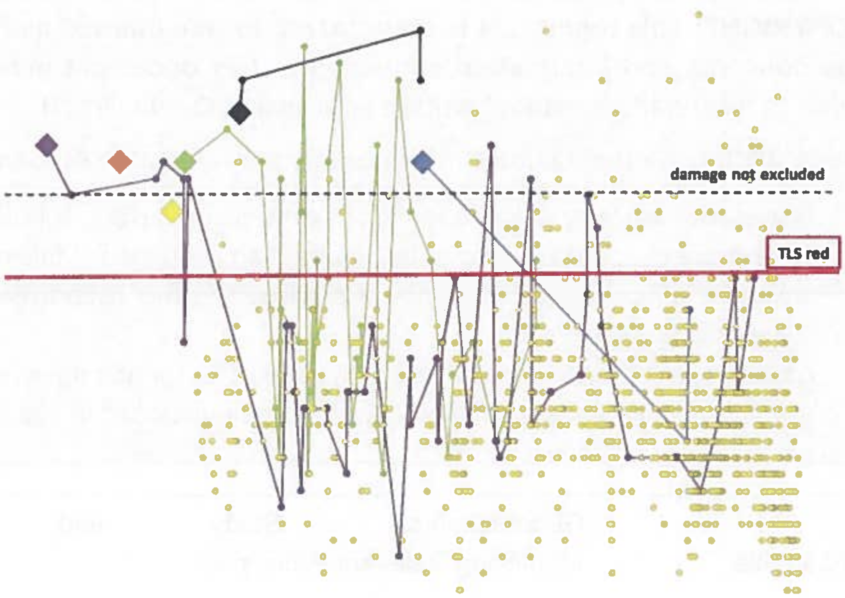
IF and Q-con will work together on this project like the previous Seismic Hazard Assessment that has been done by them. Both parties have extensive experience with geothermal projects and of with this specific project in Groningen.
IF will work out stage 2. Q-con will be in the lead for the other stages though using the IF modelling experience from the previous work. Q-con has much experiences with complicated SHA and SRA cases and will use specific simulators for the geomechanical calculations.
IF Technology will be the main contractor in this project, whereas Q-con becomes a subcontractor of IF Technology. IF Technology is responsible for administrative project management and communication, Q-con is responsible for technical input on seismicity

Bijlage 4

Geomechanical Study and TLS Design Identifying Relevant Processes

Q-con GmbH

Geothermal reservoir engineering



IF003

Report title:	Geomechanical Study and TLS Design Identifying Relevant Processes
Author(s):	
Report date:	12th August 2016
Project:	Warmtestad
Prepared for:	IF Technology
Version:	160812
Archive No.:	IF003

Contents

1 BACKGROUND

IF Technology BV and Q-con GmbH performed a seismic hazard assessment study (SHA) for the geothermal project 'WarmteStad Groningen' (Vörös et al., 2016).

As a main conclusion, the study revealed that two sources of seismic hazard must be considered at the project site. Whereas the seismic hazard resulting from geothermal operations is small and manageable, the other source of seismic hazard stems from stress changes associated with gas production from the nearby NAM field. The latter source of seismicity is strongly depending on (yet unknown) future production patterns in the gas field and on the hydraulic connectivity between the geothermal and the gas reservoir. The study concluded that the hazard associated with gas production may not necessarily be very large, but is extremely difficult to assess quantitatively. Furthermore, geothermal mitigation measures, such as stopping geothermal production, will have no impact on the seismicity caused by gas production.

Based on these conclusions, WarmteStad asked TNO for technical advice. A TNO workshop was held during which the general situation was discussed. Aspects for seismic hazard assessment in a (partially) depleted geothermal reservoir were considered and it was concluded that it might be possible to design a traffic light system (TLS) even for this specific situation.

The degree of depletion in the geothermal reservoir is unknown, but expectations changed recently. WarmteStad considers scenarios with a small depletion level more likely and will not continue geothermal activities if (after drilling the 1st well) the depletion is found to be larger than 100 bar.

2 OBJECTIVES

The main objective of this study is to provide answers to the following questions posed by WarmteStad:

i. Can the planned geothermal system be operated safely in a scenario where the geothermal reservoir is (partially) depleted by gas production from the nearby NAM field?
ii. Can a traffic light system (TLS) be designed such as to provide an effective risk mitigation measure in a depleted scenario?

The two questions are not strictly independent, since safe operations require TLS based mitigation measures, except for the case, where the seismic hazard can be completely ruled out.

3 STRUCTURE OF STUDY

The TLS for the WarmteStad geothermal system is developed in four stages.

In part 1, the theoretical background for the occurrence of induced seismicity in a depleted reservoir is provided. Observations of seismicity induced by similar operations are presented and discussed in the context of the planned geothermal operations.

In a separate study (part 2), the expected degree of depletion in the geothermal reservoir is investigated. Depending on the results, it will be decided if numerical simulations (part 3) are required and if a TLS can be defined (part 4).

The current document covers part 1.

4 TLS REQUIREMENTS

The definition of a TLS as a mitigation measure to prevent earthquake related damage rests on several assumptions regarding the characteristics of induced seismicity:

1. The strength (magnitude) of induced seismicity systematically increases with time.
2. A damage relevant seismic event is accompanied by precursory, smaller magnitude seismicity.
3. Operational mitigation measures for limiting the strength of induced seismicity can be defined.
4. The time delay (response time) between TLS stoplight and the mitigation measures becoming effective is sufficiently small to prevent magnitude escalation into the damage range.

For the geothermal project location, the lowest magnitude level at which reservoir seismicity may cause vibration related damage at the Earth's surface has been estimated as M_w=2.5 (Vörös et al., 2016). This is taken as the design criterion in the current study, i.e. TLS control should prevent the occurrence of seismicity with $M_w \geq 2.5$.

Compared to seismicity in the Groningen gas field where $M_w \geq 2.5$ seismicity occurs occasionally, this design criterion may appear overly conservative. It should be noted though, that the TLS for the geothermal system should prevent the occurrence of even the slightest material damage.

This is different for the Groningen gas field, where minor damage due to production induced earthquakes is accepted and compensated. In the time period 2012-2014 the operating company spent 160 million € on damage claims (Winningsplan 2016). The strongest earthquake that occurred in this period was the M=3.6 Huizinge earthquake. In the year 2015, where the strongest earthquake was the M=3.1 Hellum earthquake, the amount spent on damage claims increased to 207 million € (Winningsplan 2016). Although the relationship between earthquake magnitude and the amount of damage is complex and critically depending on building stock, the latter figures nevertheless indicate two important aspects for the geothermal project: (i) there is an increasing public awareness of earthquake related damage in the Groningen area and (ii) earthquakes at the magnitude M=3 level can be associated with significant (financial) damage.

In practice it is therefore desirable to define a more sensitive TLS for the geothermal project, aiming to prevent seismicity e.g. already at the M_w1.5 level. For studying the technical feasibility of a TLS, however, the minimum requirement of preventing $M_w \geq 2.5$ seismicity is considered.

5 GEOMECHANICAL PROCESSES

The physical mechanisms underlying the induced seismicity were summarized by Vörös et al. (2016). Their study focusses on seismicity induced by fluid injection. In the current context, additional deformation processes need to be considered, where seismicity is driven by reservoir compaction.

Both types of seismicity follow the same physical laws and seismic failure can be described by the stress-strength conditions on (pre-existing) faults (compare Vörös et al., 2016)

Equation 1: $\tau_{crit} = \mu \cdot (\sigma_n - P) + \tau_0$

with τ and σ_n denoting the shear and normal stress, P the *in situ* fluid pressure, μ the coefficient of friction and τ_0 cohesion (e.g. Zoback, 2007).

In the following sections, characteristics of seismicity induced by overpressure (P-type seismicity, section 5.1 and by pressure drawdown (C-type seismicity, section 5.2) are discussed separately for a scenario, where the overall pressure level of the geothermal reservoir continuously decreases due to the nearby gas field.

The seismicity classification is motivated by the availability of observation data that could be used for comparisons (chapter 6). It is noted, however, that both mechanisms (i.e. overpressure and pressure drawdown) act simultaneously during geothermal circulation and associated stress changes superimpose. Therefore, the following considerations apply to those regions in the reservoir, where overpressure (vicinity of injection well) or pressure drawdown (vicinity of production well) are dominating.

5.1 Seismicity Driven by Overpressure (P-Type)

An intuitive representation of the stress-strength conditions on a (point of a) fault is provided by Mohr diagrams. Figure 1 shows a Mohr diagram for the simple scenario, where hydraulic processes are dominated by fractures in a reservoir and poroelastic effects in the rock matrix are negligible. A normal faulting stress regime is assumed, as can be expected for the geothermal project location.

From a seismic hazard perspective, neglecting poroelastic effects for P-type seismicity is the most relevant scenario, since poroelastic stresses tend to counteract the destabilizing effect of pressure increase. This is illustrated in Figure 2, showing Mohr diagrams assuming uniaxial deformation in a horizontally extended reservoir in a normal faulting regime. The same model assumptions are commonly made for geomechanical analyses of the Groningen gas reservoir (e.g. Mulders, 2003; van den Bogert, 2015).

If poroelastic effects can be neglected, induced seismicity is controlled by hydraulic pressure diffusion leading to the characteristic spatio-temporal signature shown in Figure 3. Induced seismicity approximately follows a 'hydraulic triggering front' (Shapiro et al., 1997) and ceases due to stress relaxation ('backfront', Shapiro et al., 2009). Due to geometrical effects, the potential for the occurrence of larger magnitude events scales with the size of the pressurized (fault) area (Baisch et al., 2006). Therefore, the spatio-temporal signature shown in Figure 3 is the most important element regarding the TLS requirements:

Because of the point-source pattern of hydraulic overpressure in combination with a relatively slow diffusion process, stress criticality is reached locally before a larger fault area slips coherently. In simple terms, a slowly propagating 'hydraulic triggering front' systematically screens the reservoir for critically stressed features. Stress criticality on such features starts to increase locally, implying that the strength of induced seismicity starts at a low magnitude level and increases with time, thus fulfilling TLS requirements 1 and 2 (chapter 4). Without external stress changes, induced seismicity ceases after hydraulic conditions have become stationary.

Now consider an additional pressure depletion source driven by production from the NAM gas field. The rate of pressure changes is expected in the order of less than 1 bar/a (IF Technology, 2016) and it is reasonable to assume an approximately uniform pressure impact throughout the geothermal reservoir block, which is a common assumption for the Groningen gas reservoir (e.g. van den Boogert, 2015). Pressure decrease counteracts the P-type seismicity triggering mechanism. As long as the pressure increase associated with geothermal injection dominates, stress contributions from the NAM field have a stabilizing tendency (e.g. the stress path in Figure 1 reverses). The case where reservoir depletion is dominating is discussed in the next section.

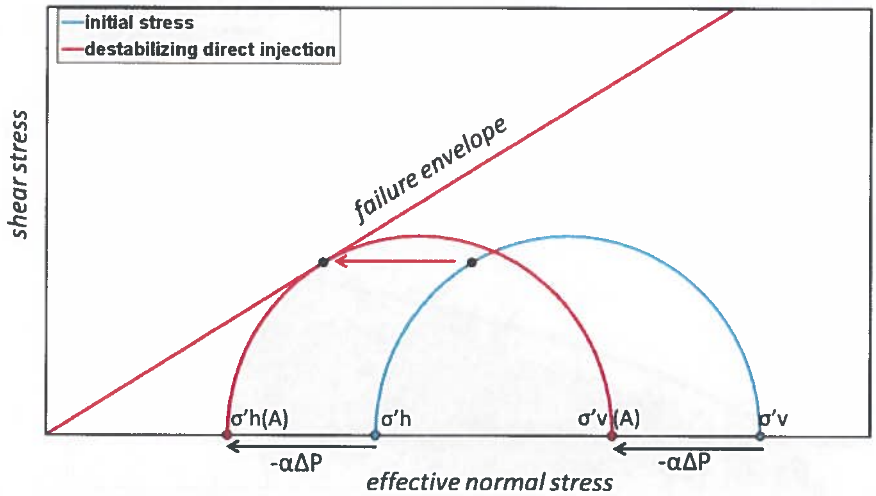


Figure 1: Mohr diagram showing the stress path during fluid injection into an open fault in a relatively impermeable reservoir (i.e. no poroelastic effects in the matrix). Fluid pressure increase (-$\alpha\Delta P$, where α denotes Biot's coefficient) shifts the Mohr circle towards the failure envelope without changing its radius (i.e. shear- and normal stress remain constant). The most critical fault orientation is marked by a black dot. Figure taken from TNO (2014).

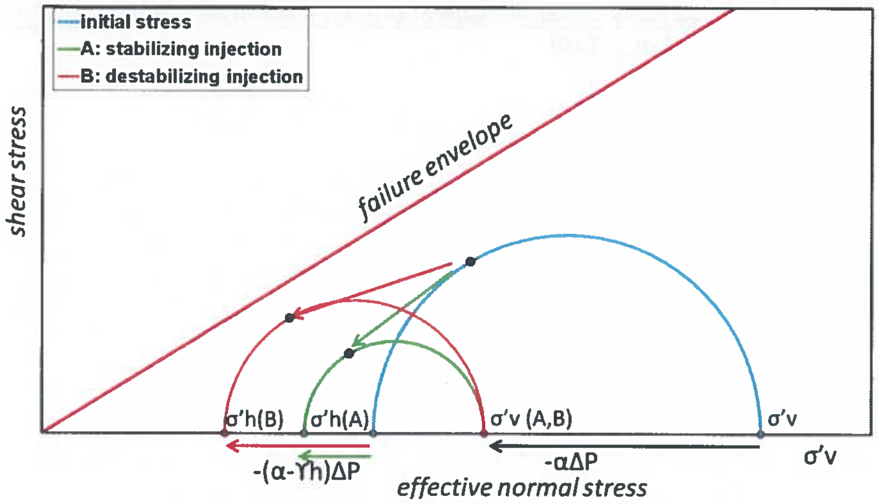


Figure 2: Mohr diagram showing the poroelastic stress path during fluid injection into a permeable reservoir in a normal faulting regime assuming uniaxial deformation. Fluid pressure increase (-$\alpha\Delta P$, where α denotes Biot's coefficient and γh the horizontal stress path coefficient) shifts the Mohr circle towards the failure line. The radius of the circle decreases due to poroelastic effects which is counteracting the destabilizing effect of pressure increase. Depending on poroelastic stresses, fluid injection could either stabilize (green) or destabilize (red) stress conditions. Figure taken from TNO (2014).

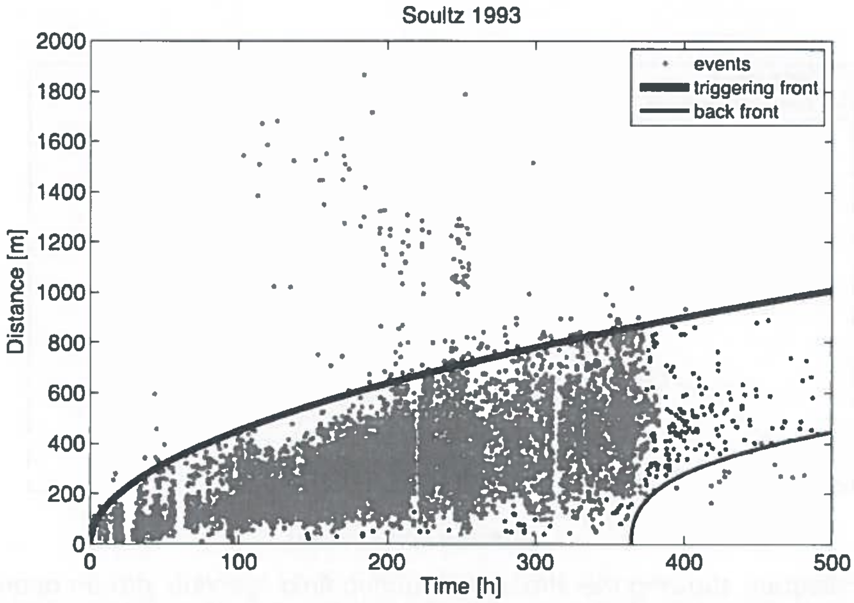


Figure 3: Fluid-injection induced seismicity in the Soultz-sous-Forêts geothermal reservoir. Seismic events (dots) are shown in a time-distance (r-t) display demonstrating that induced seismicity approximately follows hydraulic pressure diffusion, where the onset of seismicity is described by a (hydraulic) triggering front. Stress relaxation (similar to the Kaiser effect, Baisch & Harjes, 2003) causes seismic quiescence ('backfront') after seismic activation. Figure taken from Shapiro et al., 2009.

5.2 Seismicity Driven by Reservoir Compaction (C-Type)

Figure 4 shows the Mohr diagram for reservoir depletion assuming uniaxial deformation in a horizontally extended reservoir in a normal faulting regime. This is the reversed stress path of Figure 2 (note the different sign convention for pressure). During reservoir depletion, the effective vertical stress increases faster than the effective horizontal stress, causing larger differential stresses and a larger Mohr circle that may eventually lead to seismic failure.

In the initial phase of geothermal production (prior to reaching quasi-stationary conditions), the spatio-temporal signature of pressure drawdown is similar to the one discussed in the previous section for the overpressured region. This implies the same systematic increase of the strength of induced seismicity.

Now consider additional pressure depletion driven by production from the NAM gas field. Following the line of argumentation in the previous section, a uniform (i.e. reservoir wide) pressure depletion in the order of ≤1 bar/a is considered. Pressure decrease further enhances the C-type seismicity triggering mechanism. This implies homogeneous changes of stress conditions on reservoir faults towards criticality.

In the special case where poroelastic stress perturbations associated with geothermal circulation exhibit little spatial variation on a reservoir fault (i.e. stress conditions are approximately the same everywhere on the fault), seismic failure processes and associated event magnitudes are controlled by structural heterogeneities, e.g. the spatial variability of fault strength. In this case, TLS requirements 1 and 2 (chapter 4) are not necessarily fulfilled.

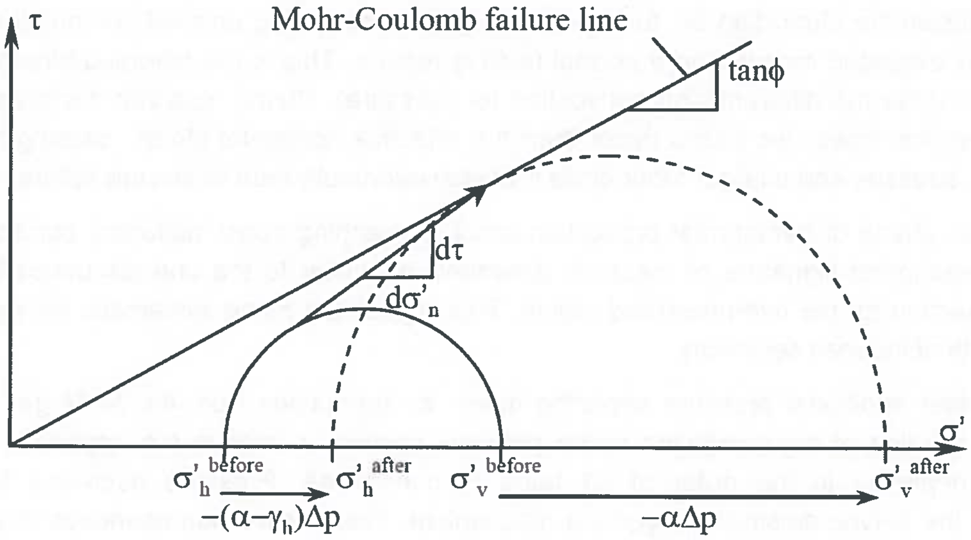


Figure 4: Mohr diagram showing the poroelastic stress path during pressure depletion in a normal faulting regime assuming uniaxial deformation. Fluid pressure decrease (-$\alpha\Delta P$, where α denotes Biot's coefficient and γh the horizontal stress path coefficient) shifts the Mohr circle away from the failure line (dotted circle). The radius of the circle increases due to poroelastic effects which is counteracting the stabilizing effect of pressure increase. Figure taken from Mulders (2003).

6 OBSERVATION DATA

The authors are not aware of any direct field analogue, where a geothermal doublet system is operated in a significantly depleted reservoir. Therefore, observations of seismicity induced by comparable injection and production operations are discussed in order to identify seismicity characteristics that are likely to apply to the Groningen geothermal system.

6.1 Injection Induced Seismicity (P-Type)

Characteristics of fluid injection induced seismicity were already discussed in a previous study (Vörös et al., 2016). Most important in the current context is the systematic and gradual temporal evolution of the strength of induced earthquakes during fluid injection (Figure 5), which is consistent with expectations (section 5.1).

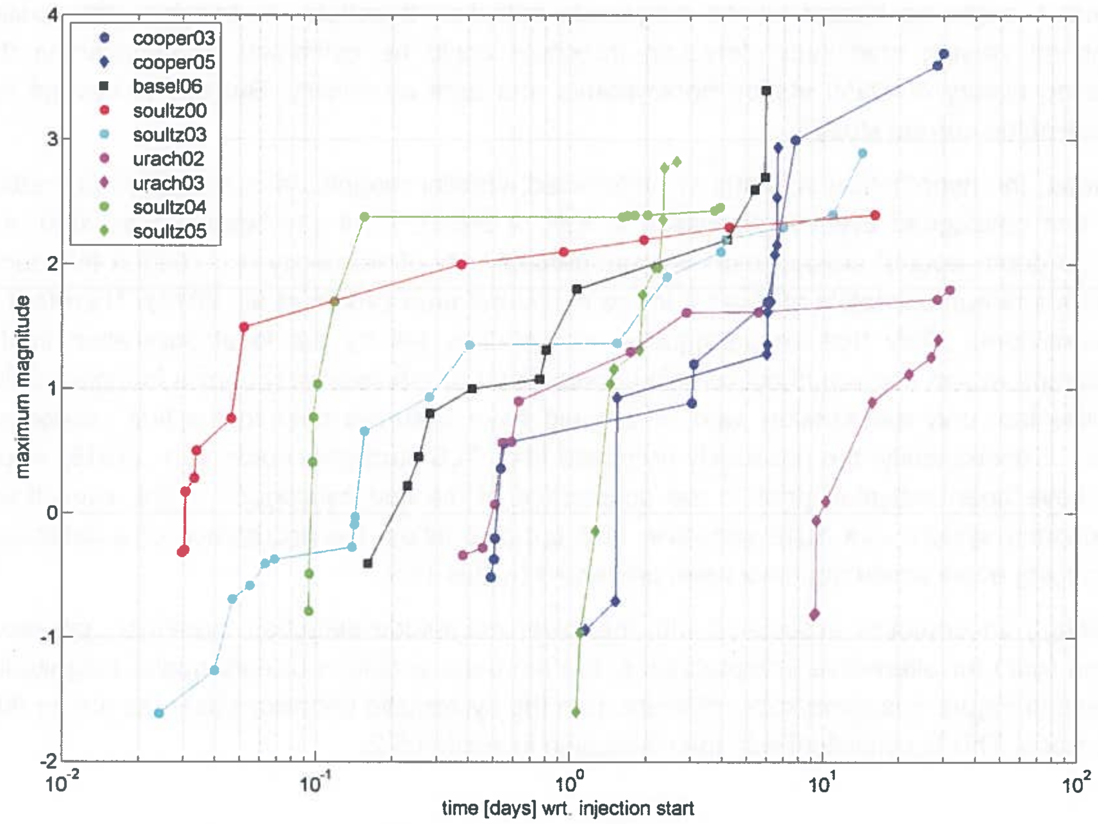


Figure 5: Maximum event magnitude as a function of injection time during hydraulic stimulation at different geothermal sites. Multiple stimulations of a well are indicated by using the same color and diamond symbols for indicating re-stimulation. Note that data points are generated whenever previous maximum magnitudes are exceeded. Thus, a large number of data points indicate a gradual increase of the maximum event magnitude. Figure taken from Baisch et al., 2009.

6.2 Production Induced Seismicity (C-Type)

In the Netherlands more than 450 gas fields have been discovered, of which about 250 fields are developed (www.nlog.nl). Besides the largest Groningen gas field, 15 of the smaller fields were associated with the occurrence of production induced seismicity (van Eijs et al., 2006). The minimum depletion level at which induced seismicity started in a field is 112 bar (van Eijs et al., 2006).

Figure 6 shows the temporal evolution of earthquake magnitude for those 6 fields which are associated with at least a single M≥2.7 earthquake. In 5 of these fields, the magnitude of the first (catalogued) seismic event already exceeds the level at which material damage cannot be excluded.

It is important to notice that the magnitude detection threshold of the earthquake monitoring system was significantly improved over time due to the deployment of additional monitoring stations (Dost et al., 2012). Therefore, it is not clear to what extend the onset of seismicity in Figure 6 might be biased by the magnitude detection threshold. In principle, the spatio-temporal varying magnitude detection threshold could be estimated by considering the detailed history of KNMI station deployments and data availability. But this is beyond the scope of the current study.

Instead, the hypothetical scenario of undetected, smaller magnitude earthquakes preceding the first catalogued event is discussed in light of the TLS. All gas fields are situated at a similar depth level of around 3 km. Human perceptibility of seismicity occurring at this depth level starts approximately at M_w=1.4 in the epicentral area (Vörös et al., 2016). Therefore, it is considered likely that an earthquake with M=2 is felt by the local population in the epicentral region and would not remain undetected. For the seismicity shown in Figure 6 this implies that only earthquakes with M<2 could have occurred prior to the first catalogued event. Consequently, the previously proposed M=2 TLS stoplight (Vörös et al., 2016) would not have been activated prior to the occurrence of the first catalogued event, even if the monitoring system was more sensitive. In 5 out of 6 fields, the occurrence of a potentially damaging event would not have been prevented by this TLS.

Although uncertainties associated with the lower magnitude detection threshold may leave some room for alternative interpretations, the temporal evolution of earthquake magnitudes shown in Figure 6 is remarkably different from the systematic behavior observed during fluid injections. This is consistent with the discussion in section 5.2.

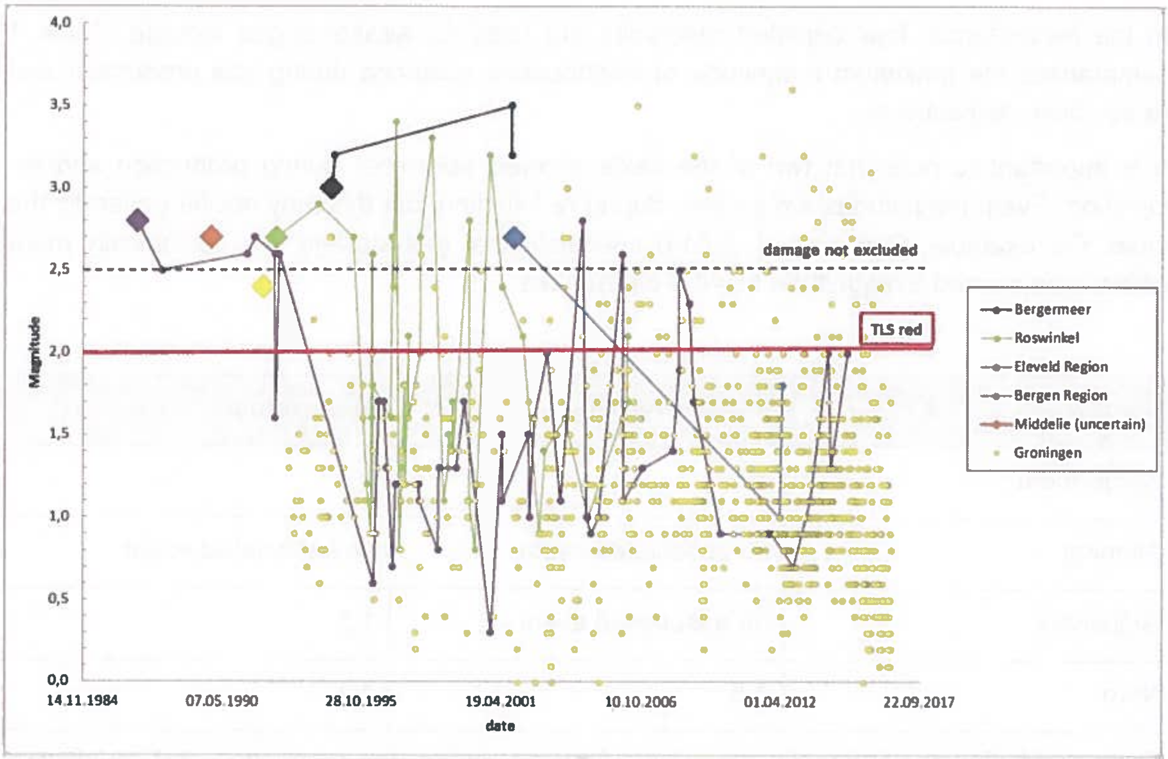


Figure 6: Temporal evolution of earthquake magnitude for selected onshore gas fields in the Netherlands according to the legend. Only those gas fields are shown in which at least one event with M≥ 2.7 has occurred. The first detected seismic event in each field is marked by a diamond. Stop light threshold of the TLS designed for an undepleted scenario as well as an estimate of the damage threshold according to SBR (Vörös et al., 2016) are indicated. Data source: KNMI earthquake catalogue (http://www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus).

6.3 Gas Injection into Depleted Reservoirs

In the Netherlands, four depleted reservoirs are used for seasonal gas storage. Table 1 summarizes the maximum magnitude of earthquakes occurring during gas production and re-injection, respectively.

It is important to note that two of the fields showed seismicity during production and re-injection. Event magnitudes are smaller during re-injection, but this may not be generally the case. For example, Cesca et al. (2014) speculate that gas storage in a tectonically more active area caused a magnitude M_w=4.3 earthquake.

Name	M_{max} production	M_{max} storage
Bergermeer	3.5	0.7
Alkmaar	no associated event	no associated event
Grijpskerk	no associated event	1.5
Norg	1.5	1.1

Table 1: Maximum earthquake magnitude induced during gas production and re-injection (storage) in the Dutch storage reservoirs. Note: The lower magnitude detection level differs for the reservoirs and also for the operations.

7 CONCLUSIONS

General requirements are identified, which need to be fulfilled for making TLS control an effective risk mitigation measure for the Groningen geothermal project.

Based on geomechanical considerations it is demonstrated that seismicity associated with hydraulic overpressure can be effectively mitigated by a TLS even in a scenario, where the overall reservoir pressure continuously decreases due to depletion of the nearby gas field.

For seismicity driven by reservoir compaction, TLS mitigation is considered possible in the initial phase of geothermal production. On a longer time scale, scenarios are possible, where larger regions of a reservoir fault reach stress criticality approximately at the same time. In these hypothetical scenarios, fundamental requirements for the TLS may not be fulfilled because damage relevant seismicity may occur without smaller magnitude precursors.

Observations from Dutch gas fields indicate that these hypothetical scenarios are actually relevant for seismicity induced by gas production. Most likely, TLS control on the level required for the geothermal project would have failed for the gas producing reservoirs considered here.

8 RECOMMENDATIONS FOR FURTHER WORK

The main findings of this study indicate that under certain conditions, TLS control is not feasible.

In our original work program we proposed using numerical models to simulate a seismicity response for a range of subsurface conditions. With this type of sensitivity study we were aiming to demonstrate that TLS control is possible in the entire range of possible subsurface conditions.

Our findings now indicate that TLS control at the desired level does not work for production induced seismicity in Dutch gas fields. Consequently, it is theoretically possible that depletion in the Groningen gas field causes a damage relevant earthquake in the geothermal license area without smaller magnitude precursors. This may happen independently from any geothermal activities.

Therefore, the planned numerical sensitivity study will most likely demonstrate that TLS control is not always possible. Based on previous experience, the occurrence of induced seismicity at small depletion levels (below 100 bar) is unlikely, i.e. the occurrence probability for a damaging earthquake is very small. However, the possibility that an earthquake occurs at an even smaller depletion level cannot be completely ruled out. Given the large consequences (e.g. potential damage sum in the order of 100 million € for an M<3.5 earthquake) the risk may be unacceptable even if the occurrence probability for a damaging earthquake is small. We therefore propose to estimate the probability of depletion driven seismicity at low depletion levels for the area relevant for the geothermal system. This should provide a depletion level at which the risk may appear acceptable. If this level of depletion is considered likely, it may be decided to drill the first well and find out what the actual level of depletion is.

To add further confidence to our findings, we propose to quantify the KNMI network detection level during the operational period of the gas reservoirs shown in Figure 6.

Additionally, we propose to investigate the probability that a damage relevant earthquake occurs on one of the mapped faults based on geomechanical models. Given the (expected) small depletion level, the steeply dipping fault geometry with relatively small throw, and the relatively small lateral extension of fault segments with the same orientation, we aim to demonstrate that the maximum magnitude that could reasonably expected is at an acceptable level.

REFERENCES

Abdullah, R. A., 2006. A study on stress-strain behaviour of granite and sandstone using closed-circuit servo-controlled testing machine, Master thesis, Universiti Teknologi Malaysia.

Baisch, S., Weidler, R., Vörös, R., and R. Jung, 2006. A conceptual model for post-injection seismicity at Soultz-sous-Forêts. *Geothermal Resources Council*, Trans., Vol. 30, 601-606.

Bourne, S. J., and Oates, S., 2015. An activity rate model of seismicity induced by reservoir compaction and fault reactivation in the Groningen gas field. NAM report, 50 pages.

Cesca, S., Grigoli, F., Heimann, S., Gonzalez, A., Buforn, E., Maghsoudi, S., Blanch, E., Dahm, T. (2014): The 2013 September-October seismic sequence offshore Spain: a case of seismicity triggered by gas injection? – Geophysical Journal International, 198, 2, p. 941-953.

Dost, B., Goutbeck, F., van Eck, T.m, and D. Kraaijpoel, 2012. Monitoring induced seismicity in the North of the Netherlands, status report 2010. *KNMI Scientific report*, WR 2012-03, DeBilt, 2012.

IF Technology, 2016. Memo to WarmteStad, August 9th, 2016.

Mulders F.M.M., 2003. Modelling of stress development and fault slip in and around a producing gas reservoir. PhD thesis, TU Delft, Delft University Press, ISBN 90-407-2454-7, 288 pages.

Shapiro, S., Huenges, E., and Borm, G., 1997. Estimating the crust permeability from fluid-injection-induced seismic emission at the KTB site. *Geophys. J. Int.*, **131**, F15-F18.

Shapiro, S., and C. Dinske, 2009. Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing. *Geophys. J. Int.*, **57**, 301-310.

TNO, 2014. Literature review on injection-related induced seismicity and its relevance to nitrogen injection. TNO report, TNO2 2014 R11761, 46 pages.

van den Bogert, P. A. J., 2015. Impact of various modelling options on the onset of fault slip and the fault slip response using 2-dimensional Finite-Element modelling. NAM report SR.15.11455, 101 pages.

Van Eijs, R.M.H.E., Mulders, F. M. M., Nepveu, M., Kenter, C. J., and B.C. Scheffers, 2006. Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands. Engineering *Geology*, **84**, 99-111.

2016. SHA Geothermal Project Groningen. Q-con report IF001 version 160531, 33 pages.

Winningsplan Groningen Gasveld 2016. NAM report EP201604259068, 86 pages.

Memo

Project:	Warmtestad Groningen
Subject:	Definition of depletion scenarios
Date:	12 august 2016
Reference:	65308/BP/20160812
Author:	
Checked by:	

1 Introduction

The municipality of Groningen and the Water Company of Groningen are considering the use of deep geothermal heat to supply heat to the district heating system for the city of Groningen. The reservoir that is considered for the geothermal wells is the Slochteren Formation. The major gas field that is located under the major part of the province of Groningen is located in the same reservoir. Since the gas production from the Groningen gas field has led to a large number seismic events, the occurrence of induced seismicity that might be related to the geothermal project is a major concern.

The experience is that induced seismicity mainly occurs when pre-existing faults are re-activated due to changes in stress. For the stress changes, not only the impact of the geothermal system is relevant, but also the possible impact of the ongoing depletion of the Groningen gas field. In order to answer the key questions of Warmtestad, assumptions are needed on the current level of depletion and the development in time. IF Technology was asked to define three hypothetical depletion scenarios. These scenarios should include the current depletion level and a prognosis about the depletion over the next 30 years. Furthermore recommendations will be given for measurements after drilling the first well, to define the state of the reservoir and stresses. In this memo, the results are described.

2 Depletion level

Relevant information for estimating the level of depletion is:

- Depletion level in nearby gas fields;
- Pressure measurements in nearby wells;
- NAM reservoir model of the Groningen gas field;
- Observed land subsidence.

In the following paragraphs each of these topics is addressed.

2.1 Pressure depletion in nearby gas fields

Based on the most recent gas production plans (winningsplannen) of the surrounding gas fields, NAM provided a map of depletion levels in these field (Figure 1). Because the Groningen gas field is (by far) the largest gas field, this field will be the most important driver for possible depletion in the region. A small gas field that may also be relevant is the Pasop gas field, wich is located on the western edge of the reservoir block where the geothermal doublet of warmtestad is planned.

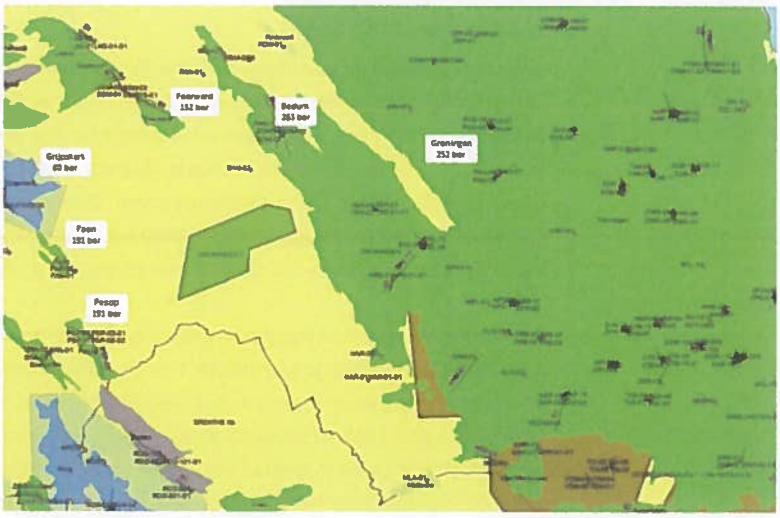


Figure 1
Depletion levels according to the most recent versions of the gas production plans for each of the surrounding gas fields.

Groningen gas field

The cumulative production from the Groningen gas field currently amounts more than 2000 bln Nm³. For the most nearby production location (Eemskanaal), Figure 2 shows the development of the gas pressure since the start of production from the Groningen gas field in the 1960's. At the location Eemskanaal, the gas pressure has decreased from an initial 340 bar in the 1960's to 125 bar in 2012 (315 bar depletion). In other parts of the gas field, the depletion amounts up to 252 bar.

Pasop gas field

The cumulative production from the Pasop gas fields amounts 0.4 bln Nm³, which is insignificant in comparison to the production from the Groningen gas field. The fact that a depletion level of 191 bar is present, despite the relatively small cumulative gas production inicates that the Pasop field must be located in a small compartment of the reservoir block. Simple calculations show that the influence of this gas field on the reservoir pressure at the geothermal location will be insignificant, even when small compressibility values are assumed.

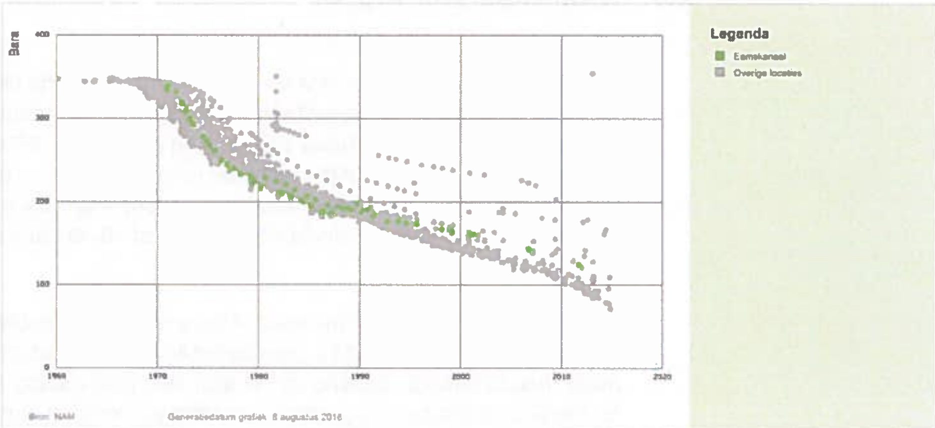


Figure 2
Gas pressures measured in the Groningen gas field. Green dots show the gas pressures for the location Eemskanaal (source: http://www.namplatform.nl/feiten-en-cijfers/feiten-en-cijfers-gasdruk.html).

2.2 Pressure measurements in nearby wells

For several locations reservoir pressures have been measured once, right after drilling a new well. The most relevant locations are SAU-01 and PSP-01.

Well SAU-01 was drilled in 1995. In this well a pressure of 37,23 MPa was measured at a true vertical depth of 3234 m sub sea. Apparently an overpressure of approximately 5 MPa was still present in 1995.

Well PSP-01 was drilled in 1991. In this well a pressure of 36,28 MPa was measured at a true vertical depth of 3135 m sub sea. The overpressure is approximately 5 MPa and is equal to that of well SAU-01.

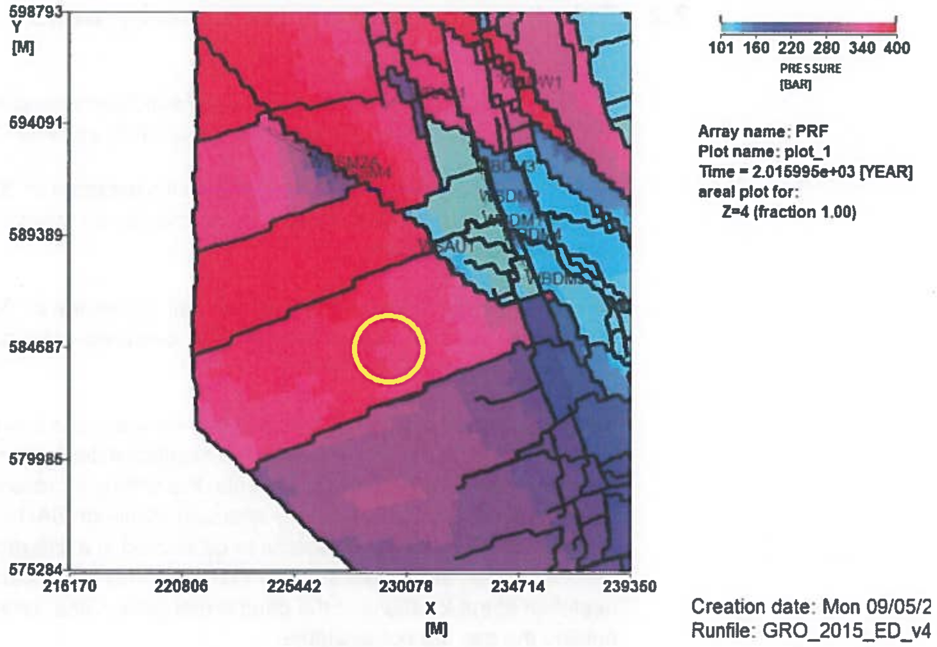
The overpressures following from these wells are in the same range as other initial pressure measurements in the area. Despite the significant depleation in the Groningen gas field at the time of the pressure measurements, the reservoir pressures at SAU-01 and PSP-01 seems to be unaffected (or hardly affected). Although SAU-01 is located in another reservoir block and PSP-01 seems to be located in a different compartment of the same reservoir block, these data suggest that there may be no depletion or a very limited depletion at the locations of the geothermal wells. Other relevant pressure measurements outside the gas are not available.

2.3 NAM reservoir model

NAM has constructed an extensive reservoir model for the Groningen gas field. This reservoir model was calibrated to the available pressure data and land subsidence measurements. Figure 3 shows a calculated pressure of 360-380 bar at the Warmtestad doublet location. The top of the reservoir is at 3400-3450 m depth. Assuming an initial overpressure of 5 MPa (see previous paragraph), the initial pressure would amount 390-395 bar. This suggests a calculated depletion of 10-45 bar for the location of the Warmtestad doublet.

It has to be noted that - for the area of the geothermal doublet of Warmtestad - the reliability of the model results should be considered limited because of a lack of pressure data. The model results strongly depend on the assumed permeability of the faults that are relevant for the Warmtestad reservoir block: assuming somewhat higher permeability values rapidly results in larger calculated depletion levels and smaller permeability values lead to smaller depletion levels.

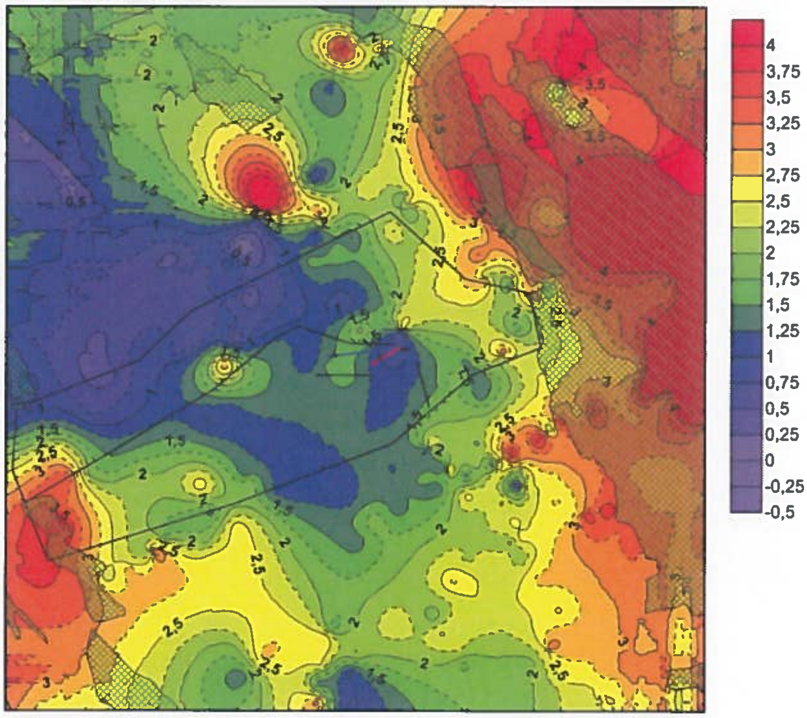
Figure 3
Reservoir pressure calculated with the NAM reservoir model for 2016. The yellow circle shows the location where the geothermal doublet of Warmtestad is planned.



2.4 Observed land subsidence

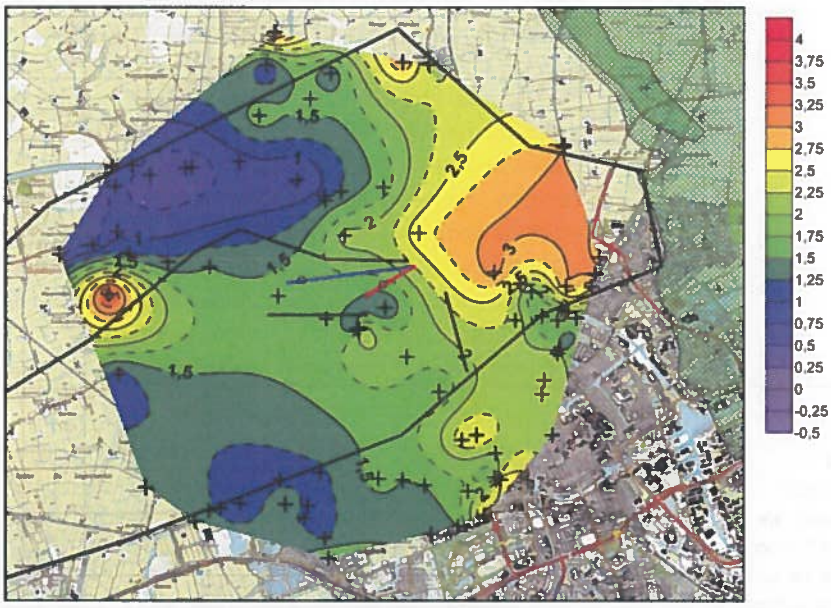
Based on land surface level measurement data that are available from the NLOG site, the average land subsidence rate in mm/year was calculated for almost 5000 locations. This average rate was calculated, based on the difference between the first measurement and the measurement in 2013 and was only used when at least 10 years was in between. This is a rough method that may not always be accurate (better to look into time – surface level graphs and derive the subsidence rate from the graph, skip locations with little data points, skip data that seem unreliable, etc. but this takes much more effort/time), but it gives quick insight in approximate values. Figure 4 shows a map with the calculated average land subsidence rates over a period at least 10 years. The Groningen and Pasop Gas fields clearly show up. To the West of the Groningen gas field the land subsidence rate clearly declines up to 3-4 km from the edge, which is equal to the reservoir depth (angle of 45 degrees in upward direction from the edge of the gas field at reservoir depth).

Figure 4
Average land subsidence rate [mm/year] during 10-40 years, calculated from land surface measurements.



For the area directly around the geothermal wells the average land subsidence rates were estimated more accurately by analyzing time – surface level graphs (Figure 5).

Figure 5
Average land subsidence rate [mm/year] during 10-40 years, derived from time - surface level graphs.



At the intended geothermal well locations the land subsidence rate is roughly between 1 and 2 mm/year. A subsidence rate of 1-2 mm/year during 50 years would result in 5-10 cm of subsidence. This is very similar to a map from NAM with the current land subsidence due to gas production, which suggests a cumulative land subsidence of 6-8 cm up to 2008 for the location (Figure 6).

Figure 6
Land subsidence up to 2008 (source: www.namplatform.nl).

According to TNO it can be assumed as a rule of thumb that 10 cm of land subsidence coincides with 50 bar of depletion. Presumably, this rule of thumb has been derived for the Slochteren reservoir in the Groningen gas field. At the location of the geothermal wells, the reservoir thickness is equal to that in the central/northern part of the gas field (where the strongest land subsidence occurs). However, the resevoir is situated approximately 500 m deeper. This is expected to result in approximately 10% less subsidence for the same level of depletion: 9 cm for 50 bar of depletion.

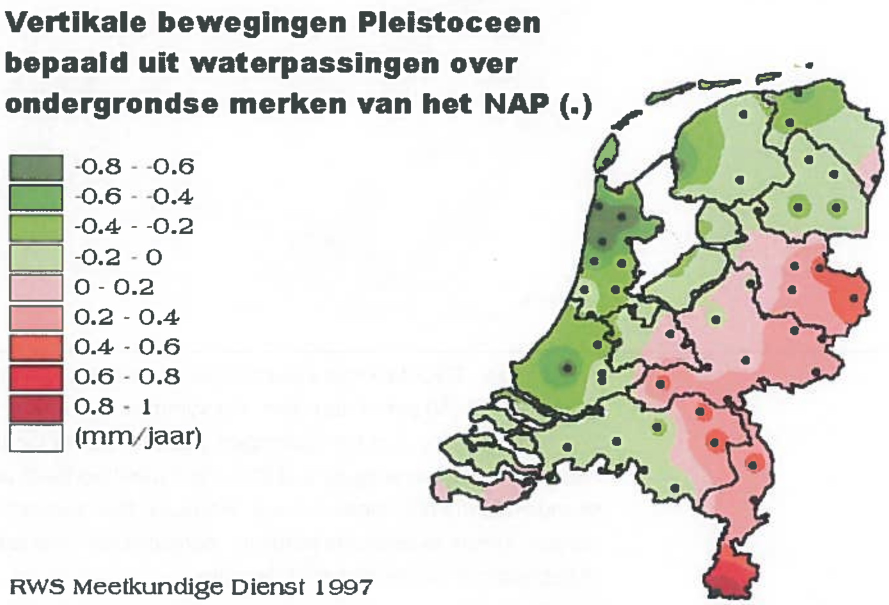
When this 5-10 cm of land subsidence is caused by depletion in the Slochteren reservoir at the geothermal site, this would result in an estimated depletion of 28-56 bar at the location of the Warmtestad doublet. However, it is expected that part of the total land subsidence is caused other factors:

- Compaction of the Slochteren reservoir in the western part of Groningen gas field (outside the geothermal reservoir block).
- Subsidence due to compaction of more shallow layers (up to Pleistocene). Subsidence rates of the Pleistocene have been mapped on a National scale bij Rijkswaterstaat (Figure 7) and are approximately 0.2 mm/year at the location (1 cm in 50 years).
- Subsidence in the Holocene deposits. Holocene layers are usually most prone to subsidence, for instance caused by groundwater level decline and/or oxidation of organic deposits.

When all of the measured subsidence is caused by these other factors, this would suggest no depletion in the reservoir at the geothermal site. When only the known subsidence of the

Pleistocene is subtracted, the land subsidence at the geothermal site would be 4-9 cm, which would suggest 25-50 bar of depletion. The depeletion level that can be derived from these land subsidence data should therefore be interpreted as somewhere between 0 and 50 bar.

Figure 7
Vertical movement of the Pleistocene, derived from subsurface monitoring locations.



2.5 Development of depletion in the future

Since the level of depletion is directly caused by gas prodution, the development of depletion in the future is expected to depend on the gas production from the Groningen gas field in the future. In the gas production plan 2016 (winningsplan 2016) three scenarios are described, starting with a gas production of 21, 27 and 33 billion Nm³ respectively in 2016. In the years after 2016 the gas production gradually declines, especially in the scenarios with the highest gas production rates. In the gas production well cluster Southwest, which is nearest to the geothermal well locations, the gas production significantly declines with respect to the years before. This is expected to reduce future depletion in this part of the gas field and therefore also reduce possible future depletion at the geothermal site.

Figure 8
Future gas production scenarios from the gas production plan 2016 for the Groningen gas field (NAM, 2016).

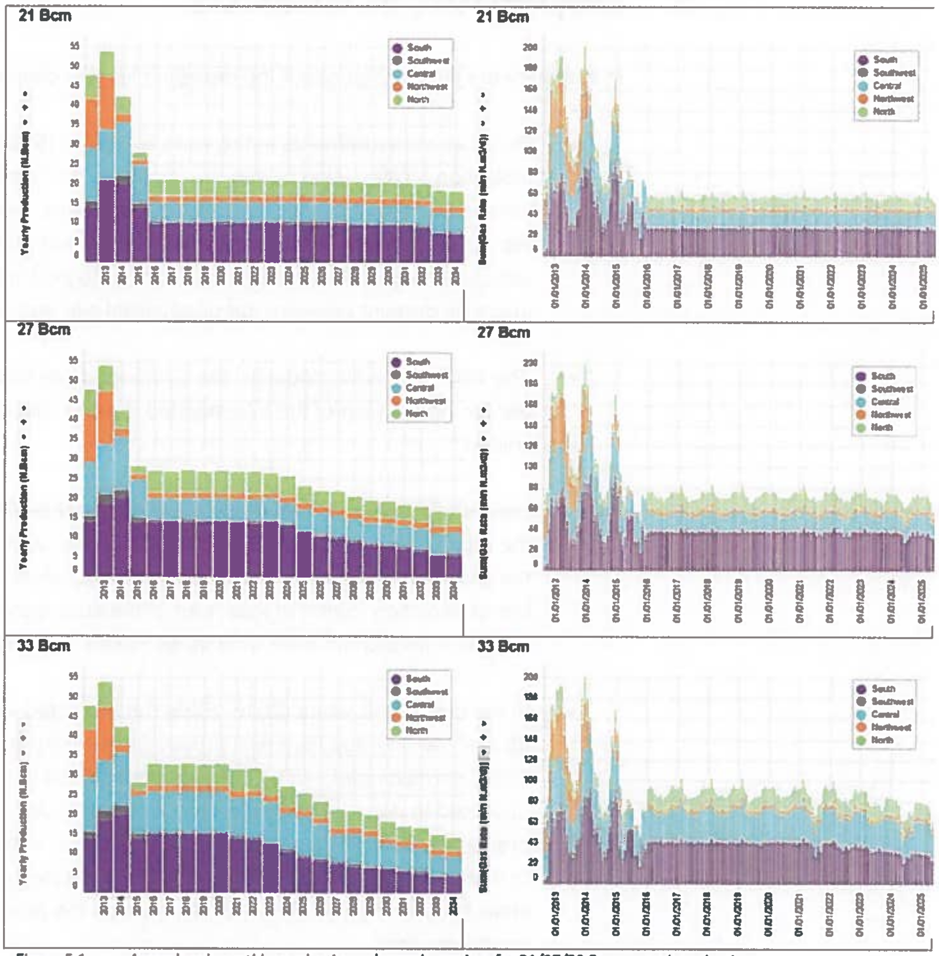


Figure 5.1 *Annual and monthly production volumes by region, for 21/27/33 Bcm annual production*

The average gas production during the last 50 years was approximately 40 billion Nm³ per year. Assuming the middle scenario, the predicted average production during the coming 10 years (2016-2025) will be 26 billion m³ per year (65% of the average production in the past). The possible rate of depletion is assumed to also reduce to 65% of the depletion rate in the past, although the relation may not be 1 to 1. In the 10 years after that (2026-2035) the predicted average production is approximately 19 billion m³ per year (48% of the average production in the past).

3 Depletion scenarios

In summary the information about the depletion level in chapter 2 is:

- Pressure measurements in the wells SAU-01 (1995) and PSP-01 (1991) show no indication for depletion due to the impact of the Groningen gas field, although a very small impact cannot be excluded. However, these wells may not be representative for the location of the geothermal wells. This demonstrates that (amost) impermeable barriers/faults must be present in the area. Similar barriers might be present between the geothermal site and the gas field.

- The NAM reservoir model for the Groningen gas field predicts a depletion of 10-45 bar for the location of the Warmtestad doublet, but the reliability is considered limited.

- Land surface level measurement data suggest 5-10 cm of land subsidence during the past 50 years. When all of this subsidence would be caused by compaction of the Slochteren reservoir at the geothermal location, then this would suggest 28-56 bar of depletion. Since at least part of the subsidence has other causes, the real depletion should be lower than these values: somewhere between 0 and 50 bar.

- In the coming 10 years (2016-2025) the projected average gas production rate is 65% of the average historical production and in the 10 years thereafter (2026-2035) approximately 48%. The rate of depletion in the Groningen gas field is expected to decrease equally. Due to the relatively strong decrease in gas production from the Southwest cluster (nearest to the city of Groningen), the rate of depletion in this part of the gas field is expected to decrease more than elsewhere in the field. This will also reduce the possible future depletion rate at the geothermal site.

Currently the estimated depletion level at the geothermal site is between 0 and 50 bar (0-1 bar per year during the last 50 years). At these depletion levels, no induced seismicity is expected, which is confirmed by the observations. In the next 20 years, the depletion rate in the Groningen gas field is expected to decline due to reduction of the yearly production. The future rate of depletion at the geothermal site will therefore also reduce, but this reduction will probably be significantly retarded. Therefore the average depletion rate during the coming 20 years will be somewhere between the average depletion rate of the past 50 years and 50% of that.

3.1 Scenario 1

Current depletion: 20 bars
Future depletion: 0,3 bar per year

The lowest depletion expected is no depletion at all. Since the question for this phase of the project is what can be expected in a (partially) depleted situation, zero depletion is no option. Therefore we suggest a limited depletion of 20 bar for scenario 1. The associated average depletion rate during the last 50 years is 0,4 bar/year. For the coming 20 years the expected average rate of depletion would then be somewhere between 0.2 and 0.4 bar/year: here we assume 0.3 bar/year. After 20 years this would result in 26 bar of depletion.

3.2 Scenario 2

Current depletion: 50 bars
Future depletion: 0,7 bar per year

In this scenario the current depletion is assumed to be equal to the upper bound of the depletion range that as derived from land subsidence data. The associated average depletion rate during the last 50 years is 1.0 bar/year in this case. For the coming 20 years the expected average rate of depletion would then be 0.7 bar/year. After 20 years this would result in 64 bar of depletion.

3.3 Scenario 3

Current depletion: 70 bars
Future depletion: 1,1 bar per year

In this scenario the current depletion is assumed to be higher than expected, but still below 100 bar. The associated average depletion rate during the last 50 years is 1,4 bar/year in this case. For the coming 20 years the expected average rate of depletion would then be 1,1 bar/year. After 20 years this would result in 92 bar of depletion.

4 Recommendations

The current and future level of depletion is essential for the assessment of the risk of induced seismicity. At this moment it is only possible to make a rough estimate. These rough estimates indicate that the level of depletion at the geothermal site is limited. This

would suggest that the main process relevant for induced seismicity would be the impact of the geothermal system. According the seismic hazard assessment study it is possible to design a TLS for the non depleted case. This means that the impact of the geothermal system can be mitigated.
However, the results of stage 1 indicate that a TLS would not have prevented significant events in case of depletion driven induced seismicity. Although the probability of induced seismicity will be very low at small depletion levels, the risk may still be unacceptable due to the potentially enormous consequences (e.g. a damage of 100-200 million euros for a magnitude 3.x event). The recommended next step is therefore to quantify the probability of depletion driven induced seismicity in case of low depletion levels. This should provide insight in the levels of depletion that would result in an acceptable risk.

The only way to find the actual level of depletion is measuring it after the first well has been drilled. The decision whether or not to drill the first well, will depend on (1) the expected depletion levels and (2) the depletion levels that would result in an acceptable risk.

When it is decided to drill the first well, it is also recommended to perform a pumping test. The results of the pumping test can be used to derive the hydraulic properties of the reservoir, which are decisive for the capacity and the associated hydraulic and thermal impact of the geothermal system.

Furthermore it is recommended to perform a mini frac test. The results of this test can be used to derive the characteristics of the prevailing stress field. Based on the acquired information, the seismic hazard assessment can be updated. When this updated assessment shows that the geothermal system can be operated safely, then the next well can be drilled and the system can be completed.

Bijlage 6

IF Technology
Velperweg 37
6824 BE Arnhem
Postbus 605
6800 AP Arnhem
T 026 35 35 555
F 026 35 35 599
E info@iftechnology.nl
I www.iftechnology.nl

Rabobank 38.39.42.047
IBAN NL60 RABO 0383 9420 47
KvK Arnhem 09065422
BTW nr. NL801045599B01

WarmteStad BV
Attn:
Griffeweg 99
9723 DV GRONINGEN

Date	August 29th 2016
Reference	65308/BP/20160829
Your reference	---
Subject	**Offer Geomechanical Study additional work Geothermie WarmteStad Groningen**
Handled by:	
Checked by:	

Dear ,

Hereby you will find our offer for additional work on the Geomechanical Study for the WarmteStad geothermal project as discussed with Q-con and IF Technology last week.

1. Background

The current proposal is a modification of our previous proposal of 29 July 2016 (IF Technology 65308/BP/20160729) where a four-stage geomechanical analysis was outlined After completing stages 1 and 2, a milestone decision was foreseen. Results from the stage 1 analysis indicate that it may not be possible to design a traffic light system at the required level. Therefore, it is likely that the planned sensitivity analysis (stage 3) will not provide the desired output.

As an alternative strategy it is recommended to focus on estimating the seismic risk associated with the depletion scenarios stated in stage 2 (IF Technology 65308/BP/20160729).
The current work proposal replaces stages 3 and 4 of our previous proposal (65308/BP/20160729).

2. Work Proposal

Referring to chapter 2 of report 160812_IF003 (Q-con), save operation of the geothermal system in a depleted scenario require:

3 ספטמבר 16

1. Either a risk mitigation measure (TLS),
2. Or the seismic risk to be at an acceptable level.

The current proposal focuses on the second aspect.

The seismic risk is commonly expressed in terms of probabilistic estimates (e.g. PSRA, probabilistic risk analysis). A formal PSRA for the Groningen geothermal project, however, is considered technically and economically not feasible.

Instead it is proposed to use results from various NAM studies to estimate the probability that a damage relevant earthquake occurs given the depletion scenarios identified in stage 2.

The work comprises the following steps:

1. Defining a conceptual model where the combined depletion impact from NAM production and geothermal production can be assessed using geomechanical studies from the NAM. For this, estimates of the order of magnitude of Coulomb stress changes associated with geothermal production are obtained from numerical models.
2. Derive a qualitative estimate of seismicity occurrence for the given model geometry using numerical sensitivity studies performed by the NAM with the objective to demonstrate that induced seismicity is not expected at the depletion levels considered here.
3. Use results from the NAM strain partioning model for relating depletion scenarios to seismic activity (it is acknowledged that the NAM recently **developed an alternative seismicity model. This 'strain thickness model',** however, cannot be applied without access to the NAM reservoir model). Derive mean hazard estimates for depletion scenarios.
4. Interpret (mean) hazard estimates in light of expected consequences (order of magnitude estimates as stated in 160812_IF003 (Q-con)). Provide recommendations regarding the maximum acceptable depletion level.

5. IF and Q-con

IF Technology will be the main contractor in this project, whereas Q-con becomes a subcontractor of IF Technology. IF Technology is responsible for project management, Dutch summary, quality check and communication, Q-con is responsible for technical input.

Bijlage #7

SGS

PROPOSAL

Seismic Risk Analysis Zernike Geothermal project - Sensitivity Analyses

Client	WarmteStad BV Griffeweg 99 9723 DV Groningen The Netherlands
For the attention of	
Issue Date	September 13, 2016
Issued by	SGS Horizon B.V. Stationsplein 6 NL-2275 AZ Voorburg Netherlands
Prepared by	Business Development and Sales Oil, Gas and Chemicals
SGS Reference	OGC/NL/HAG/2016/S1607-13-REV1

DB

Warmtestad - Seismic Risk Analysis Zernike Geothermal project - Sensitivity Analyses

Proposal for

WarmteStad BV
Griffeweg 99
9723 DV Groningen
The Netherlands

1 INTRODUCTION

SGS Horizon B.V. (SGSH) was requested by WarmteStad BV to prepare a proposal for the Seismic Risk Analysis Zernike Geothermal project - Sensitivity Analyses

WarmteStad, a joint venture between the municipality of Groningen and the Groningen water company, has been set up to investigate whether geothermal systems can be installed close to the city of Groningen to supply households with energy/hot water.

A cold water injection well and a production well are envisaged to be drilled within the Zernike license boundary. The target would be an aquifer in the permeable Slochteren formation. The area is downdip and located west of the Groningen Gas Field.

The city council has asked for supporting technical documentation, which would explain that the risk of induced seismicity/earthquakes is limited. If there is a (small) risk of seismicity, a traffic light system (TLS) should be devised (monitoring system and forward action plans).

Geothermal systems induce seismicity by changing the pressure and temperature in the reservoir. Fractures and faults in the reservoir are subject to stresses. If the stress that works on a fault or fracture exceeds a critical value it will "fail", resulting in seismicity. In addition, in the neighbouring Groningen Gas Field gas production has caused significant pressure depletion, inducing numerous seismic events. As the Zernike area is located close to the Groningen Gas Field, pressure depletion in the Zernike area due to production from the Groningen Gas Field might potentially induce seismicity.

A consultant Qcon/IF has performed a simple geomechanical study, under the assumption that the aquifer is not depleted. In addition, SGSH carried out a previous phase (Phase 1). This phase comprised a review of the work done by Qcon/IF, evaluation of the seismicity in the Groningen Gas Field and the Zernike area, determination of the pressure depletion in the Zernike area, and setting up a static and dynamic model for Zernike block.

The objective of the study proposed in this document (Phase 2) is the evaluation of the sensitivity of the different parameters that control seismicity in the Zernike area. Based on the results of the sensitivity analysis the main parameters controlling and affecting seismicity are identified.

These parameters can then used to focus further studies, i.e. Phase 3 (or Phase 2-5 as per previous proposal submitted on July 27, 2016) to determine the probability of fault reactivation in the Zernike area, estimate the magnitude of potential seismic events, and devise a traffic light system to mitigate the effects of seismicity.

This proposal and budget estimate is for a work phase intermittent between Phase 1 (completed) and Phase 3 (or Phase 2-5 as per previous proposal submitted on July 27, 2016) only.

Based on SGS's understanding of WarmteStad's requirements, please find below the proposed scope of work, selected key staff members, and proposed budget.

1.1 SGS TRACK RECORD

SGS's relevant track record was provided in a previous proposal submitted on July 27, 2016.

2 MAIN RESULTS OF PHASE 1

In the first phase the seismic activity in the Groningen Gas Field and the Zernike area was evaluated. Figure 2.1 shows the seismic activity over the last 20 years, including natural seismic events and induced seismic events. Induced seismic events have similar magnitudes as natural seismic events but occur significantly more often. No seismic events have been recorded within the Zernike license boundary. However, two small seismic events have been recorded within the reservoir block that is targeted for the geothermal system.

The pressure depletion in the Zernike area was calculated based on the observed subsidence in the area [1]. Based on subsidence data from the NAM winningsplan 2016 [1] and NLOG, the pressure depletion in the Zernike area was determined to be approximately 10 bar (the effect of natural subsidence is excluded), which is insignificant compared to the pressure depletion in the Groningen Gas Field which is on average 250 bar. Note that during the lifespan of the geothermal system, which is expected to be 30 years, the pressure in the Zernike area may deplete further depending on the amount of gas production from the Groningen Gas Field.

Fig. 2.1

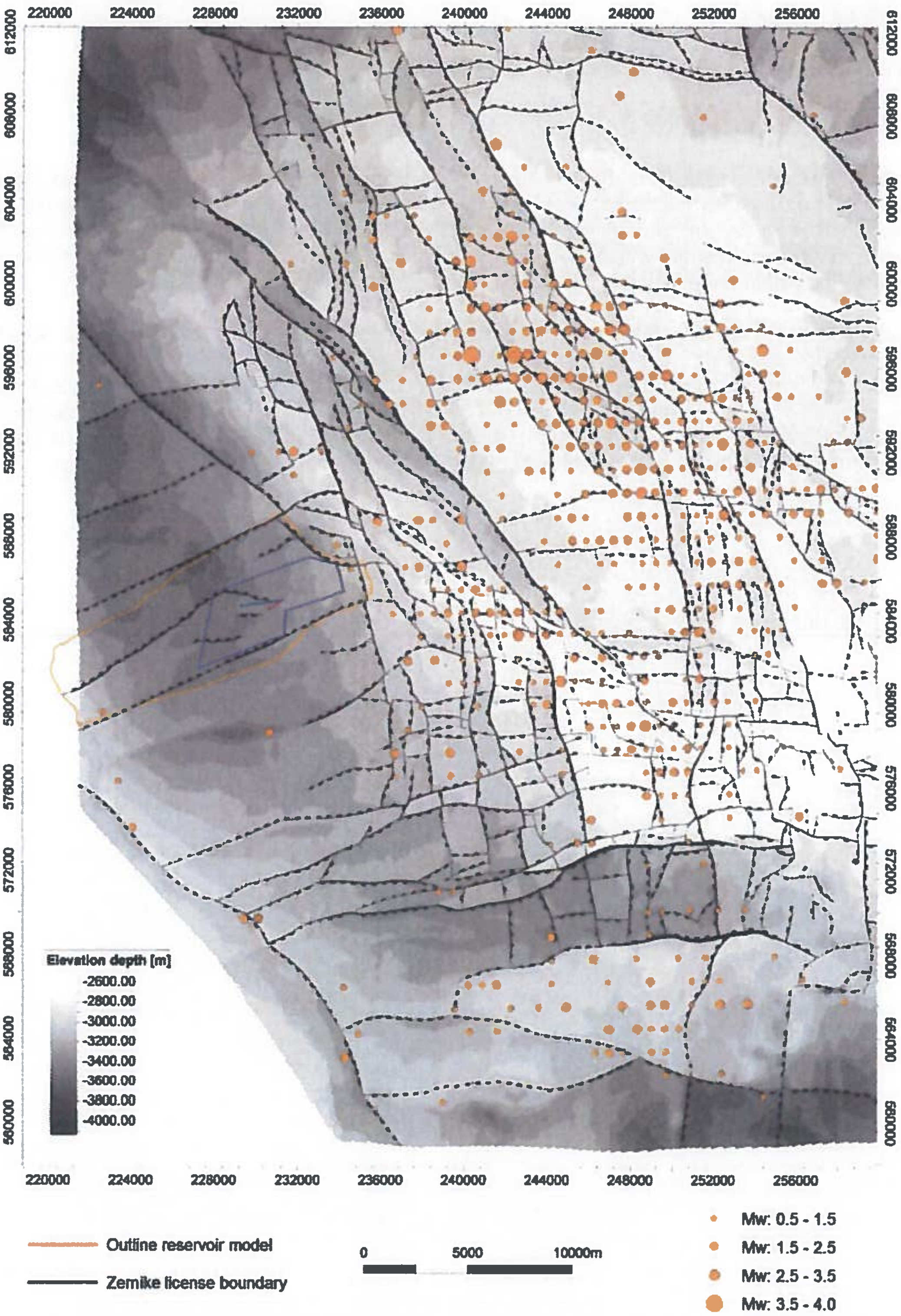


Fig. 2.1 Map showing the top structure of the Slochteren Formation and the seismic activity in the last 20 years in the Groningen Gas Field and the Zernike area. The planned injection and production wells of the geothermal system are indicated by the blue and red line respectively.

A preliminary 3D reservoir model was constructed for the reservoir block that is targeted for the geothermal system. The boundaries of this model are formed by faults with large offsets (Figure 2.1). Several smaller, roughly NE-SW oriented faults are present within the reservoir model. Based on information from the Groningen Gas Field these smaller faults are expected to be open, although the possibility exists that they have sealing capabilities which might have considerable effects on the pressure and temperature variations in the reservoir. Vertically, the model was extended 250 meters above the top of the Slochteren Formation and 250 meters below the bottom of the Slochteren Formation in order to consider all the thermal interactions of reservoir with its adjacent layers. The Slochteren Formation was subdivided into seven zones; the porosity was modeled separately for each zone based on core data from wells surrounding the Zernike area. Permeability distributed in zones based on por-perm relations which reported by Pantera [5] (Figure 2.2).

Fig. 2.2

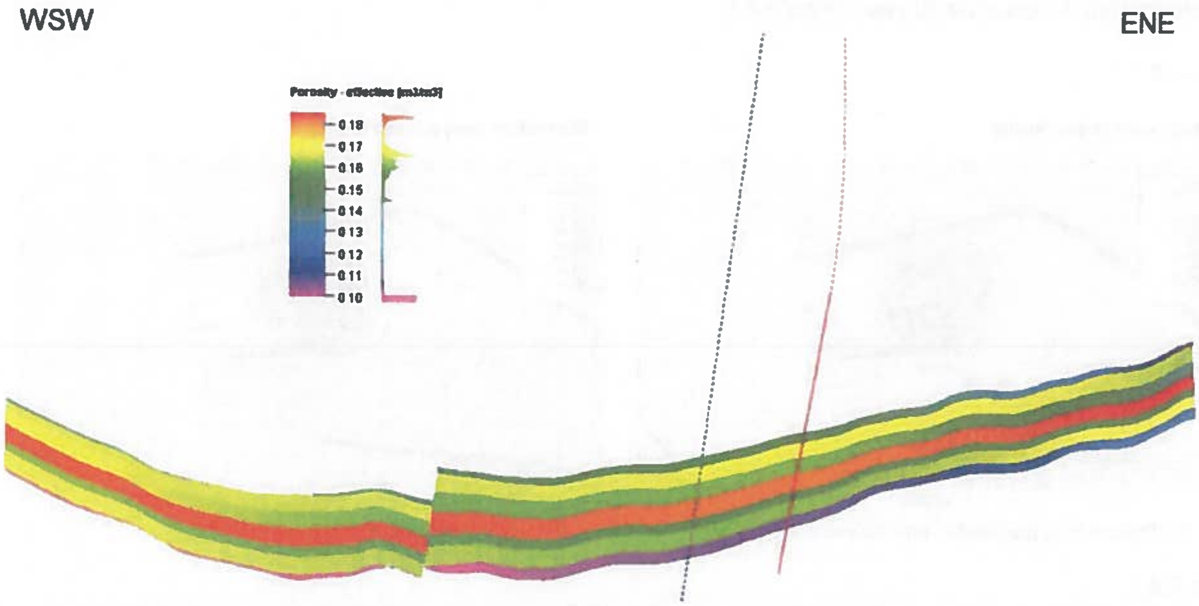


Fig. 2.2 A west-southwest to east-northeast cross-section through the reservoir model for the Zernike area, showing the porosity of the Slochteren Formation and the planned injection and production wells of the geothermal system in blue and red respectively.

The 3D reservoir model was used to run dynamic simulations of the geothermal system. For these simulations the operational parameters as defined by Warmtestad were used, while the hydrothermal properties were based on previous reports [1][6] and literature [2] [3] [4]. The pressure depletion over time related to production from the Groningen Gas Field was modeled using a declining pressure boundary over time. Two scenarios were considered: the base case scenario in which the faults are open (a fault transmissibility of 1) and an alternative scenario in which the faults are sealing (a fault transmissibility of 0).

The preliminary results of the simulations show that the cold front from the injection well does not reach the production well or the surrounding faults after 30 years of operation (Figure 2.3). This implies that thermal stresses induced by the geothermal system on the faults will be minimal. In contrast, the pressure variations due to the geothermal system reach the surrounding faults within a year. In the base case scenario with open faults, the pressure difference across the faults is small, in the order of 1 bar. However, in the scenario with sealing faults the pressure difference across the fault reaches up to 21 bar after one year and increases to approximately 40 bar after 30 years (Figure 2.4).

<u>Fig. 2.3</u>

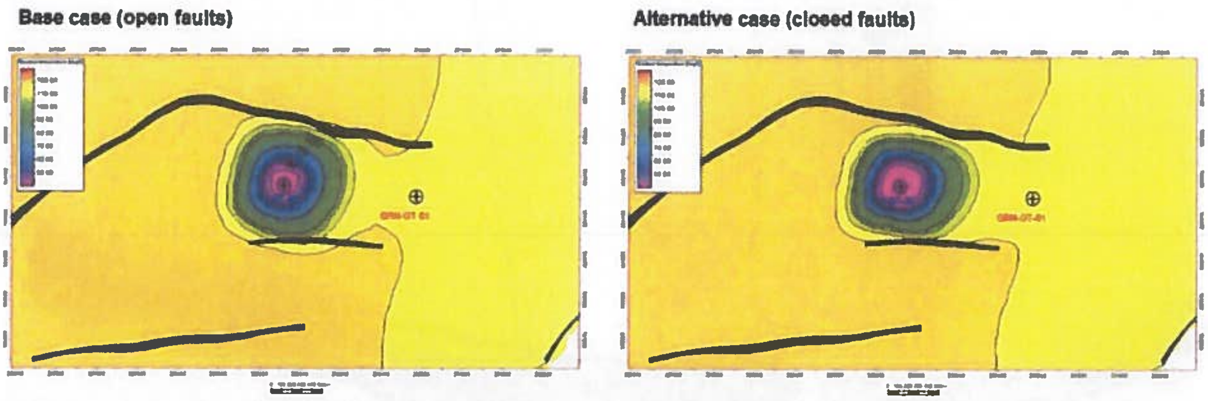


Fig. 2.3 Thermal front propagation after 30 years of production.

<u>Fig. 2.4</u>

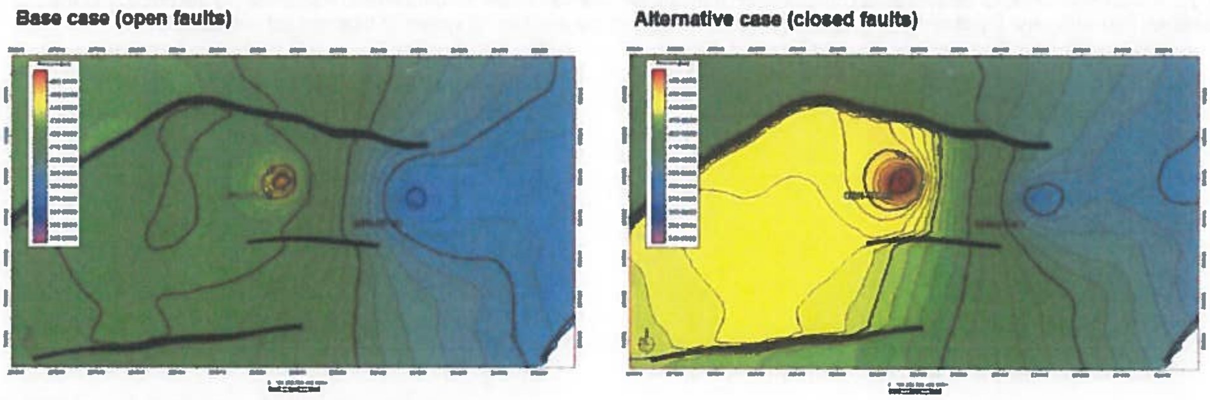


Fig. 2.4 Pressure distribution after 30 years of production.

3 PROPOSED SCOPE OF WORK

3.1 PHASE 2

SSG proposes to complete the following scope of work as a work phase intermittent between Phase 1 (completed) and Phase 3 (or Phase 2-5 as per previous proposal submitted on July 27, 2016.

As explained in the introduction, pressure and temperature changes caused by the geothermal system can induce seismicity by affecting the stress regime. The parameters that control the pressure and temperature changes in the reservoir are subdivided into three categories: operational parameters, physical parameters, and boundary conditions (Figure 3.1). The chart below shows the list of parameters in each category which affect temperature and pressure.

Fig. 3.1

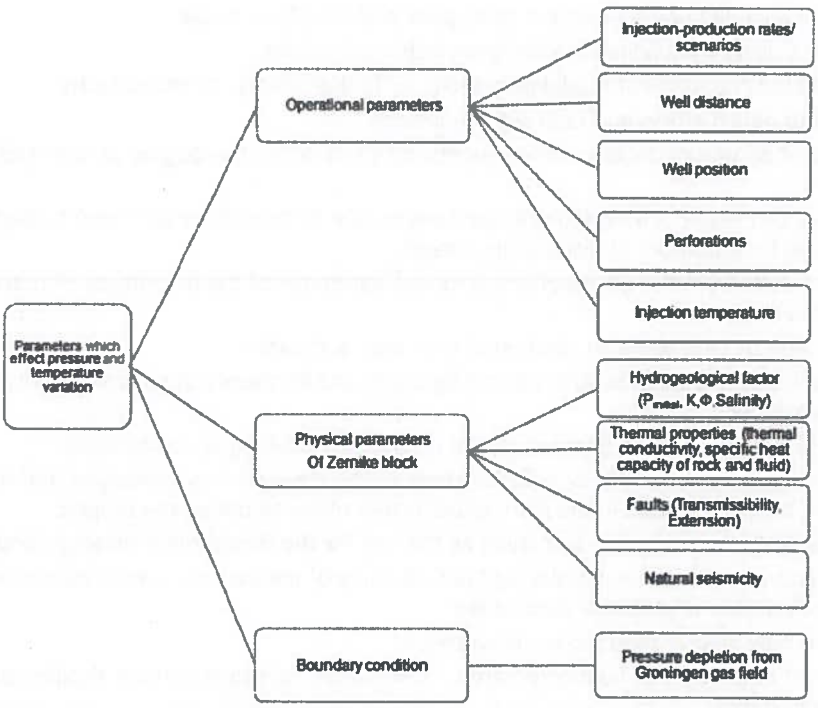


Fig. 3.1 Overview of the parameters affecting pressure and temperature changes in the reservoir due to the geothermal system.

The results of this phase will indicate the main parameters which controls and affect seismicity in Zernike block. This will be useful to focus further studies where mitigation options are desired and for implementing a traffic light system (TLS).

The following steps will be carried out in this phase in order to

1. Analysis of the background seismicity in the Zernike area
2. Evaluation and quantification of each parameter and its range of uncertainty.
3. Sensitivity analysis to identify the parameters with the highest impact on the pressure and temperature changes. This is achieved by carrying out a minimum of 50 simulations in which the input parameters are varied using the uncertainty ranges established in step 1.
4. Construction of a probability curve and defining a P10, P50, and P90 value for the expected changes in

pressure and temperature based on the results of step 2.

5. Review of analogue geothermal systems and the Groningen Gas Field and comparison with the Zernike area.
6. Evaluation of the change in stress regime across the faults in the Zernike area for the low, mid, and high cases achieved in step 3.

3.2 PHASE 3

An updated workflow for further studies (Phase 3) is included here for reference. The completion of the current scope of work will reduce the time and budget required for completion of Phase 3.

During Phase 3, geomechanical modeling will be performed to determine the probability of fault reactivation in the Zernike area, estimate the magnitude of potential seismic events, and devise a traffic light system. For this, the following steps will be carried out (note that the scope might be adapted based on the results of Phase 2):

1. Review and Enhance (if needed) existing geological- and fluid flow model
2. Assess stresses using a 2D finite element geomechanical model
   1. Generate a 2D finite element model perpendicular to the critically stressed faults.
   2. Run model to obtain stress and fault slip predictions.
   3. For a range of degree of depletion and injection rate scenarios, the degree of fault sliding, if any, will be calculated
   4. A matrix will be created linking fault slip (and eventually earthquake magnitude) to depletion and injection rate, for a number of discrete timesteps.
3. Based on the results from the geomechanical model, estimates of the magnitude of potential future seismic events will be made
   1. Determine size of fault plane, ie. section of fault that is stressed.
   2. Apply empirical relationship to determine magnitude and frequency of seismic events based on fault sliding parameters.
   3. Estimate PGV/PGA based on geomechanical model by modelling or correlations.
4. For each depletion/flowrate scenario, a TLS system will be devised. It is envisaged that the following ingredients will be incorporated in the plan, to be further matured during the project:
   1. Similar TLS systems will be studied, such as the one for the Bergermeer underground gas storage.
   2. The TLS system may involve monitoring the frequency of the seismic events over time. Consider the location and number of potential geophones.
   3. TLS system may involve reduction in flowrates.
   4. The "SBR-A" directive may be incorporated. "Oscillation" speed at surface should not exceed ~3mm/s (PGA 0.008-0.036g).
5. The technical work will be documented in a comprehensive report (in English), with a summary which can be understood by non-technical personnel (in Dutch, if desired).

3.3 DATA REQUIREMENTS

SGS has all data required to complete the scope of work, however, the following data will improve the results of the study if made available before the start of the study:

- 3D reservoir model for the Slochteren Formation developed by the Rijks Universiteit Groningen (RUG) (2015)
- 3D reservoir model for the Groningen Gas Field developed by the NAM (or, alternatively, forecasting results for the Groningen Gas Field from the NAM).
- NAM pressure measurements in the aquifer

Norwegian North Sea, Russia and Far East clastics. Andreas has a profound expertise in carbonate reservoir characterization, static and dynamic 3D reservoir modelling and the planning of vertical and horizontal oil and gas wells. During the early 1990s he was heavily involved in the development and management of digital E&P databases. In 2010 Andreas joined SGS Horizon as Geosciences Manager and Geology team leader. As head of the Innovations & Special Studies group he coordinates SGS's new technologies for the mineralogical, geochemical and geomechanical characterization of conventional and unconventional reservoirs.

Andreas will coordinate the SGS team composed of experienced staff, selected on criteria of suitability of technical skills and availability, as listed below.

4.2 KEY STAFF

Key staff are listed below

holds an engineering degree from the School of Mines of Nancy (France) and a PhD in geomechanics from Sherbrooke University (Canada). Axel-Pierre is involved in petroleum geomechanics since the mid-nineties. He first worked for Simecsol consulting company in Paris (1994), before becoming an independent consultant in 2000 and creating CurisTec in 2009. He has been involved in various projects all over the world, America (Bolivia, Canada, USA, Venezuela), Europe (France, Italy, Netherlands, Norway, UK), Africa (Algeria, Angola , Cameroon, Congo, Egypt, Gabon, Ivory Coast, Nigeria, Soudan, Uganda), and Asia (Brunei, China, Kazakhstan, Kuwait, Oman, Qatar, UAE). His main skills are in the fields of geomechanics (in situ state of stress, formation property evaluation, wellbore stability, hydraulic fracturing, reservoir mechanical behaviour, field modelling at geological scale, Drill cuttings re-injection), well integrity (cement sheath integrity, casing integrity, well integrity risk analysis), and lab testing on rock and cement. His is the author of more than twenty technical papers and a member of SPE. He is the chairman of the API work group on mechanical testing of cement systems. He is an associate for SGS Horizon since 2009.

holds a PhD in Geophysics from Karlsruhe University, Germany. He started his professional career as a post-doctoral researcher at several research institutes in Germany and France, focusing on computational geophysics, wave propagation on random media and seismic imaging. From 2003-2009 he was involved as a senior advisor geophysicist for oil/gas companies working in Indonesian area amongst other: PGSC, Pertamina, JOB Pertamina-ConocoPhillips, Inpex, EMP (Lapindo-Brantas), Elnusa responsible for QC/QA data processing, PSDM, seismic inversion based reservoir characterisation studies. From 2010-2013 he worked in the reservoir technology department of the German Research Centre for Geosciences (GFZ) as senior research geophysicist, specifically involved with a project on the integrated imaging of active and passive seismic data, and temperature-stress dependence of rocks. Makky joined SGS Horizon in 2013 and has been involved as Senior Geophysicist in seismic data processing, imaging and quantitative interpretation studies. He is currently the project manager and the technical coordinator of R&D studies on seismic processing, imaging and quantitative interpretation.

holds an MSc in Mining Engineering-Mineral Exploration from University of Tehran, Iran (2004). She has worked as a Mining Engineer in ParsOlang Co., Iran for two years. Sanaz has undertaken statistical and geostatistical modelling during her study and work. Sanaz has received her PhD with the title of "Experimental and numerical study of heat flow under hydrothermal conditions", from the Faculty of Civil engineering and Geosciences, Delft University of Technology, The Netherlands. She has spent a year at Deltares in Delft where she designed and conducted experiments for heat flow under hydrothermal conditions. During her PhD she has conducted many numerical and analytical studies to model heat flow for geothermal systems and developed a prototype design model for deep low-enthalpy hydrothermal systems. Sanaz joined SGSH in 2012 as a Reservoir Engineer. She has been involved in many integrated reservoir studies, reserve estimation projects, field development, dynamic modelling, history matching, production forecasting and opportunity seeking for different types of oil and gas reservoirs in Netherlands, Nigeria, Algeria, Nigeria, Egypt, Congo, and UK. She has done some research on steam injection EOR for screening and modelling. She has also been involved in a joint study with Technical University of Delft on the numerical modelling of geo-sequestrated CO_2 leakage through abundant wells and faults, in Eclipse.

3.4 PROJECT SCHEDULE

To complete the proposed scope of work based on the time required to complete each work component, SGS has designed an execution plan as outlined in Table 3.1. Provided the work can be initiated on or before September 19, SGS expects to complete this Phase and present the deliverables to Warmtestad on or before October 7.

Table 3.1

Table 3.1 Project schedule

Task	Week 38	Week 39	Week 40
Analysis of the background seismicity			
Parameters evaluation and quantification			
Sensitivity analysis			
Define low, mid , and high case			
Review of analogue geothermal systems			
Stress analysis			
Reporting			

3.5 DELIVERABLES

The deliverable of phase 2 is a high-level report detailing the key results and conclusions of the work steps described in this proposal. SGS proposes to present the key results during a workshop with Warmtestad personnel, which will also facilitate discussions on further work to be carried out.

Following the completion of the draft report, WarmteStad is invited to provide comments and a request for changes to the SGS project manager within two weeks (10 business days) following delivery. If no comments or communications are received from WarmteStad within this time period, SGS will automatically consider the deliverables as accepted, submit the final report and close-out the project.

4 PROPOSED TEAM

4.1 PROJECT MANAGER

PROJECT MANAGER

will be the Project Manager for this study. He will coordinate the day-to-day technical work in the Project Team. He will:

- Manage the budget, timing and resources of the project.
- Manage all communication between SGS and Warmtestad.
- Be responsible for quality assurance and control (QAQC) of the project work.

holds an MSc in Geology from Free University Berlin. He joined Deminex in Essen, Germany, in 1980 as a staff geologist and worked for the company - which was 1997 acquired by VEBA Oil & Gas and in 2002 by Petro-Canada – on assignments in Norway, The Netherlands, UK, Syria and in Libya. He has more than 30 years of experience as an exploration geologist and development geologist in various regions and reservoirs i.e. North Sea chalk, North Africa and Middle East carbonate fields, Trinidad offshore turbidites, holds an MSc in Geology from Utrecht University, the Netherlands. He joined IF Technology in 2011 where he worked on the characterization of geothermal reservoirs. In a secondment to the Dublin Institute for Advanced Studies he gained experience in the acquisition, processing, and analysis of magnetotelluric data. Merijn joined SGS in 2013 where he worked in multiple field production and development studies in Nigeria and Algeria. In addition, he is one of the lead geologists in SGS research and development studies on unconventional shale resources. His activities focus on determining the mechanical behaviour of shale using innovative techniques, i.e. QEMSCAN, nanoindentation, for reservoir quality assessment. During a secondment to Sirius Exploration Geochemistry, based in the US, Merijn gained extensive experience in basin modeling.

<u>Other staff to be involved as needed</u>

holds an MSc in Petroleum Engineering from the Mining University of Leoben and NTNU Trondheim (2002) and a PhD in Reservoir Engineering from the Mining University of Leoben (2006). From 2002 to 2006 she worked as assistant professor for Reservoir Engineering at the University of Leoben in research and teaching. In this period she also participated in several full field studies. In 2007 she joined FieldProSystem Integration where she was involved in production data integration projects in Egypt, Romania and the UK. In 2007 she moved to the consultancy Heinemannoil as Reservoir Engineer, where her main tasks were fluid characterisation, SCAL analysis, history matching, production forecasting and software development for special applications in reservoir engineering. One of her major projects was a simulation study for an UGS. Her areas of focus included Libya, Iran, Russia and Hungary. In January 2011 she joined Zueitina Oil Company (Libyan NOC), working as reservoir engineer for two immiscible gas injection simulation studies in the Sirte basin. In July 2011 she joined SGS Horizon as Reservoir Engineer, where she worked on field development planning projects in Angola, Algeria, Congo, UK and the Netherlands, a subsidence study in the Netherlands, field re-developments and prospect evaluation in Germany. In 2013 she was promoted to a Senior Reservoir Engineer. Barbara is an experienced user of Eclipse, Petrel, Saphir, MBal, Propser, GAP, PVTSim, MoRes, EnAble and MEPO.

4.3 QAQC

SGSH enforces thorough internal QAQC standards and procedures, which will be applied in the course this project. QAQC is ensured by peer reviews at significant project milestones, which will be conducted by our experienced subject matter experts. For the current project, the following staff will carry out the QAQC:

holds an MSc in Physics from Utrecht University. He joined Shell in 1989 and worked as Reservoir Engineer in the Netherlands and the UK. He continued his career in 1997 with Wintershall in the Netherlands, focusing on production optimisation and reservoir management of gas fields in the Southern North Sea, both in hands-on and supervisory roles. His 20+ years of experience with an operator also includes exploration well testing and prospect evaluation, field development planning, gas network modelling, reservoir modelling, asset evaluation, unitisation issues, field reserves determination and company reserves coordination. In these roles he gained ample project coordination experience and a high level of understanding of technical, commercial and business aspects of small and large gas fields in the offshore environment. Maarten joined SGS Horizon in 2012 and has been project manager for integrated static and dynamic reservoir modelling studies on oil and gas fields in Nigeria, Egypt, Croatia, the Netherlands, and Italy. He has also been involved in data rooms, asset evaluations, reserves evaluations (PRMS) and technical peer reviews.

holds an MSc in Petroleum Engineering from Delft University of Technology. He has written his MSc thesis at NAM (JV Shell&Exxon) in the Netherlands, where he investigated and modelled gas well liquid loading. After his study in 2005, he joined SGS, and is currently a Senior Reservoir Engineer. He has taken part in a number of integrated field development studies, analysing oil and gas assets in the North Sea, Continental Europe, North & West Africa and Russia, among others. He carried out activities for a various clients such as Majors, small/mid-size operators and non-operators. His main tasks consisted of classical reservoir engineering analyses, history matching and production forecasting by means of reservoir simulation. As from 2011 he has been project manager of various reservoir studies for clients in the Netherlands, UK, Italy, Algeria, Ecuador, Tunisia, Algeria, Cameroon and Russia. During his working period with SGS, Niek has also participated in - and led various reserves evaluations, using SPE-PRMS. He also gained experience with Underground Gas Storage developments and Geomechanical studies. In 2008, 2009, 2014 and 2015 he has been part of data room review teams evaluating various UK, Italian, Polish and Nigerian assets.

5 LOCATION

SGSH operates globally from its office in Voorburg (The Hague area), the Netherlands. The office is fully equipped with all necessary hard and software to run complete integrated projects. It is assumed that the bulk of the services outlined in this proposal will be executed from our office in Voorburg and the Curistec office in Lyon. Meetings at client's office may be organized, in agreement with the client as appropriate and required by the development of the study.

Regular telephone conferences may be scheduled to ensure good communication and alignment between client and SGSH teams involved in the project.

6 REFERENCES

[1] NAM (2016) Technical Addendum to the Winningplan Groningen 2016

[2] Robertson, E.C. (1988) Thermal properties of rocks. No 88-441 US Geological Survey

[3] Eppelbaum, L.V., Kutasov, I. and Pilchin, A. (2014) Applied geothermics. Berlin Springer

[4] Saeid, S., Al-Khoury, R., Nick, H.M. and Hicks, M.A. (2015) A prototype design model for deep low-enthalpy hydrothermal systems. Renewable Energy 77, 408-422

[5] Geothermal Energy in Groningen - Geological Investigation (Groot Geologisch Onderzoek Groningen) (Panterra, 2014).

[6] Geothermal Project Groningen - GRN-GT-01 & GRN-GT-02 Detailed Design, Gemeente Groningen, 2014.

SGS

Bijlage 8

WarmteStad B.V.

Seismic Risk Analysis Zernike Geothermal Project: Phase 1 Summary Report

12/23/2016

DISCLAIMER

This report has been prepared by SGS Horizon B.V. ("SGS") for the exclusive use and benefit of WarmteStad B.V. ("WarmteStad") as the sole addressee. Third parties should be aware that SGS does not accept any liability towards them for the content of this report and that any form of taking knowledge of this report beyond this disclaimer is held to imply that such third party accepts this condition and those further restrictions stipulated in the below.

This report must always be reproduced in its entirety and WarmteStad shall – as far as reasonably possible - procure that sufficient supplemental (contextual) information is supplied and will endeavour there will not arise misunderstandings regarding the content of this report. SGS cannot be held liable for the consequences of acts in contradiction with the foregoing.

SGS has made every effort to ensure that the findings, conclusions and recommendations presented in this report are in accordance with good industry practice and its own quality management procedures. SGS does however not guarantee the correctness of same and shall not be liable or responsible for any damage incurred by anyone for the sole reason that any interpretation, finding, conclusion or recommendation in this report is incorrect

This report is limited to the scope of step 1 as stipulated in the SGS proposal with reference OGC/NL/HAG/2016/S1607-13, namely the Seismic Risk Analysis Zernike Geothermal Project, more specifically on the estimation of the range of depletion in the Zernike block.

The review was carried out by employing solely the methodology set forth by SGS in this report. No research has been carried out with another aim than fulfilling this scope and beyond the methodology set forth in this report. Although this report addresses matters related to seismicity/geomechanical modelling, it does not encompass an exhaustive risk assessment that would be required to assess the risk of tremors. The findings and conclusions of this report are based on the information provided by WarmteStad, of which a non-exhaustive overview is provided in the References.

SGS has relied on the documentation and information provided for by WarmteStad and assumed that all such information was complete and that there is no information relevant to the review carried out by SGS that was not provided, whether intentionally or unintentionally. Except where specifically mentioned in this report, SGS has not independently verified the accuracy and completeness of data and information provided by WarmteStad.

SGS has not investigated nor rendered, whether by implication or otherwise, any advice on any legal, management, investment, commercial, accounting or (other) financial matters. Where in this report such matter is referred to, this is for information purposes only and does not form part of the advice and communicative purpose of this report. This report is not intended to act in any way as a recommendation to WarmteStad to proceed (or not to proceed) with investment, management or entrepreneurial decisions regarding the Zernike Geothermal System or otherwise. This report should not be relied upon as a substitute for appropriate decision making processes and standing good governance principles and practices.

This report is subject to the qualifications contained herein and any liability in connection with this report towards WarmteStad is subject to the contractual conditions applicable between WarmteStad and SGS in relation thereto. This report and any dispute in connection therewith is exclusively governed by Dutch law.

Signed:

Project Manager

Date: 23.12.2016

Managing Director

Date: Dec 23rd, 2016

SAMENVATTING

WarmteStad onderzoekt of een geothermie systeem (GS) kan worden geïnstalleerd dicht bij de stad Groningen, het "Zernike GS". Het systeem zal worden gebruikt om gebouwen te voorzien van energie in de vorm van warm water. Een deel van het onderzoek richt zich op de risico's van het veroorzaken van seismiciteit (aardbevingen) ten gevolge van de geothermie operaties. Om deze risico's in kaart te brengen is SGS gevraagd om vorige studies te reviewen, de invloed die het Groningen gasveld heeft te onderzoeken, een risico analyse van de seismiciteit uit te voeren en om een "Stoplicht Systeem" te ontwikkelen. De resultaten van dit werk zijn hier kort samengevat en er worden aanbevelingen gedaan voor vervolgonderzoeken.

Het rapport dat door IF en Q-Con ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]) is gemaakt, over de risico's voor reactivering van breuken op reservoirniveau en bijkomende micro-seismiciteit door het geothermie project, is door SGS gereviewd. Er is geconstateerd dat in de hiervoor genoemde studie enkele aspecten niet volledig onderzocht zijn. Bijvoorbeeld, een van de primaire onzekerheden, de mogelijke drukverlaging in de Zernike concessie ten gevolge van de productie van het Groningen gasveld, is niet in detail bestudeerd. Ook de implicatie van het bestaan van geheel impermeabele breuken binnen, of rondom, het Zernike reservoir compartiment (een onwaarschijnlijk, maar mogelijk scenario) is niet volledig onderzocht. De Seismic Hazard Analyse van IF en Q-Con geeft dan ook geen compleet beeld van het risico op breuk reactivatie (en de bijkomstige seismiciteit) ten gevolge van de geothermie operaties.

Om deze risico's beter te beoordelen raadt SGS een vervolgstudie aan waarin de impact van verschillende scenario's (onzekerheden) gedegen wordt onderzocht. Dit kan het beste gedaan worden door middel van het gebruik van commerciële reservoir simulatie software en methodes die ook vaak in de olie- en gas industrie worden ingezet. Omdat er geen gemeten ondergrondse gegevens zijn binnen de Zernike concessie, met als gevolg bepaalde onzekerheden, wordt een probabilistische methode aangeraden. Hierin zullen meerdere scenario's worden gemodelleerd om een volledig risicoprofiel te krijgen voor het veroorzaken van micro-seismiciteit door de geothermische operatie. Zowel de onzekerheid betreffende de ondergrond, evenals verschillende operationele scenario's, zullen hierin worden meegenomen. SGS heeft al enkele scenario's gemodelleerd, waarbij de toegevoegde waarde van dit werk duidelijk werd.

Er is een kans dat de Groningen gas productie de druk in het Zernike gebied heeft beïnvloed. SGS heeft door middel van meetgegevens van bodemdaling [3][8] een drukverlaging berekend voor het reservoir van het Zernike GS. Deze drukverlaging is ongeveer 10 bar, maar heeft een onzekerheid van tussen de 2 en 50 bar. SGS raadt daarom ook aan om de mogelijke drukverlagingen veroorzaakt door de (huidige en toekomstige) gas productie van het Groningen gasveld in de onzekerheidsscenario's mee te nemen.

SGS heeft de (micro-)seismiciteit, die de laatste 20 jaar is waargenomen in het nabij gelegen Groningen gasveld, in kaart gebracht. Sinds 1996 zijn er meer dan 1000 seismische trillingen waargenomen in en rond het Groningen gasveld, variërend in magnitude van -0.8 tot 3.6 op de schaal van Richter. Deze trillingen zijn gerelateerd aan de productie van gas van het Groningen gasveld [3]. Er is vastgesteld dat er geen 'natuurlijke' seismiciteit in het gebied voorkomt [4]. Twee processen die worden veroorzaakt door de gasproductie, en die mogelijk seismiciteit veroorzaken, zijn 1) compactie en 2) breuk reactivatie. Het merendeel van de micro-seismiciteit met een magnitude lager dan 1.5 (op de schaal van Richter) is waarschijnlijk gerelateerd aan de compactie van de poreuze zandsteen-lagen van het gas reservoir (Slochteren Formatie). Door de extractie van het gas wordt de druk in het reservoir lager en ontstaat de mogelijkheid tot compactie. In andere gevallen wordt de micro-seismiciteit waarschijnlijk veroorzaakt door reactivatie van bestaande breuken diep in de ondergrond doordat de "stress" langs de breuk toeneemt. Gas-extractie en resulterende ongelijkmatige drukverlaging in verschillende reservoir compartimenten die door breuken worden gescheiden kan dit teweegbrengen.

Gebaseerd op de huidige kennis is het hoogstwaarschijnlijk dat de gas productie uit het Groningen gasveld ook in de toekomst tot micro-seismiciteit zal leiden [3]. Er wordt verwacht dat de magnitude niet veel hoger zal zijn dan wat er in het verleden is gemeten [4]. Het dichtstbijzijnde gebied waar veel aardbevingen zijn ontstaan, ligt ongeveer 6km ten oosten van de geplande Zernike GS putten. SGS raadt echter aan om de kans op het ontstaan (en de mogelijke sterkte) van micro-seismicitiet in het Zernike gebied door de Groningen gasproductie verder te onderzoeken. Hiervoor dient een gedetailleerde analyse van de micro-seismiciteit van het Groningen gasveld gebied uitgevoerd te worden. Uit deze analyse zal een prognose volgen van de (globaal) te verwachten seismische magnitudes die kunnen ontstaan binnen het Zernike GS reservoir compartiment.

SGS raadt ook aan om de (micro-)seismische data van het Groningen veld te gebruiken om seismische magnitudes en de mate van drukverschillen rondom breuken te correleren. Deze informatie, samen met de drukverschillen in de verschillende gemodelleerde scenario's, zal dan gebruikt worden om een risicomatrix te maken. In deze risicomatrix zullen de geothermische operaties (en/of mogelijke geologische configuraties), met de hoogste risico's op het veroorzaken van micro-seismiciteit, worden geïdentificeerd.

Om bepaalde risico's beter te kwantificeren is er ook een onderzoek nodig waarin de geomechanische eigenschappen van het reservoir en de breuken worden gemodelleerd. SGS is van mening dat het essentieel is dat deze gedetailleerde geomechanische modellering, waaronder "slip tendens" analyse wordt uitgevoerd om een volledige risicobeoordeling voor de Zernike GS te voltooien. Het in-situ "stress veld" en de gesteente-sterkte zal bestudeerd moeten worden om seismiciteit als gevolg van vloeistofinjectie te voorkomen. Vervolgens kunnen geschikte grenzen aan de operationele injectie-druk worden bepaald.

Met de risicomatrix kan dan een Stoplicht Systeem gedefinieerd worden, waaraan een plan voor het monitoren en herkennen van bepaalde signalen is gekoppeld. Mochten bepaalde signalen indicatief zijn voor verhoogde kans op seismiciteit dan kunnen de nodige vervolg acties direct geïdentificeerd worden is.

EXECUTIVE SUMMARY

WarmteStad B.V. (Warmtestad) is investigating whether a geothermal system (GS) can be installed close to the city of Groningen to supply buildings with energy/hot water, the "Zernike GS". Part of this investigation is the assessment of potential risk of causing earthquakes (seismicity) due to the geothermal operations. In relation to this, SGS has been contracted to review previous studies on this topic, investigate the influence of the nearby Groningen Gas Field, and identify the risk of inducing seismicity. The results of this work are summarized in this report and recommendations for further work are presented.

SGS reviewed the report issued by IF and Q-Con ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]) concerning the risk of re-activating faults and inducing micro-seismic events during the operation of the Zernike geothermal project. Based on its review, SGS concluded that the IF and Q-Con study has certain limitations and there are relevant aspects that were not considered by that study. For instance, one of the key uncertainties for the Zernike GS that has not been studied in detail is whether pressure depletion caused by the Groningen gas production may influence seismicity in the area. Also, the impact of faults that may be fully sealing (an unlikely, but possible scenario) within, or surrounding, the Zernike area was not taken into account. The seismicity models of IF and Q-Con do not conclusively indicate whether a reactivation of the faults in the Zernike area (leading to seismic events) may occur during the geothermal operations.

In order to better assess the risk of fault reactivation caused by the GS activities, SGS recommends that sensitivity modeling is carried out using commercial reservoir simulation tools applied in the oil and gas industry. During sensitivity modeling the uncertainty of geological and operational parameters are captured in multiple scenarios. The potential for inducing seismicity for each scenario can then be evaluated to understand the overall risk of inducing seismicity by the geothermal operations. SGS has carried out a small number of preliminary sensitivity analyses that indicated that such simulations could add a valuable contribution to the overall risk assessment.

There is a possibility that the Groningen gas production has affected the pressure in the Zernike area. SGS calculated a pressure depletion in the Zernike area based on the observed subsidence in the area [3][8]. The pressure depletion in the Zernike area was determined to be approximately 10 bar with uncertainty range from 2-50 bar. It is thus an important parameter to consider in further sensitivity modeling too.

SGS also analyzed the micro-seismic events recorded in the neighboring Groningen gas field area during the past 20 years. Since 1996, more than 1000 (micro-)seismic events were recorded in the Groningen gas field region with local magnitudes ranging from -0.8 to 3.6 units on the Richter scale. The seismic events are related to the gas production [3]. It is thought that no "natural" seismicity occurs in this region [3]. Two processes related to the gas production in the Groningen field are known to induce micro-seismicity 1) compaction and 2) fault reactivation. SGS is of the oppinion that the majority of the low magnitude seismic events (< 1.5 on the scale of Richter) are related to the compaction in the high porosity intervals of the Rotliegend reservoirs - caused by the gas withdrawal and subsequent pressure depletion. In other cases the micro-seismic events are likely related to the reactivation of deep-seated faults predominantly due to increased stress along the fault as a result of differential depletion in various reservoir compartments.

Based on current knowledge, it almost certain that the continued production from the Groningen gas field will continue to cause micro-seismic events in the immediately surrounding region [3]. These micro-seismic events will most likely not exceed the order of magnitude as presently observed [4]. The potential occurrence of seismicity in the Zernike area as a result of further gas production of the Groningen gas field should be investigated in further detail to understand the risk and potential magnitude. SGS recommends that a detailed analysis of the micro-seismic events in the Groningen gas field area is carried out.

Furthermore, certain aspects of the subsurface conditions causing the seismicity in the Groningen gas field could be used as analogues for the Zernike GS. In particular the pressure differential around faults that result in reactivitation may be usefull to understand potential seismic magnitudes in similar scenarios of the Zernike GS.

The identification of parameters that may contribute to the occurrence of potential (micro-)seismic events will require detailed geomechanical modeling. SGS believes that it is essential that this detailed geomechanical modeling, including slip tendency analysis, is carried out to complete a full risk assessment for the Zernike GS. The in situ stress field and rock strength will need to be studied in detail to avoid seismic events as a result of fluid injection. As a result suitable operational injection pressure limits can be established.

The result of this entire risk assessment is a riskmatrix. This matrix will highlight which geological and operational parameters may contribute to the occurrence of (micro-)seismic events in the Zernike area during Geothermal activities. These parameters will the need to be considered for the development of a traffic light system (TLS) to manage risks.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

WarmteStad B.V. (WarmteStad), a joint venture between the city of Groningen and the Groningen water company, has been established to investigate whether a geothermal system can be installed close to the city of Groningen to supply households with energy/hot water.

A cold water injection well and a warm water production well are envisaged to be drilled. The target would be a water bearing region ("an aquifer") in the permeable Slochteren formation. The area is located several kilometers west (down-dip) of the Groningen Gas Field.

The Groningen city council has asked for technical investigations to assess the risk of induced seismicity/earthquakes as a result of operation of the geothermal project. If there is a (small) risk of seismicity, a traffic light system (TLS) can be devised (monitoring system and forward action plans) to manage the risks.

In 2016, IF and Q-Con performed a geomechanical study, under the assumption that the aquifer in the Zernike area is undepleted (i.e. is not affected by gas production from the Groningen gas field). For this scenario, their modeling work indicated that the risk for seismic events is limited.

Based on the discussions with experts in the industry (TNO) on the 20th of July 2016, it was recommended that simulations will need to be performed assuming that the reservoir is (partly) depleted. TNO suggested that there is a chance that the aquifer may be depleted by production from the Groningen gas field (which has up to 250 bar depletion). No data are available for the Zernike fault compartment that support this statement, this is however an assumption that needs to be taken into account for a risk assessment prior to, and possible mitigation during, operation of the geothermal project.

Pressure changes in the aquifer / reservoir resulting from depletion or fluid injection modify the local stress state that may include nearby faults. If the stress state of a fault plane is sufficiently disturbed, the fault may slip and reactivate.

There are a number of (minor) NW/SE striking boundary faults between the Zernike block and the Groningen field. It is not known whether these faults are open or closed. If the faults are open (through sand-sand juxtaposition), this may facilitate communication between the aquifer in the Zernike area and the Groningen gas field and therefore contribute to further pressure depletion in the Zernike area over time. Even if the faults are closed, due to the heavy depletion of the Groningen gas field, minor leakage ("sweating") may occur once differential pressure over the fault exceeds several tens of bars.

In the subsurface area where water injection and production take places during operation of a geothermal project a pressure source and sink will develop. This may affect the local stress state and may induce local fault reactivation (i.e. a seismic event), depending on the areal influence of the pressure variation relative to local faults. In addition, thermal stress due to cold water injection during geothermal operation is also recognized as a factor that could initiate fault reactivation.

No significant seismic events have been measured up to date that originate in consession area of the Zernike GS area. However, in the nearby Groningen gas field, significant seismic events have been recorded including a number that contributed to structural damage at the surface.

WarmteStad intends to develop a TLS covering those geological / operational parameters that may contribute to the occurrence of seismic events as a result of geothermal operations. Such a system can be implemented during operation of the geothermal project to initiate appropriate actions once certain defined thresholds for individual parameters may be breached.

In support of the development of the TLS, SGS carried out a study with the aim to determine the impact of partial pressure depletion in the Zernike reservoir on inducing seismic events in the Zernike area.

SGS performed the following worksteps for which a summary of activities and results is listed in the subsequent section.

1. Review of previous study reports by IF and Q-Con [1]
    a. Including detailed investigation in geomechanical input parameters
2. Review of the seismic activity in the Groningen and Zernike area
3. Evaluation of the potential level of the pressure depletion within the Zernike area due to Groningen gas production based on regional (subsidence) data.
    a. Sensitivity analysis on variation on uniaxial compressibility, Poisson ratio, reservoir thickness, reservoir depth, and Groningen gas field pressure depletion.
4. Preliminary 3D reservoir modeling for Zernike Area due to geothermal activity
    a. Including the effect of pressure depletion in Zernike block due to Groningen Gas production
    b. Evaluate the impact of sealing faults on pressure differentials caused by the geothermal activity

2 KEY FINDINGS

2.1 Review of Previous study Reports

One element of the study performed by SGS was the review of the study report by IF and Q-Con ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]). This study was conducted to evaluate whether seismic events (earthquakes) could be induced during the operation of the Zernike GS. The review focused on the key assumptions made by IF and Q-Con and input used for the geomechanical model (i.e. Young's modulus, Poisson's ratio, Biot's coefficient, etc). The latter was carried out in partnership with Curistec, an SGS associate company specialized in geomechanical modeling and seismicity prediction.

The following observations are offered on the basis of review of the above-mentioned report:

- The assumption by IF and Q-Con that poro-elastic stress is not associated with differential compaction is subject to investigation, as changes in poro-elastic stress can alter horizontal stress within the geothermal reservoir, thus impacting both normal and shear stress acting on the faults.
- IF and Q-Con mentioned that the deformation process in the gas reservoir may cause stress interference with the geothermal reservoir resulting from two interference mechanisms: changes in poro-elastic stress resulting from compaction in the Groningen gas reservoir and (partial) depletion inside the geothermal reservoir. Poro-elastic stress is reflected by a subsidence pattern extending beyond the gas field into the geothermal concession. The associated stress perturbations, however, do not result in differential compaction but in a spatially continuous stress change.
- IF and Q-Con also mentioned that a (partial) depletion of the geothermal reservoir occurs if hydraulic connectivity has been established with the gas reservoir. Whether such a connection exists is unclear at this stage however no investigations were carried out on this topic.

It is SGS' opinion that the review carried out by IF and Q-Con and the resulting report are not comprehensive to the point that all risks for geothermal operation are fully investigated. It is noted that some assumptions are simplified, some critical uncertainties remain, and further validation work to reduce uncertainties has not been carried out.

2.1.1 Recommendations

Based on modeling carried out to date and the remaining uncertainties, SGS believes that the potential risk for causing a potential seismic event as a result of geothermal operation has not been investigated comprehensively.

Therefore, SGS strongly recommends that further investigations will be carried out to decrease uncertainties and define parameter (ranges) that may potentially cause induced seismic events as a result of geothermal operations in order to implement a suitable TLS. Below, SGS offers some observations and findings from preliminary investigations that were carried out during this study that may provide valuable insights.

2.2 Seismic Activity in The Groningen and Zernike Area

SGS carried out an evaluation of the seismic activity in the Groningen gas field and the Zernike area to gain insights in the base-level regional seismicity. Figure 2-1 shows the induced seismic events recorded over the last 20 years (1996-2015) in the proximity of Groningen Gas Field and Zernike license area [9]. The majority of induced seismic events have (local) magnitude ranges from -0.8 to 3.6 (Richter scale). The majority of these events that have a magnitude larger than 1.6 are observed directly above the Groningen gas field. Only a small number of seismic events (with a magnitude below 0.9) have been recorded in the vicinity (within 2 km) of the Zernike GS. To the west of the Zernike GS, very few seismic events have been recorded. This regional seismicity analysis is a first-pass screening of seismic activity relevant to the Zernike GS that gives an indication of prominent aspects (e.g. magnitude ranges) for induced seismic events in the region.

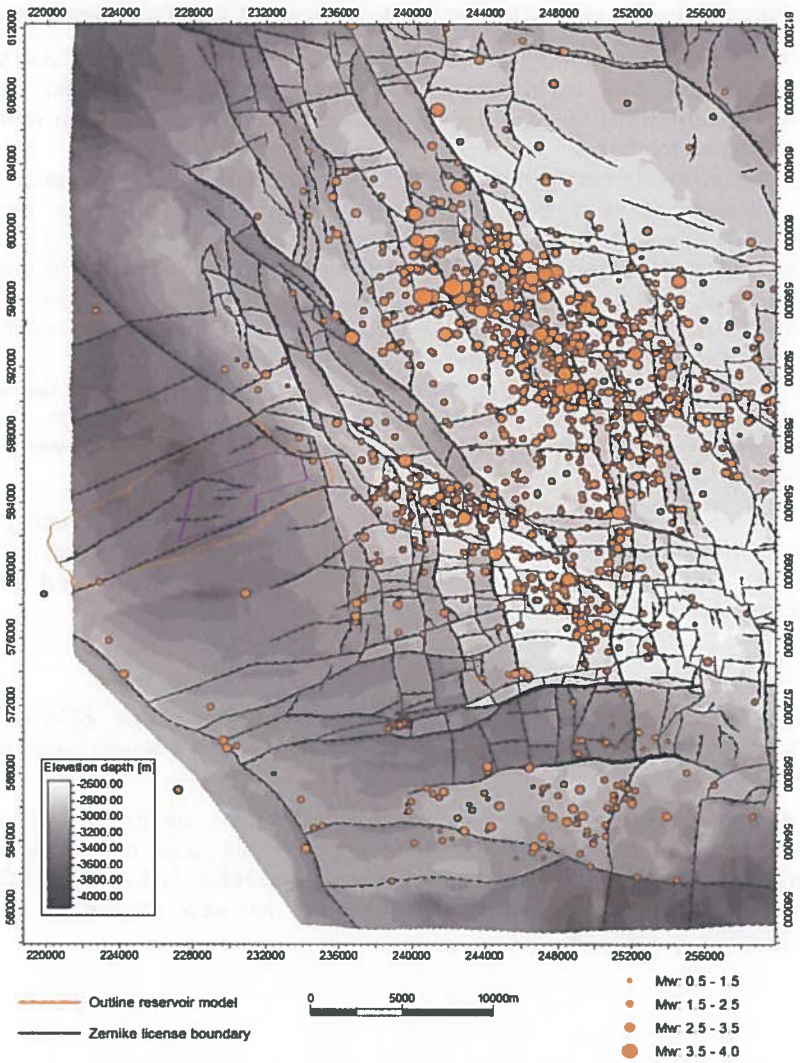


Figure 2-1 Map showing the top structure of the Slochteren Formation and the seismic activity in the last 20 years in the Groningen Gas Field and the Zernike area. The planned injection and production wells of the geothermal system are indicated by the blue and red line respectively. Source of seismic data: KNMI [9].

Additional findings from the evaluation of the seismic activity are listed below:

- The recorded seismic events in the area are related to the Groningen gas production.
    - The majority of seismic events with magnitude between 1.2 - 3.6 occurred near the faults (at the reservoir level).
    - The seismic events with the largest magnitude between 2.2 - 3.6 are associated with the fault zones at the reservoir level.
    - The subsidence pattern correlates with the occurrence of most seismic events.
    - The majority of the low magnitude seismic events (< 1.5 on the scale of Richter) are presumably related to the compaction in the high porosity intervals of the Rotliegend reservoirs (Slochteren formation) - caused by the gas withdrawal and subsequent pressure depletion.
    - In some cases the micro-seismic events are likely related to the reactivation of deep-seated faults predominantly due to increased stress along the fault as a result of differential depletion in various reservoir compartments.
- (Micro-)seismic events will continue to originate form the Groningen gas field subsurface activities [3]; most likely not exceeding the order of magnitude as presently observed [4].
- No "natural" seismicity has been recorded in the region and it is very unlikely to occur in the future [4].
- No seismic events have been recorded that originate from within the Zernike license boundary.
- Two small seismic events (magnitude <0.9) have been recorded within the reservoir compartment that is targeted for the geothermal system.
    - It is likely these events are related to Groningen gas field production

2.2.1 Recommendations

The evaluation of the historic seismic activity in the Zernike and Groningen area has identified several seismic events (with a low magnitude) near the Zernike GS area. These events are believed to be associated with the production from the Groningen gas field. To have a complete understanding of the future risk of seismic events occuring within the Zernike area it is therefore important to study this 'background' seismicity further.

Furthermore, as the Groningen gas field produces from the same reservoir that is targeted for the GS, it can be used as a good analogue in terms of geomechanical properties. However, it should be considered that from the two possible mechanisms, compaction and fault reactivation, only the latter one is relevant and can be used as analogue to GS in Zernike block. By linking historic seismic events to pressure differentials (and fault reactivation) it should be possible to use Groningen seismicity data to benchmark the impact of pressure differentials developing as a result of the Zernike GS.

2.3 Pressure Depletion by Groningen Gas Production

In the previous study by IF and Q-Con [1] pressure depletion due to production of the Groningen gas field was not taken into account. However, subsidence has been measured in the Zernike area [3], which may be an indication of pressure depletion in the subsurface. The observed subsidence ranges from 4 to 8 cm [3], where 6 cm was used as the average value for this comparison.

The pressure depletion in the Zernike area was calculated based on the observed subsidence in the area [3]. Based on subsidence data from the NAM winningsplan 2016 [3] and NLOG [8], the pressure depletion in the Zernike area was determined to be approximately 10 bar with uncertainty range from 2-50 bar (the effect of natural subsidence is excluded). This is much less compared to the pressure depletion in the Groningen gas field which is on average 250 bar. However, during the lifespan of the geothermal system, which is expected to be 30 years, the pressure in the Zernike area may deplete further, largely depending on the amount of gas production from the Groningen gas field.

2.3.1 Uncertainties and Sensitivity Analysis

As there are no direct pressure measurements in the Zernike block, the level of pressure depletion, if any, is not known. Therefore, to study the range of potential pressure depletion magnitude, a sensitivity analysis was conducted by SGS using a semi-numerical approach. As part of this analysis, a number of scenarios with variations in key parameters including uniaxial compressibility, Poisson ratio, reservoir thickness, aquifer depth, Groningen gas field pressure depletion and subsidence magnitude where tested, in order to understand the impact of each of these parameters on potential pressure depletion in the Zernike GS.

The results of this preliminary sensitivity analysis show that Rotliegend reservoir (aquifer) thickness has the highest impact on the potential pressure depletion in the Zernike block. An aquifer that is 20% thinner than assumed in the base case scenario can lead to 46% more pressure depletion. Further pressure depletion of the Groningen gas field by an additional 50 bar could cause an incremental 18% pressure drop in the Zernike GS. The pressure depletion was also calculated for the lower and upper range of the observed subsidence (4 to 8 cm). A subsidence of 8 cm can be caused by a pressure depletion of about 40 bar (versus 10 bar related to 6 cm subsidence).

2.3.2 Recommendations

The results from the high-level sensitivity analyses indicate that several uncertain parameters may have significant impact on the level of pressure depletion in the Zernike GS.

It is important to stress that many of the uncertainties related to pressure depletion will be reduced once the first well is drilled, a pressure measurement is aquired, and subsequent pressure development can be measured. Before that time it is recommended to evaluate the full range of potential subsurface conditions to understand the true risk of inducing seismic events from the geothermal activities. Based on current understanding of the uncertainties, pressure depletion ranging from 2 to ~50 bar is possible. Therefore it is important to perform further study to reduce this uncertainty. Also, pressure depletion should be included in the sensitivity analyses to achieve a more comprehensive seismicity risk evaluation of the Zernike GS.

2.4 Reservoir Modeling of the Geothermal System

A preliminary 3D reservoir model was constructed for the Zernike GS by SGS. The boundaries of this model are formed by faults with large offsets (Figure 2-1). Several smaller, roughly NE-SW oriented faults are present within the reservoir model. Based on information from the Groningen gas field these smaller faults are expected to be open [3], although the possibility exists that they are sealing faults. Whether the faults are open or closed will have considerable impact on the pressure variation in the reservoir. The fault and surface geometries were adopted from earlier work performed by Panterra [2]. Vertically, the model was extended 250 meters above the top of the Slochteren Formation and 250 meters below the bottom of the Slochteren Formation in order to consider all the thermal interactions of the reservoir with its adjacent layers. The Slochteren Formation was subdivided into seven zones (distinct geological units); the porosity was modeled separately for each zone based on core data from wells surrounding the Zernike area (Figure 2-2). Permeability was distributed in zones based on porosity-permeability relations which were reported by Panterra [2].

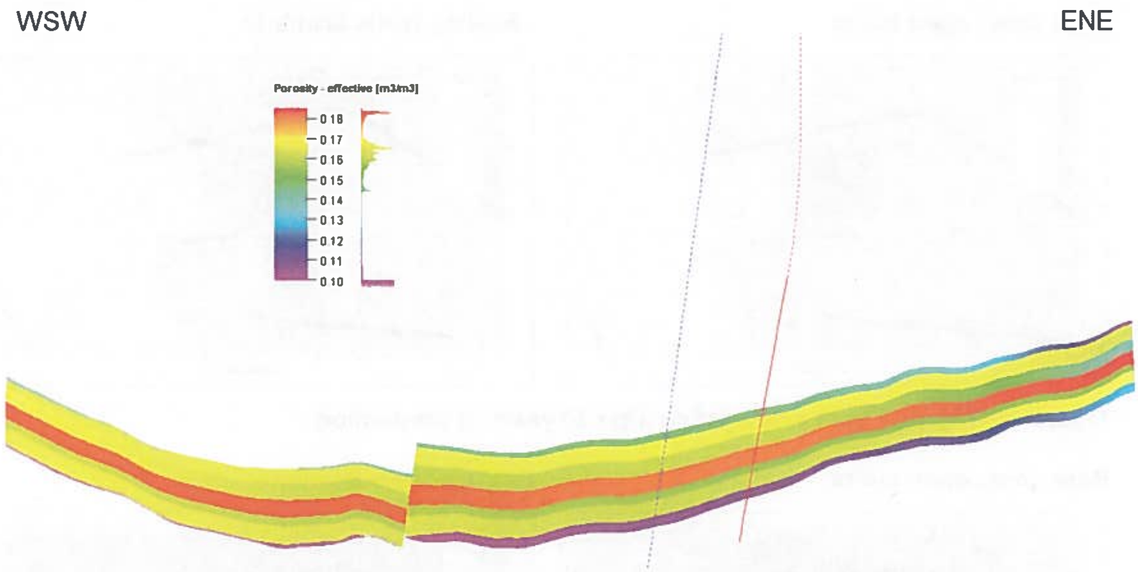


Figure 2-2 A west-southwest to east-northeast cross-section through the reservoir model for the Zernike area, showing the porosity of the Slochteren Formation and the planned injection and production wells of the geothermal system in blue and red respectively.

The 3D reservoir model was used to run dynamic simulations of the geothermal system. For these simulations the operational parameters as defined by WarmteStad were used, while the hydrothermal properties were based on previous reports [1] and literature [5][6][7]. The pressure depletion over time related to production from the Groningen gas field was modeled using a declining pressure boundary over time (assuming the same depletion rate as currently in the Groningen gas field). Two scenarios were considered: the base case scenario in which the faults are open (a fault transmissibility of 1) and an alternative scenario in which the faults are sealing (a fault transmissibility of 0).

The preliminary results of the simulations show that the cold front from the injection well does not reach the production well or the surrounding faults after 30 years of operation (Figure 2-3). This implies that thermal stress on the faults induced by the operation of the geothermal system will be minimal. Thermal stress could form in the area near to the injecting wellbore though and further investigation would be needed to identify any possible risks due to thermal stress.

In contrast, the pressure variations due to the operation of the geothermal system will influence the faults in less than a year. In the base case scenario with open faults, the pressure differential across the faults is small, in the order of 1 bar. However, in the scenario with sealing faults the pressure differential across the faults may reach up to 21 bar after one year and increase to approximately 40 bar after 30 years (Figure 2-4).

Base case: open faults **Sealing faults Scenario**

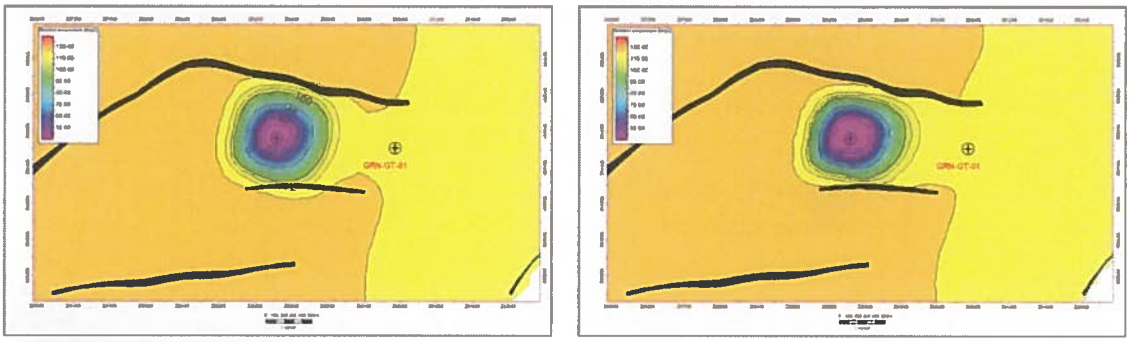


Figure 2-3 Thermal front propagation after 30 years of production

Base case: open faults **Sealing faults Scenario**

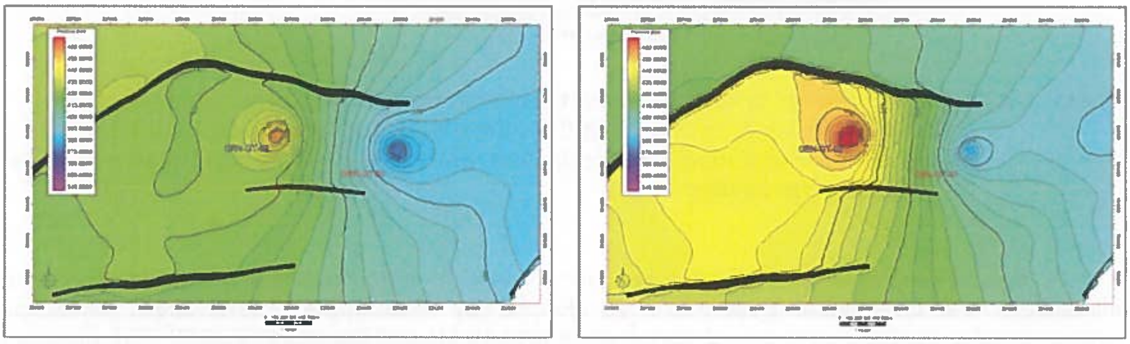


Figure 2-4 Pressure distribution after 30 years of production.

2.4.1 Recommendations

In addition to the uncertainty related to fault permeabilities other uncertainties exist around physical parameters (i.e. porosity, permeability, salinity, thermal properties, etc.) since there has not been any direct measurements in the Zernike area. Also operational parameters (i.e. injection and production rate, well distance, injection temperature, etc.) carry uncertainty since there is no final operational plan (shared with SGS) yet. Lastly, there is uncertainty around boundary parameters (i.e. influence of further depletion of Groningen gas field; see section 2.3) since there has not been any pressure measurements in this fault block.

On the basis of these findings, SGS recommends that further sensitivity analyses for operational parameters, physical parameters and boundary conditions are to be carried out in order to assess the full range of aquifer / reservoir pressure changes and cross-fault pressure differentials. This will aid in evaluating in more detail which parameters may contribute to causing potential seismic events.

Following these sensitivity analyses, developed models could be used in a geomechanical simulator to assess the risk of seismic event occurrence due to fault reactivation or pressure depletion.

3 SUMMARY OF KEY RECOMMENDATIONS

SGS recommends to perform a study in which an comprehensive sensitivity analysis will be carried out. The parameters that control the pressure and temperature changes in the reservoir, and can influence seismicity, are subdivided into three categories: operational parameters, physical parameters and boundary conditions (Figure 3-1). The chart below shows the list of parameters in each category which affect temperature and pressure.

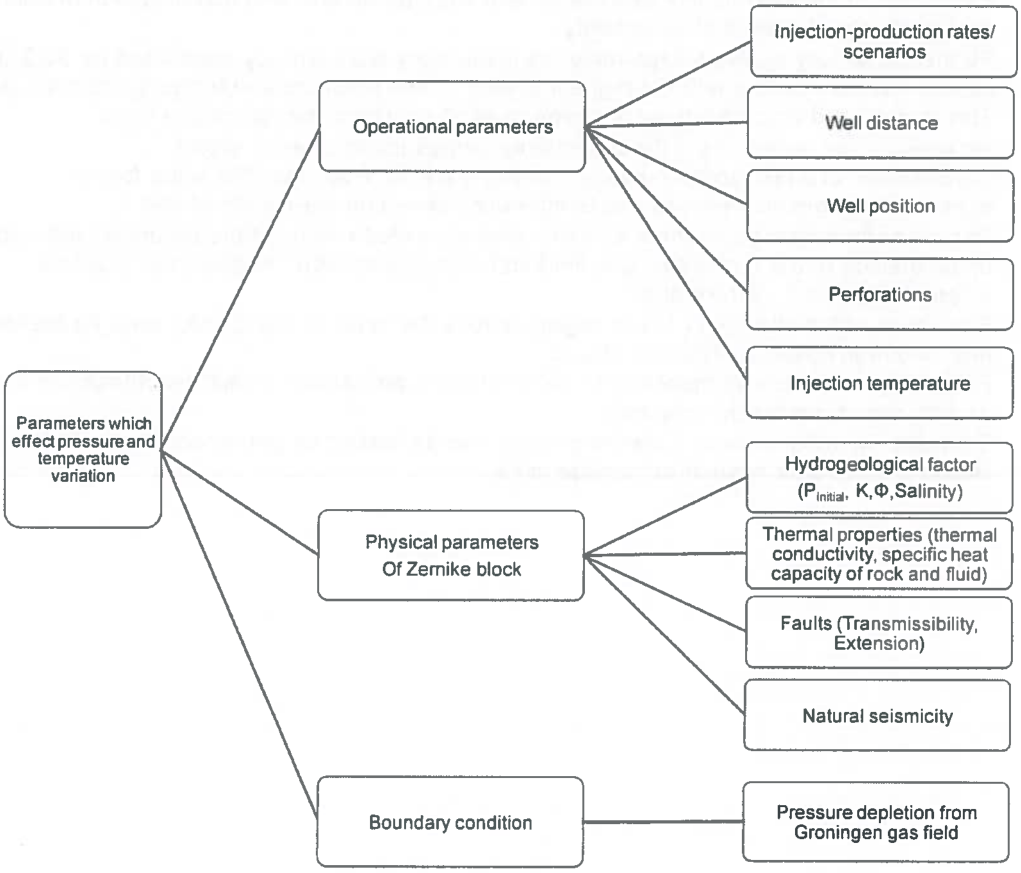


Figure 3-1 Overview of the parameters affecting pressure and temeperature changes in the reservoir due to the geothermal system.

The result of the sensitivity analysis is the identification of the main parameters which control and affect seismicity in the Zernike area in relation to the GS. This will be achieved by comparing model results (i.e. pressure differential across faults) to analogue geothermal systems and to the seismicity response of similar settings within the Groningen gas field.

Increased understanding of the main parameters affecting seismicity will be necessary to focus further studies (i.e. perform geomechanical modeling), to identify mitigation options and for implementing a TLS.

It is recommended to carry out the following work steps:

1. Detailed analysis of the background seismicity in the Zernike area
2. Evaluation of the seismic risk associated with each parameter and quantification of each parameter and its range of uncertainty.
3. Further sensitivity analysis expanding the preliminary work already conducted by SGS to identify the parameters with the highest impact on the pressure and temperature changes. This is achieved by carrying out a minimum of 50 simulations in which the input parameters are varied using the uncertainty ranges established in step 1.
4. Construction of a probability curve and defining a P10, P50, and P90 value for the expected changes in pressure and temperature based on the results of step 2.
5. Review of analogue geothermal systems and expanded review of the seismicity induced by production of the Groningen gas field and comparison with the (potential pressure differentials) of the Zernike area.
6. Evaluation of the change in stress regime across the faults in the Zernike area for the low, mid, and high cases achieved in step 3.
7. Perform geomechanical modeling to determine the probability of fault reactivation in the Zernike area for different scenarios.
8. Estimate the magnitude of potential seismic events (based on geomechanical modeling)
9. Define a traffic light system to manage risks.

4 REFERENCES

[1] "Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016
  a. Bijlage 1: "Reservoirmodellering, Warmtestad Groningen", IF Technology, 2016
  b. Bijlage 2: "Geomechanische Evaluatie, Geothermie WarmteStad Groningen", IF Technology, 2016
  c. Bijlage 3: "SHA Geothermal Project Groningen" Q-con GmbH, 2016

[2] "Geothermal Energy in Groningen Geological Investigation", Panterra, 2014. Including associated subsurface data: Petrel model and well logs (LAS files).

[3] "Winningsplan Groningen 2016", NAM, 2016.

[4] A.G. Muntendam-Bos et al., "A guideline for assessing seismic risk induced by gas extraction in the Netherlands", The Leading Edge, 2015

[5] E. C. Robertson, "Thermal properties of rocks," USGS, 1988.

[6] L. Eppelbaum et al., "Applied Geothermics - Lecture Notes in Earth System Sciences", Springer-Verlag Berlin Heidelberg, 2014.

[7] S. Saeid et al., "A prototype design model for deep low-enthalpy hydrothermal systems", Renewable Energy, 2015.

[8] NLOG website: http://www.nlog.nl/

[9] KNMI Seismic Data: http://rdsa.knmi.nl/dataportal/about.html

SGS

Bijlage 9

WarmteStad B.V.

Seismic Risk Analysis Zernike Geothermal Project Phase 2 - Summary Report

Final Report Version

15/03/2017

DISCLAIMER

This report has been prepared by SGS Horizon B.V. ("SGS") for the exclusive use and benefit of WarmteStad B.V. ("WarmteStad") as the sole addressee. Third parties should be aware that SGS does not accept any liability towards them for the content of this report and that any form of taking knowledge of this report beyond this disclaimer is held to imply that such third party accepts this condition and those further restrictions stipulated in the below.

This report must always be reproduced in its entirety and WarmteStad shall – as far as reasonably possible - procure that sufficient supplemental (contextual) information is supplied and will endeavour there will not arise misunderstandings regarding the content of this report. SGS cannot be held liable for the consequences of acts in contradiction with the foregoing.

SGS has made every effort to ensure that the findings, conclusions and recommendations presented in this report are in accordance with good industry practice and its own quality management procedures. SGS does however not guarantee the correctness of same and shall not be liable or responsible for any damage incurred by anyone for the sole reason that any interpretation, finding, conclusion or recommendation in this report is incorrect

This report is limited to the scope of project Phase 2 as stipulated in the SGS proposal with reference OGC/NL/HAG/2016/S1607-13-REV1 (dated September, 13th 2016), namely the Seismic Risk Analysis Zernike Geothermal Project, more specifically on the estimation of the range of depletion in the Zernike block.

The review was carried out by employing solely the methodology set forth by SGS in this report. No research has been carried out with another aim than fulfilling this scope and beyond the methodology set forth in this report. Although this report addresses matters related to seismicity/geomechanical modelling, it does not encompass an exhaustive risk assessment that would be required to assess the risk of tremors. The findings and conclusions of this report are based on the information provided by WarmteStad, of which a non-exhaustive overview is provided in the References.

SGS has relied on the documentation and information provided for by WarmteStad and assumed that all such information was complete and that there is no information relevant to the review carried out by SGS that was not provided, whether intentionally or unintentionally. Except where specifically mentioned in this report, SGS has not independently verified the accuracy and completeness of data and information provided by WarmteStad.

SGS has not investigated nor rendered, whether by implication or otherwise, any advice on any legal, management, investment, commercial, accounting or (other) financial matters. Where in this report such matter is referred to, this is for information purposes only and does not form part of the advice and communicative purpose of this report. This report is not intended to act in any way as a recommendation to WarmteStad to proceed (or not to proceed) with investment, management or entrepreneurial decisions regarding the Zernike Geothermal System or otherwise. This report should not be relied upon as a substitute for appropriate decision making processes and standing good governance principles and practices.

This report is subject to the qualifications contained herein and any liability in connection with this report towards WarmteStad is subject to the contractual conditions applicable between WarmteStad and SGS in relation thereto. This report and any dispute in connection therewith is exclusively governed by Dutch law.

Signed:

Project Manager	Managing Director
Date: 16.1.2017	Date: March 20th, 2017

SAMENVATTING

WarmteStad B.V. onderzoekt of een Geothermaal Systeem (GS) geïnstalleerd kan worden nabij de stad Groningen om gebouwen te voorzien van energie/warm water. Dit geothermie systeem heet Geothermie Systeem Zernike. Onderdeel van dit onderzoek is eeninschatting van het potentiële risico op het veroorzaken van aardbevingen (seismiciteit) door de geothermie operaties.

SGS is ingehuurd om een technische evaluatie de doen van de eerdere studies over dit onderwerp door IF en Q-Con. Gedurende een tweede fase van de studie heeft SGS een sensitiviteitsanalyse uitgevoerd met behulp van dynamische reservoirmodelleringstechnieken om geologische en operationele parameters van het GS Zernike te identificeren die potentieel seismische activiteit kunnen veroorzaken. Een ander onderzoeksdoel was een evaluatie van de impact van verdere depletie gerelateerd aan toekomstige gaswinning uit het aardgasveld van Slochteren. De conclusies van dit onderzoek zijn samengevat in dit rapport.

SGS heeft het door IF en Q-Con gepubliceerde rapport ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]) betreffende het risico op heractivering van ondergrondse breuken and het opwekken van microseismische gebeurtenissen gedurende de exploitatie van het GS Zernike geëvalueerd.

De conclusie van SGS is dat de studie door IF en Q-Con zekere beperkingen heeft en dat er relevante aspecten zijn die niet in deze studie zijn meegenomen. Eén van de belangrijkste onzekerheden voor GS Zernike is dat er in de voorgaande studies niet geëvalueerd is hoe de toekomstige drukdepletie veroorzaakt door het gasveld van Slochteren het GS Zernike zou kunnen beïnvloeden. In deze studies is ook niet gekeken naar de invloed van injectie- en productie-operaties op kleine interne ondergrondse breuken die geïdentificeerd zijn in het Zernike-gebied. De mogelijkheid tot heractivering van breuken in het Zernike-gebied veroorzaakt door veranderingen in het tektonische spanningsveld en de daaropvolgende microseismische gebeurtenissen zijn niet meegenomen in de voorgaande studies.

Tijdens de haalbaarheidsstudie heeft SGS een gedetailleerde evaluatie uitgevoerd van de micro-seismische gebeurtenissen in de regio Groningen. Tevens heeft SGS een gedetailleerde evaluatie gedaan van reeds gepubliceerde informatie over gemeten seismische activiteit in andere geothermie systemen die vergelijkbaar zijn met GS Zernike als referentie. Om een voorspelling te doen van de druk- en temperatuurontwikkeling in het GS Zernik tijdens de operationele periode heeft SGS een gesimplificeerd 3D reservoir model ("shoe box model") ontwikkeld. Zeventig realisaties zijn gemodelleerd en geanalyseerd. De belangrijkste parameters die de drukontwikkeling en distributie beïnvloeden tijdens een 30-jarige operationele periode zijn geëvalueerd.

De haalbaarheid van een stoplichtsysteem (Engels: "Traffic Light System", TLS) voor GS Zernike is geëvalueerd. Het doel van het TLS is te voorzien in een checklist en protocollen om de geologische en operationele risico's op gevaar te beperken. Deze studie toont aan dat een TLS voor GS Zernike haalbaar is. Hiervoor is een gedetailleerde risicoanalyse van de technische en geologische parameter noodzakelijk om de grenswaarden te bepalen voor de risicobeperkende maatregelen.

De analyse van de modelleringsresultaten van de 70 scenario's toont aan dat de permeabiliteit van het reservoir en de doorlaatbaarheid (afsluitingscapaciteit) van de interne breuken de grootste invloed hebben op de druk- en temperatuurpropagatie in GS Zernike. De gemodelleerde drukdistributieprofielen rondom GS Zernike van de verschillende scenario's zijn zeer verschillend. Dit wordt voornamelijk veroorzaakt door de bovengenoemde factoren, alhoewel ook significante verdere depletie van het aardgasveld van Slochteren een rol kan spelen.

In de scenario's waar gedeeltelijk of volledig ondoorlatendeinterne breuken gemodelleerd zijn acht SGS het waarschijnlijk dat drukveranderingen in de tijd het tectonische spanningsveld en rondom GS Zernike beïnvloeden. De veranderingen van het tektonische spanningsveld rondom de interne breuken in de nabijheid van injectie of productieputten (veroorzaakt door een drukdifferentiaal (ΔP) langs de breuken) zouden micro-seismische gebeurtenissen kunnen initiëren. Met behulp van de

in deze studie gebruikte technieken kon er geen drempelwaarde voor de ΔP vastgesteld worden waarbij breuk re-activering of potentiële micro-seismische gebeurtenissen opgewekt worden.

SGS acht het mogelijk dat er micro-seismische gebeurtenissen veroorzaakt worden door injectie (koeling/hydraulisch stimuleren) gedurende de operaties van GS Zernike. Het TLS voor GS Zernike zal de nodige risicobeperkende maatregelen bevatten, die de kans op het plaatsvinden van micro-seismische activiteit minimaliseren.

Het ontstaan van micro-seismische gebeurtenissen rondom GS Zernike ten gevolge van natuurlijke seismische activiteit of compactie van de ondergrond is zeer onwaarschijnlijk. Er wordt aangenomen dat de grensbreuken rondom GS Zernike volledig afsluitend zijn (ten opzichte van het aardgasveld van Slochteren). De veranderingen in drukdistributie bereiken nooit de grensbreuken tijdens de operationale periode van GS Zernike (30 jaar). De voortgang van drukdepletie in het gasveld van Slochteren zal waarschijnlijk verantwoordelijk zijn voor veranderingen in het spanningsveld langs de grensbreuken rondom GS Zernike. Dit zou micro-seismische activiteit kunnen initiëren, net zoals wordt waargenomen in het aardgasveld van Slochteren.

De volledige risico-inschatting en kwantificatie van de risico parameters van de operaties van GS Zernike die benodigd zijn voor de implementatie van het TLS waren geen onderzoeksdoel tijdens deze studiefase. SGS raadt aan om in de 3e fase van dit project verdere en meer gedetailleerde reservoir modellering en een volledig 3D geomechanische model op te bouwen met behulp van de eindige elementenmethode om de risico's te kwantificeren en operationele grenswaarden te bepalen voor het TLS.

EXECUTIVE SUMMARY

WarmteStad B.V. (Warmtestad) is investigating whether a geothermal system (GS) can be installed close to the city of Groningen to supply buildings with energy/hot water, the "Zernike GS". Part of this investigation is the assessment of potential risk of causing earthquakes (seismicity) triggered by the geothermal operations. SGS was contracted to perform a technical review of the previous studies performed by IF and Q-Con on this topic. In the course of a second study phase SGS conducted a sensitivity analysis using dynamic reservoir modelling technologies in order to identify geological and operational parameters of the Zernike GS, which could potentially induce seismicity. The scope also included the assessment of the impact of further depletion related to future gas production in the nearby Groningen Gas Field. The results of this work are summarized in this report.

SGS reviewed the report issued by IF and Q-Con ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]) concerning the risk of re-activating faults and inducing micro-seismic events during the operation of the Zernike geothermal project. SGS concluded that the IF and Q-Con study has certain limitations and there are relevant aspects that were not considered by the stuies. One of the key uncertainties for the Zernike GS that has not been assessed in the previous studies is the impact of pressure depletion caused by the Groningen gas production in the future and how it may influence the Zernike GS operations. Also, the impact of the injection and production operations on the minor internal faults, identified in the Zernike block, were not studied. The possibility of re-activation of the faults in the Zernike area due to changes in the block's tectonic stress regime and subsequent micro-seismic events were not considered in the previous studies.

In the course of the feasibility study SGS performed a detailed review of the micro-seismic events in the Groningen region. Furthermore SGS conducted a detailed review of published information on seismicity measured in other geothermal systems in order to find suitable analogues for the Zernike GS to benchmark the seismicity forecast. A simplyfied 3D reservoir ("shoe box") model for the Zernike GS was constructed and multiple forcast scenarios were simulated to provide a prediction of the pressure and temperature development in the geothermal system during operations. 70 realizations were modelled and analyzed and the key parameters were assessed, which impact the pressure development and distribution in the Zernike GS in the course of 30 years of operation.

The feasibility of a Traffic Light System (TLS) for the Zernike GS was evaluated. Purpose of the TLS is to provide a checklist and protocol system for the geothermal operations in order to mitigate geological and operational hazards. The study concludes that the TLS for the Zernike GS is feasible and require the detailed risk analysis of the technical and geological parameters in order to establish thresholds for the mitigation action.

The analysis of the forward modelling results of the 70 scenarios highlight the reservoir permeability and the fault transmissibility (sealing capacity) of the internal faults as the parameters, which have the most significant impact on the pressure and temperature propagation in the Zernike GS. The pressure distribution patterns in the Zernike block of the various scenarios show significant differences, predominantly controlled by the above mentioned factors but also the effect of significant further depletion in the Groningen gas field might play a role.

In the scenarios with partial or full sealing internal faults it is regarded likely that the pressure changes over time will have an impact on the tectonic stress field in the Zernike block. The changes of the tectonic stress regime along the internal faults close to the injection and producing wells - caused by a pressure differential across the fault (ΔP) - could trigger micro-seismic events. However, by the methodologies applied in the course of this study phase, no ΔP threshold could be established, which trigger fault re-activation and induce potentially micro-seismic events.

Micro-seismic events triggered by injection (cooling / cracking) in the course of the Zernike GS operations are regarded possible. The Zernike TLS system will include adequate mitigation measures in order to minimize the risk of occurrence.

The occurrence of micro-seismic events in the Zernike Block triggered by natural seismicity or compaction is very unlikely. The Zernike Block boundary faults are assumed to be sealing (against the Groningen field). The changes of pressure distribution related to the Zernike GS activities do not reach the block boundary faults during operation life time (30 years). The continuation of pressure depletion in the Groningen gas field will likely be responsible for changes of the stress field along the Zernike Block boundary faults and could trigger micro-seismicity along those faults - as observed in the Groningen field.

The full risk assessment and quantification of the risk parameters related to the Zernike GS operations and required for the implementation of the TLS, were out of the scope of this study phase. Further and more detailed reservoir modelling and the full 3D geomechanical finite element modelling are recommended for the 3rd phase of the study in order to quantify the risks and establish operational thresholds required for the TLS.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

WarmteStad B.V. (WarmteStad), a joint venture between the city of Groningen and the Groningen water company, has been established to investigate whether a geothermal system can be installed close to the city of Groningen to supply households with energy/hot water.

A cold water injection well and a warm water production well are envisaged to be drilled. The target would be a water bearing region ("an aquifer") in the permeable Slochteren formation. The area is located several kilometers west (down-dip) of the Groningen Gas Field.

The Groningen city council has asked for technical investigations to assess the risk of induced seismicity/earthquakes as a result of operation of the geothermal project. If there is a (small) risk of seismicity, a traffic light system (TLS) can be devised (monitoring system and forward action plans) to manage the risks.

In 2016, IF and Q-Con performed a geomechanical study, under the assumption that the aquifer in the Zernike area is undepleted (i.e. is not affected by gas production from the Groningen gas field). For this scenario, their modeling work indicated that the risk for seismic events is limited.

Based on the discussions with experts in the industry (TNO) on the 20th of July 2016, it was recommended that simulations will need to be performed assuming that the reservoir is (partly) depleted. TNO suggested that there is a chance that the aquifer may be depleted by production from the Groningen gas field (which has up to 250 bar depletion). No data are available for the Zernike fault compartment that support this statement, this is however an assumption that needs to be taken into account for a risk assessment prior to, and possible mitigation during, operation of the geothermal project.

SGS performed the dynamic reservoir modelling of the Zernike fault block and Zernike GS area. Multiple scenarios were modeled using the reservoir modeling software ECLIPSE 100. Several parameters describing the reservoir characteristics, the pressure, the temperature and injection rate as well as the impact of further depletion in the Groningen area were altered in the course of the modelling.

The objective of the forward modeling of the injection and production operations to forcast its impact on the pressure distribution in the operation area over the planned lifetime of the geothermal operations. Pressure changes in the aquifer / reservoir resulting from depletion or fluid injection modify the local stress state of the Zernike block, especially in the vicinity of the internal faults. If the stress state of a fault plane is disturbed, the fault could be re-activated and cause microseismic events.

Based on the obtained pressure distribution scenarios the potential of the induction of micro-seismic events was evaluated. In order to assess the impact and uncertainty of the control parameters on the Zernike GS operations Based on the analysis of the results of 70 realizations, SGS established best case and worst case scenarios which are presented in this report.

There are a number of NW/SE striking boundary faults between the Zernike block and the Groningen field. It is assumed that these faults are sealing – but no data are available in the Zernike block to confirm this assumption. If the faults are open (through sand-sand juxtaposition), this may facilitate communication between the aquifer in the Zernike area and the Groningen gas field and therefore contribute to further pressure depletion in the Zernike area over time. Even if the faults are sealing, due to the heavy depletion of the Groningen gas field, minor leakage ("sweating") may occur once differential pressure over the fault exceeds several tens of bars.

Water injection and production in the course of the geothermal project will create pressure differentials, which affect the original pressure distribution pattern in the geothermal reservoir. This may affect the local stress state and may induce local fault re-activation (i.e. a seismic event), depending on the areal influence of the pressure variation relative to local faults. In addition, thermal stress due to cold water injection during geothermal operation could initiate fault re-activation.

No significant seismic events have been measured up to date that originate in consession area of the Zernike GS area. However, in the nearby Groningen gas field, significant seismic events have been recorded including a number that contributed to structural damage at the surface.

WarmteStad intends to develop a Traffic Light System (TLS) describing mitigation measures for the operational parameters that may contribute to the occurrence of seismic events induced by the geothermal operations. The implementation of a TLS system prior to the start of the operations of the Zernike GS project is recommended in order to trigger appropriate counter-actions once certain defined thresholds for individual parameters may be breached.

Definition of Terms:

Zernike block: Horst block defined by major boundary faults (see below)

Zernike GS: Zernike Geothermal System defined by license boundary

Zernike boundary faults: major block boundary faults (Figure 1-7 faults no. 2, 4, 9, 6, 10,13, 3, 12 and 8) limiting the Zernike horst block

Zernike internal faults: minor faults within the Zernike block and Zernike GS

Micro-Seismicity: Induced seismic events with a Magnitude (M Richter scale) smaller than 2.0 [25]

Seismicity: Seismic events with a Magnitude (M Richter scale) larger than 2.0 [25]

1 KEY FINDINGS

1.1 Review of Previous Study Reports

In the course of the first phase of the study, SGS performed a review of the study reports by IF and Q-Con ("Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016 [1]). The objective of those studies were to evaluate whether seismic events (earthquakes) could be induced during the operation of the Zernike GS. The review focused on the key assumptions made by IF and Q-Con and input used for the geomechanical model (i.e. Young's modulus, Poisson's ratio, Biot's coefficient, etc). The latter was carried out in partnership with Curistec, an SGS associate company specialized in geomechanical modeling and seismicity prediction.

The following observations are offered on the basis of review of the above-mentioned report:

- The assumption by IF and Q-Con that poro-elastic stress is not associated with differential compaction is subject to investigation, as changes in poro-elastic stress can alter horizontal stress within the geothermal reservoir, thus impacting both normal and shear stress acting on the faults.
- IF and Q-Con mentioned that "the deformation process in the (Groningen) gas reservoir may cause stress interference with the geothermal reservoir" resulting from two interference mechanisms: changes in "poro-elastic stress resulting from compaction in the Groningen gas reservoir and (partial) depletion inside the geothermal reservoir. Poro-elastic stress is reflected by a subsidence pattern extending beyond the gas field into the geothermal concession. The associated stress perturbations, however, do not result in differential compaction but in a spatially continuous stress change" [1].
- IF and Q-Con also highlight that a (partial) depletion of the geothermal reservoir occurs if hydraulic connectivity has been established with the Groningen gas reservoir. Whether such a connection exists is unclear at this stage however no investigations were carried out on this topic.

It is SGS' opinion that the studies performed by IF and Q-Con and the resulting reports are not sufficiently comprehensive to the point that all risks for geothermal operation are fully investigated. It is noted that some assumptions reflect simplifications and some critical uncertainties have not been addressed appropriately. Further work to validate and reduce uncertainties is required.

1.2 Seismic Activity in The Groningen Area

Induced seismic activity in the Groningen area, have been described in numerous publications, i.e., Dost et al. 2012 [17], van Thienen-Visser and Breunese 2015 [18], Muntendam-Bos et al. 2015 [4]. From those papers and other references mentioned therein, it is widely accepted that seismicity has been induced by the re-activation of faults because of the pressure depletion related to gas production.

Figure 1-1 shows the epicentres of induced seismic events recorded over the last 20 years (1996-2015) in the proximity of Groningen Gas Field and Zernike license area [9]. The majority of induced seismic events have (local) magnitude ranges from -0.8 to 3.6 (Richter scale). The majority of these events that have a magnitude larger than 1.6 are observed at the crest of the Groningen gas field. The distribution of seismic events in the Groningen area classified in its magnitude (Figure 1-2) shows that events with lower magnitudes (<2) are distributed around the production area; while seismic events with the higher magnitudes (≥2) are generally located in the vicinity of the major faults. The historic seismicity magnitude distribution for the last 25 years and the recent two years are plotted in the upper graph of Figure 1-2. The frequency-magnitude characteristic shown the upper graph of Figure 1-2, highlight potentially induced seismic events with a maximum magnitude 3.9 might occur with a very low probability.

Only a small number of seismic events (with a magnitude below 0.9) have been recorded in the vicinity (within 2 km) of the Zernike GS. To the west of the Zernike GS, very few seismic events have been recorded.

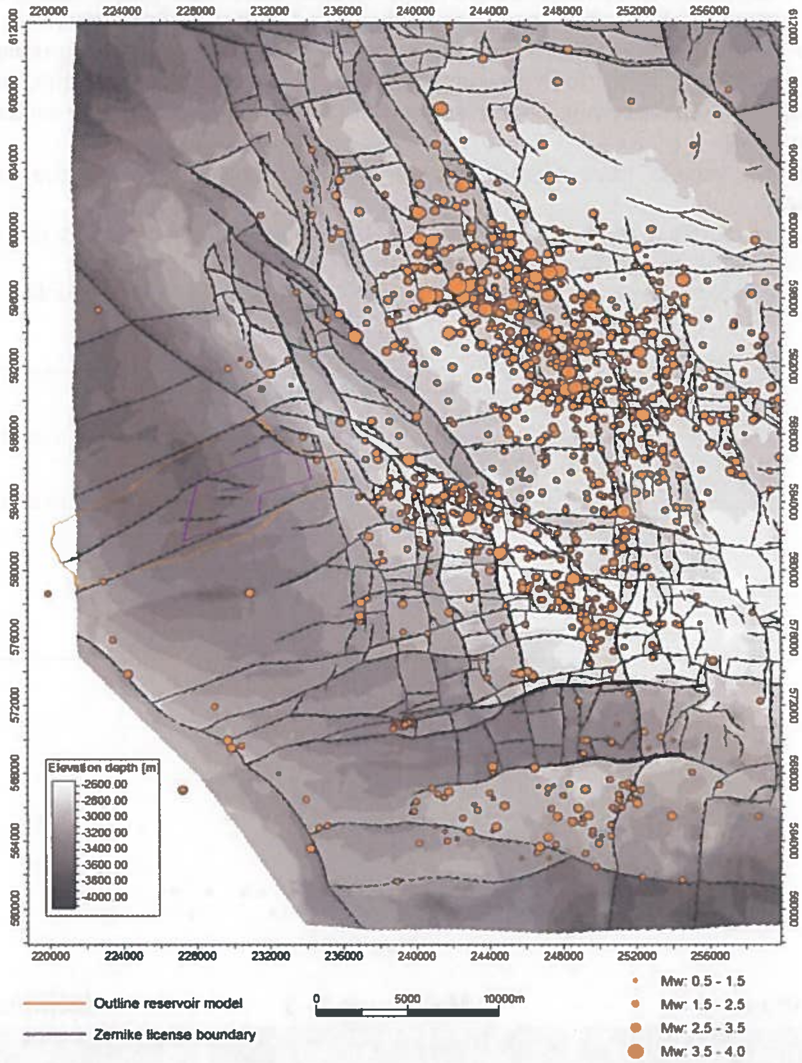


Figure 1-1 Map of epicenters of induced seismic events in the last 20 years in the Groningen Gas Field and the Zernike area (highlighted in blue) ; Background: Top Slochteren Depth Structure; Source of seismic data: KNMI [9].

Additional findings from the evaluation of the seismic activity are listed below:

- The recorded seismic events in the area are related to the Groningen gas production.
  - The majority of seismic events with magnitude between 1.2 - 3.6 occurred near the faults (at the reservoir level).
  - The seismic events with the largest magnitude between 2.2 - 3.6 are associated with major faults at the reservoir level.
  - The subsidence pattern correlates with the occurrence of most seismic events.

  - The majority of the low magnitude seismic events (< 1.5 on the scale of Richter) are presumably related to the compaction in the high porosity intervals of the Rotliegend reservoirs (Slochteren formation) - caused by the gas withdrawal and subsequent pressure depletion.
  - In some cases the micro-seismic events are likely related to the reactivation of deep-seated faults predominantly due to increased stress along the fault as a result of differential depletion in various reservoir compartments.
- (Micro-)seismic events will continue to originate form the Groningen gas field subsurface activities [3]; most likely not exceeding the order of magnitude as presently observed [4].
- No "natural" seismicity has been recorded in the region and it is very unlikely to occur in the future [4].
- No seismic events have been recorded that originate from within the Zernike license boundary.
- Two small seismic events (magnitude <0.9) have been recorded in the vicinity of the Zernike fault block, which is targeted for the Zernike GS.
  - It is likely these events are related to Groningen gas field production

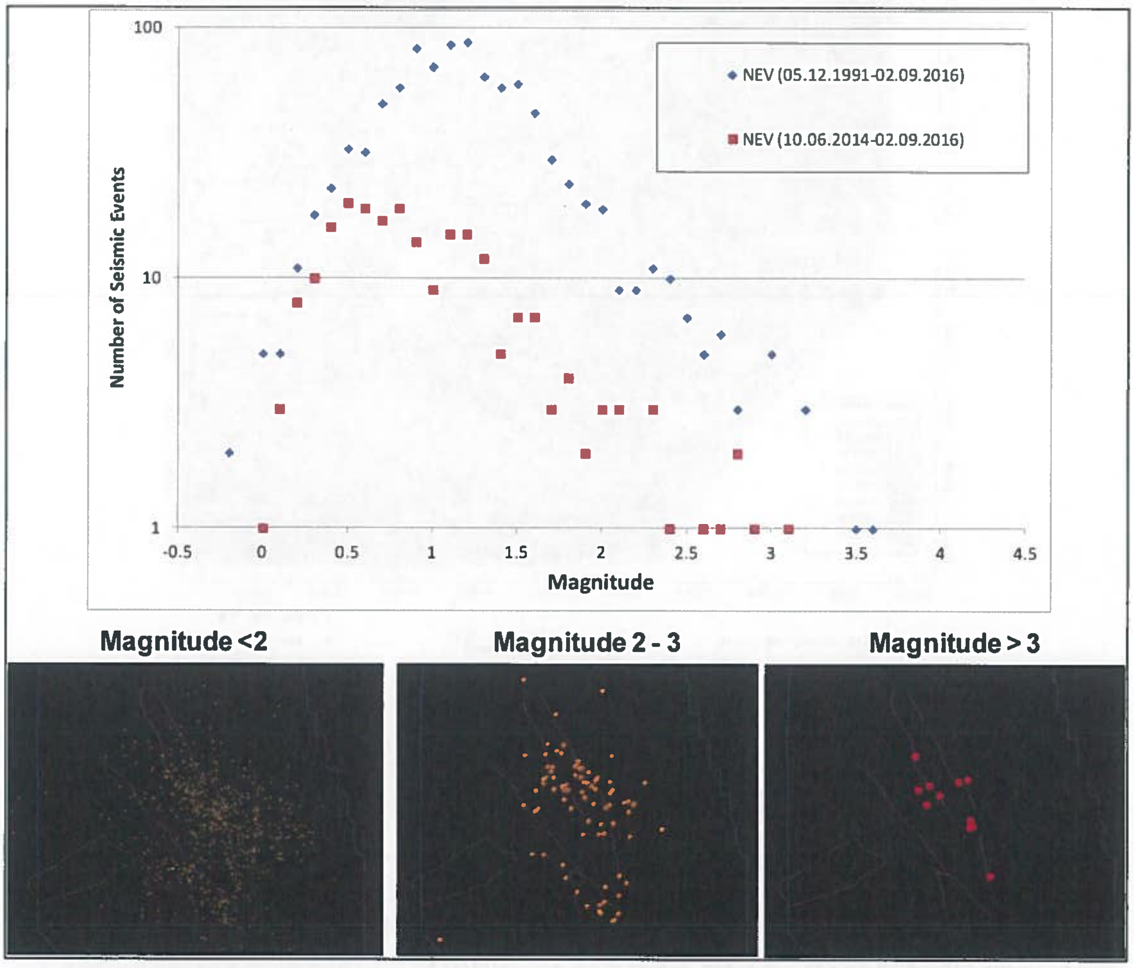


Figure 1-2 **Top picture: Number of seismicity events in Groningen area as a function of magnitude for the seismicity recorded in the last 25 years (blue diamond) and in the last 2 years (red rectangle). Bottom picture: distribution of seismic events in Groningen area, highlighted in its magnitude order.**

1.3 Analogues for Zernike Geothermal System

1.3.1 Case Histories in the Netherlands

As of 2016 a total of fourteen geothermal sites have been installed in the Netherlands. Twelve of them have been in operation since 2015 (Table 1-1). The geothermal installations are classified doublets as they consist of two wells: one production well (for pumping up the warm water) and one injection well (for pumping down the cooled water into the aquifer). Eleven of these geothermal systems are operational in 2015 [19].

The heat is produced from different stratigraphic/geological depth intervals between 1600 and 2700 meter. The four production installations in Noord-Holland and Overijssel produce warm water from Rotliegend strata[19].

No	Name of geothermal energy installation	Wells	Geothermal energy licence	Operational in 2015
1	Californie Geothermie	CAL-GT-1,2&3	Californie I	Yes
2	De Lier Geothermie	LIR-GT-1&2	De Lier	Yes
3	Honselersdijk Geothermie	HON-GT-1&2	Honselersdijk	Yes
4	Installatie Berkel en Rodenrijs	VDB-GT-3&4	Bleiswijk 1b	Yes
5	Installatie Bleiswijk	VDB-GT-1&2	Bleiswijk	Yes
6	Koekoekspolder Geothermie	KKP-GT-1&2	Kampen	Yes
7	Mijnwater energiecentrale Heerlen	HLH-G-1&2	Heerlen	Yes, HCS
8	Pijnacker-Nootdorp Geothermie	PNA-GT-1&2	Pijnacker-Nootdorp 4	Yes
9	Pijnacker-Nootdorp Zuid Geothermie	PNA-GT-3&4	Pijnacker-Nootdorp 5	Yes
10		HAG-GT-1&2	Den Haag	Closed In
11	Heemskerk Geothermie	HEK-GT-1&2	Heemskerk	Yes
12	Middenmeer Geothermie I	MDM-GT-1&2	Middenmeer	Yes
13	Middenmeer Geothermie II	MDM-GT-3&4	Middenmeer	Yes
14	Vierpolders.	BRI-GT1&2	Vierpolders	No

Table 1-1 Geothermal installations in the Netherlands since 2015. Four geothermal sites highlighted with blue color have been producing heat taken from aquifer in the Rotliegend-Slochteren formation [19].

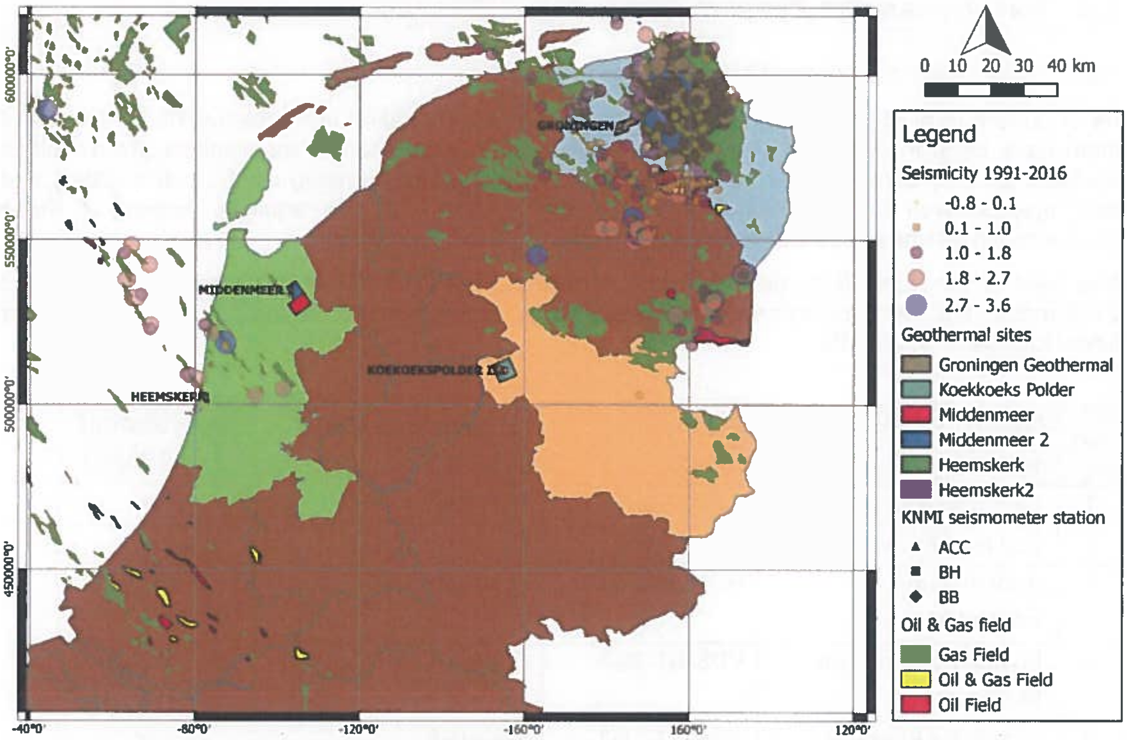


Figure 1-3 **Location of four producing geothermal sites highlighted in Table 1-1 together with Zernike geothermal area. The circle with different colors and sizes show the seismic events recorded and compiled by KNMI for the period 1991-2016. The black triangles, rectangles and diamonds are KNMI surface monitoring, borehole and broadband seismometer, respectively.**

No micro-seismic events have been reported from those four geothermal sites in North Holland and Overijssel provinces. Seismic events with magnitudes ranging from 1.9 - 2.1 were observed at the vicinity of Heemskerk geothermal site. In this area, gas production and gas storage sites are operational.

1.3.2 Comparison to Induced Seismicity From Other Fluid Injection/Extraction Sites

The work of Evans et al. 2012 [21] documented induced seismic response observed in geothermal sites of different geological environments: igneous rocks (Granite, Basalt, Gneiss), sedimentary rocks (Sandstone and Carbonates). Geothermal activities considered relevant to the Zernike geothermal site are included in Table 1-2. The table gives information that almost in all geothermal sites of BGS type producing from sedimentary rocks documented from the previous work, no significant seismic events have been observed. Except those from Unterhaching and Landau which have recorded seismic events with maximum magnitudes of 2.4 and 2.7, respectively.

Seismic hazard analysis requires a model that includes an estimate of the frequency-magnitude relation in the region (Dost et al., 2012 [17]). In order to provide estimate expected maximum magnitudes of induced seismicity due to fluid injection planning in a geothermal area a seismo-tectonic analysis based on Gutenberg-Richter frequency-magnitude analysis [23] is used. The method is an empirical-probabilistic model, which makes use of the relationship between the frequency of occurrence (number of events) and the magnitude of the event. The most important parameter derived from Gutenberg-Richter analysis is b-value, the seismo-tectonic site specific parameter, which describes the relation between frequency of occurrence and magnitude. It is not applicable to estimate the frequency of occurrence of micro-seismic events.

Note that the predictive application of the Gutenberg-Richter method could be limited by several factors (Király et al., 2015 [20]) due to the uncertainties in reservoir characteristics and geomechanical properties of the reservoir prior to the first injection/production operation.

The b-value for the Groningen area was calculated based on the seismicity monitoring of Groningen area and is shown in Figure 1-2 (upper figure) using linear regression fitting for the total number of events with M>1.3. The b-value calculated is similar to those calculated by Dost et al., 2012 [17]. Figure 1-4 shows the comparison of Gutenberg-Richter frequency-magnitude plots for three different fluid injection/extraction sites: The Basel EGS site (left), Unterhaching BGS site (middle) and Groningen gas production area (right).

Location / Country	Depth (km)	Setting Rock	Date	Inject. Type	Qmax (l/s)	Pw-max (bar-a)	Vinj (m3)	Max M_L
Geothermal: igneous rocks								
Le Mayet/FR	0.75	Granite	1987	Stimulation	73	250.0	200	N-Felt
Landau/DE	3.00	Gr/SS/Carb.	2007	Circulation	70	60.0	Balanced	2.7
Basel/CH	5.00	Granite	2006	Stimulation	55	300.0	12,000	3.4
Geothermal: sedimentary rocks								
Neustadt-Glewe/DE	2.40	SS	1995	Circulation	31	8.0	Balanced	N-Rep
Neubrandenburg/DE	1.25	SS	1989	Circulation	28	11.0	Balanced	N-Rep
Munich-Pullach/DE	3.40	Carb.	2005	Circulation	32	40.0	Balanced	N-Rep
Unterhaching/DE	3.60	Carb.	2007	Circulation	120	25.0	Balanced	2.4
Bruchsal/DE	2.50	SS	2008	Circulation	24	5.0	Balanced	N-Rep

Table 1-2 Shorted table from Table 1 of Evans et al. (2012) documenting induced seismicity related to geothermal activities.

Table legend:

CH: Switzerland; DE: Germany; FR: France.

Carb.: carbonate; GR: granite; SS: sandstones.

Stimulation: relatively short high-pressure injection to enhance rock mass permeability; Circulation: simultaneous injection and production from doublets or triplets whose flow volumes may or may not be equal.

Balanced: Balanced Geothermal System (BGS) where injection and production rates are equal.

N-Rep: No events reported either by local population or a regional/local network. N-Felt: events of uncertain magnitude recorded by a local network but none were felt by the local population.

Pw-max indicates estimated downhole injection pressure above the natural formation pressure.

The Unterhaching Balanced GS has similar operations parameter as planned for the Zernike GS: Injection pressure of 410 bar, water injection rate of 55 l/s (~200m^3/h) and low – moderate permeability of the reservoir section and thus is regarded as good analogue to estimate the magnitudes of induced seismicity.

The Gutenberg-Richter frequency-magnitude analysis of Unterhaching geothermal site was adapted to the Zernike GS by using the b-value of Groningen area. The result indicates that the majority of events would have magnitude between -1 to 1, which can only be measured using sensitive seismometer and generally not recognisable by human perception.

The b-value derived from the Gutenberg-Richter frequency-magnitude plot (Figure 1-4) also allows (with limitations) an estimate of the maximum magnitude of induced seismicity in this (tectonic) region. The maximum magnitude in the Zernike block will most likely not exceed the magnitude of 3.5 on the Richter scale.

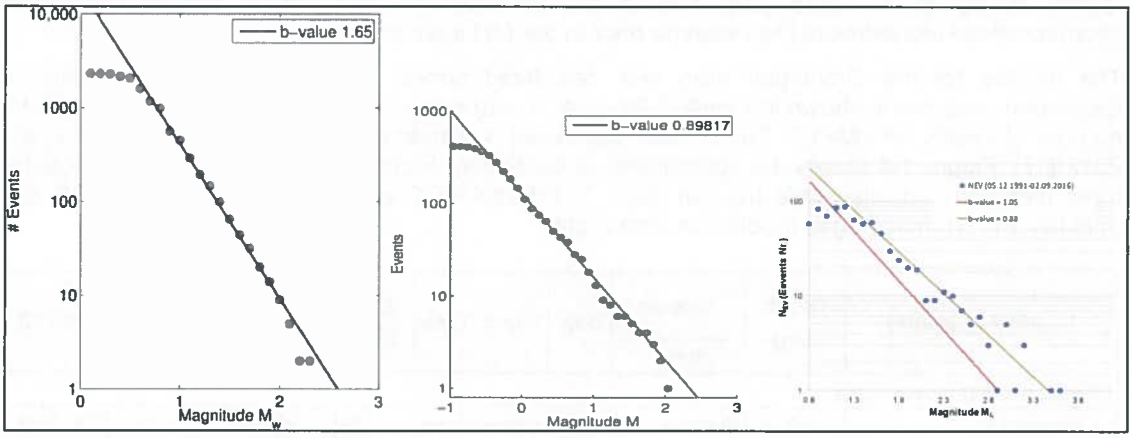


Figure 1-4 Gutenberg-Richter frequency-magnitude plots of seismic events induced by three different fluid injection/extraction schemes in: (Left) Enhanced Geothermal System (EGS) in Basel; (Middle) Balanced Geothermal System (BGS) in Unterhaching geothermal site; (Right) Groningen gas production. Left and centre diagrams from [23]

1.4 CONCEPTUAL RESERVOIR MODELING OF THE GEOTHERMAL SYSTEM

Dynamic reservoir modelling is a standard tool applied in the oil and gas industry to predict reservoir conditions (pressure, temperature) and the extraction quantities of fluids and gases. SGS applied this technology in order to predict the changes of pressure and temperature distribution in the Zernike GS during 30 years of water injection and production operations.

A simplyfied 3D reservoir ("shoe box") model was constructed for the Zernike GS with the purpose to run forecasts of the pressure and temperature development in the geothermal system and to test the sensitivity of various parameters with impact on the pressure development in the Zernike block during the time of the geothermal operations. Changes of the pressure distribution pattern could possibly induce change in the local tectonic stress fields, which can cause micro-seismic events.

The boundaries of this model are defined by the major faults separating the Zernike GS from the neigbouring Groningen and Pasop gas fields (Figure 1-1). Based on the seismic interpretations provided by Panterra [2] and Daniilidis et. al. 2016 [10], several NE-SW trending faults with minor throw were intergrated into the reservoir model and implemented in some of the model scenarios as transmisibility obstacles. In most of the modelled scenarios the internal faults are modelled with high transmissibility (open) and only in some worst case scenarios the transmissibility of the internal faults were reduced (fault sealing / partially sealing).

Vertically, the SGS model include 250 meters of (sealing) overburden above the top of the Slochteren Formation and 250 meters below the bottom of the Slochteren Formation. The Slochteren Formation was subdivided into seven zones ("flow units" with individual properties). Each zone has reservoir properties allocated based on the data published by Daniilidis et. al. 2016 [10]. No distribution patterns for permeability or porosity for the individual zones were implemented.

The impact of of contination of pressure depletion related to future production from the Groningen gas field on the Zernike block cannot be fully excluded especially if one of the Zernike block boundaries is not fully sealing. In some worst case model scenarios the impact of the future Groningen depletion was simulation by implemention of a declining pressure boundary over time ("leak") of the Zernike block pressure system.

70 realizations were modelled and analyzed in order to assess the sensitivity of key parameters impacting the pressure development and distribution in the Zernike GS in the course of 30 years of operation.

General Observations:

- Reservoir permeability, the fault transmissibility of the internal faults (sealing / partial sealing or open) and the effect of future depletion in the Groningen field appear to have largest impact on the pressure distribution patterns in the Zernike block
- The pressure changes due to injection and prodution operations in the geothermal system will reach the closest internal faults within the first year of operations
- In none of the modelled scenarios the pressure changes reaches the major Zernike block boundaries

In the following chapters the simulation input parameters are described and the results of the best (optimistic) and worst (pessimistic) case scenarios are introduced. The best and worst cases define the upper and lower boundary constraints of the "envelope" which covers all "realistic " scenarios. No "best technical case" (base case) could be established with confidence predominantly due to the large uncertainties attached to the modelling input parameters and the limited number of realizations (70), which do not provide sufficient statistical back-up.

1.4.1 Modeling Concept & Sensitivities

Several parameters are regarded sensitive and control the pressure development over time in the Zernike GS. Figure 1-5 below highlights blue the parameters included in the sensitivity run and give the value ranges for those parameters. The parameters not highlighted in blue were kept constant – see also input parameter tables Table 1-3,Table 1-4.

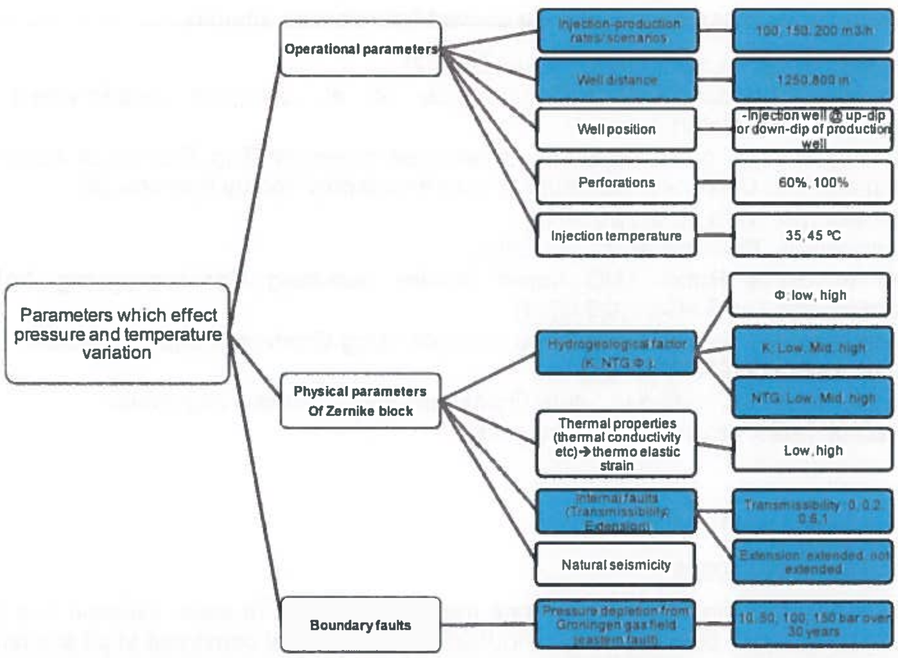


Figure 1-5: Initial parameters for Zernike GS Sensitivities (parameter highlighted in blue finally applied)

Modeling assumptions:

- Zernike block is almost at virgin aquifer pressure (i.e. not affected much by depletion related to the Groningen gas production) – estimated initial reservoir pressure 383 bar @datum (3279mSS)
- The western, southern and northern boundary fault are sealing and prevent any influx of depletion from the Groningen area
- Eastern block boundary faults are very likely to be also sealing, however, some minor subsidence observed in the Zernike block may indicate some degree of communication across those faults
- Initial reservoir temperature is calculated based on thermal gradient of 31.3°C per kilometer
- It is assumed that Slochteren reservoir in the injector will be perforated over the entire interval – approx. 250m
- The internal minor faults in the vicinity of the injector and producer are regarded as non-sealing, thus in the majority of the realizations the transmissibility of the faults is set 0.6 or 1.0 i.e. partially open / open.

1.4.2 Model dimensions and Input Data

SGS constructed a layer-cake "shoe-box" reservoir model using Petrel™ 3D modelling software. The average cell dimensions in the injection zones are 100 x 100 x 2 meters.

The input data for the reservoir model were derived from various sources:

- Primary faults: Panterra Petrel model 2014[2]
- Additional internal faults from Daniilidis et. al., 2016[10] (implemented only via transmissibility factor)
- Slochteren layer gross thickness constructed based on Top Slochteren depth structure map and Top Carboniferous depth structure map provided by Panterra [2]
- Porosity: Daniilidis et. al., 2016[10]
- Permeability: Daniilidis et. al., 2016[10]
- Net to Gross Ratio: TNO report "Advies aanvraag Garantieregeling AARDO4001 Aardwarmte ZernikeGeo", 2015[11]
- Initial reservoir pressure calculated at depth using Groningen aquifer gradient. Reference datum 383 bar @3283mSS
- Aquifer depletion related to future Groningen field activities - assumption
- Injection rates: provided by Warmtestad

Operational Parameters

Injection and production rates

A stepwise increase of the GS operation rate from 100 to 200m^3/h water injection and production within the first 4 years of operations was modelled as operational constraint in all scenarios. In the course of the sensitivity analysis the impact of lower injection / production rates i.e. 100 and 150m^3/h were modelled in order to analyse the implication on the pressure propagation within the Zernike GS.

The injection temperature, which is impacted by the annual temperature cycle was averaged for modelling purposes.

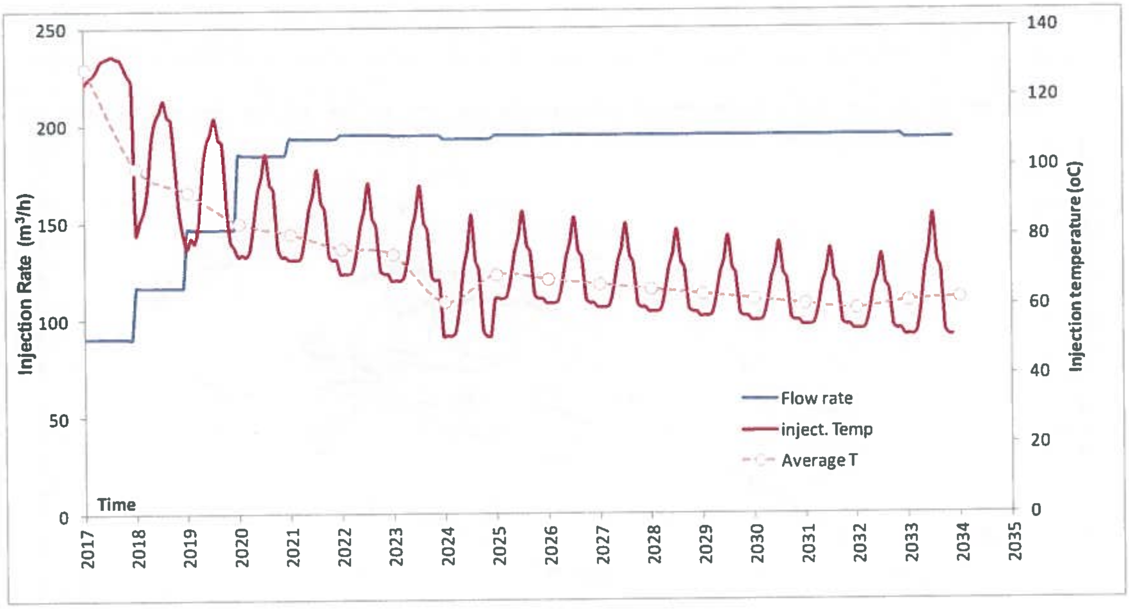


Figure 1-6: Initial Injection Rates and Modelled Temperatures

Geological and Physical Parameters

<u>Structural / Fault Model</u>

The structural model was compiled from various sources:

1) Top Slochteren depth horizon from Panterra Petrel model[2]
2) Base of "reservoir" section defined by Top of the Carboniferous section as interpreted by Panterra [2]
3) Main block boundary faults and internal faults (fault number 1 – 13 in Figure 1-7) obtained from the Panterra static (Petrel) model [2]
4) Internal faults (black coloured zick-zack faults in Figure 1-7 FA label) were implemented using transmissibility factors in the reservoir model (no fault object). Approximate location obtained from Daniilidis et. al., 2016 [10]

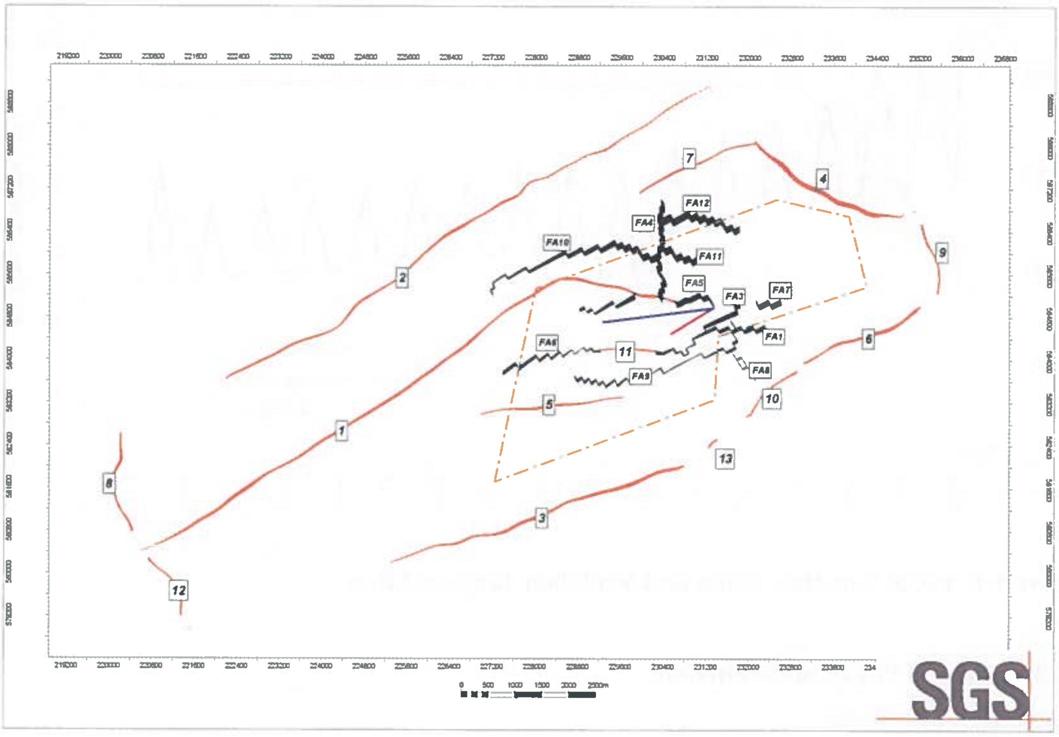


Figure 1-7: Structural elements in the Zernike model

Fault transmissibility of internal faults

SGS utilized his seismic data base in the region to verify the fault interpretations of Panterra [2] and Daniilidis [10] provided by the client. All faults shown in Figure 1-7 could be verified with varying degree of confidence. It is observed that especially the minor faults appear more distinct on the PSDM seismic, which is not accessible in the public domain.

Figure 1-8 and Figure 1-9 show example of PSTM vertical Section crossing through faults included in the sensitivity study. PSTM data is vintage processing published by TNO covering the Zernike geothermal block. In Figure 1-8, fault FA6 is considered not significant, while in Figure 1-9 fault FA1 can be recognized easily. The interpreted internal fault has throw ranging from 10-40 m.

The interpreted fault throw is generally significant less than the Slochteren reservoir thickness, i.e., 200-250 m. It is therefore concluded that for internal faults the seal related to a lithological sealing (sand / shale) is very unlikely. A reduction of the transmissibility of the internal faults related to shale gauge (sealing fault plane) is also regarded unlikely and is not particularly observed for the E-W trending fault regime in the region. Thus in most of the modeling scenarios the faults are simulated with high transmissibility ratios. (open). However, in order to acknowledge the observations of “locally” sealing faults in the Groningen gas field, some “worst case” scenarios were modeled with sealing or partial sealing internal faults.

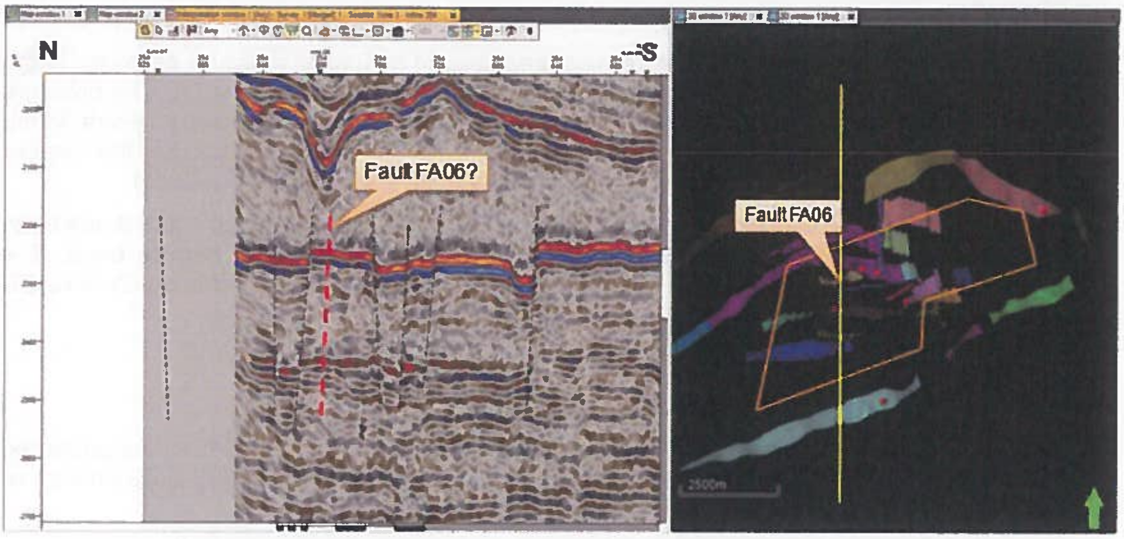


Figure 1-8 **Seismic composite line of L3NAM1987C PSTM data crossing through the major and minor faults in the Zernike geothermal area**

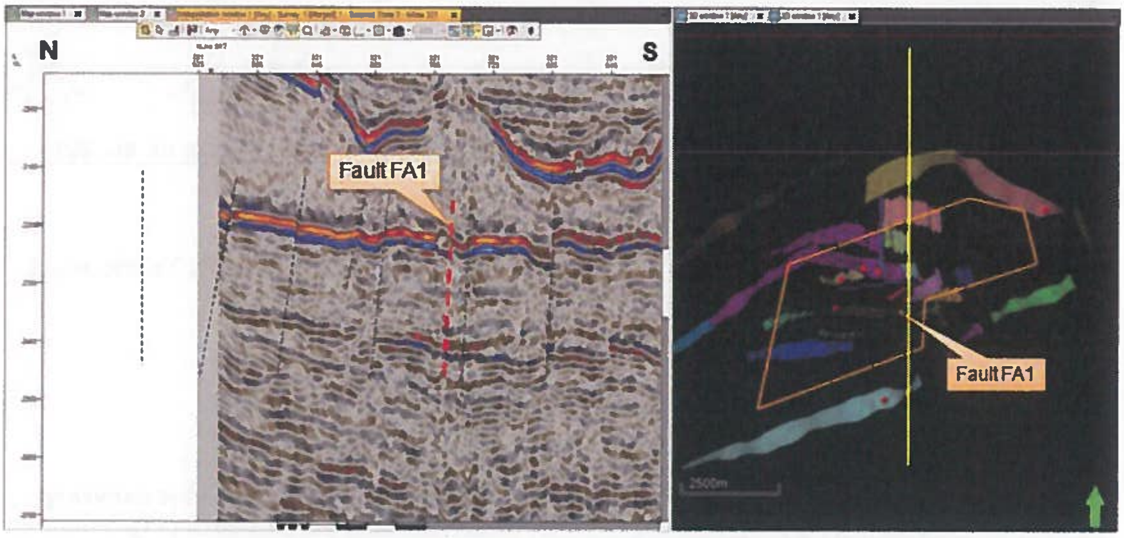


Figure 1-9 **Seismic composite line of L3NAM1987C PSTM data crossing through the major and minor faults in the Zernike geothermal area**

Initial Reservoir Pressure

No formation pressure measurements are available for the Zernike block. Based on the concept that the major block boundary faults (2, 4, 9, 6-10-13-3) provide an effective seal of the Zernike block against the Groningen gas field, a "virgin" reservoir pressure of approximately 400 bar is expected to be encountered at the injection location of the Zernike GS.

Minor depletion in the order of tens of bar cannot be excluded. Large pressure differentials of more than 100 bars are observed from some field compartments bounded by major faults in the Groningen field. The maximum present day pressure depletion in the Groningen gas field is in the range of 250 to 300 bar compared to initial reservoir pressure.

The initial reservoir pressure was not implemented as sensitivity in the course of this study phase.

Impact of future Groningen field depletion

Possible future pressure depletion in the Zernike area caused by further pressure depletion in the Groningen area was predicted based on the observed subsidence in the area [3]. The pressure depletion in the Zernike area is assumed to be in the order of 10 bar over the next 30 years. In the best case scenario it is assumed that the boundary faults remain sealing and shelter the Zernike block from depletion, independent from the activities planned in the Groningen gas field.

However in some "worst case" scenarios the impact of the partial breach of fault 4 and 9 has been simulated causing up to 100 bar pressure depletion in the NE part of the Zernike block. The pressure depletion of 50 to 100 bar effects significantly the operation conditions in the Zernike GS (see also Figure 1-12).

Reservoir Properties

The layer Porosities and permeability ranges applied in the model are derived from the published data set as shown in the Table below. Both data set could not be verified by SGS since no core or well data are available from the Zernike block.

Reservoir Layer (top to base)	Vertical thickness (m, avg)	Porosity (%)	Permeability (mD)		
			P90	P50	P10
7	59	17.4	1	2	9
6	30	18.5	15	48	152
5	34	17.7	14	44	140
4	44	19.5	14	46	153
3	24	17.5	11	35	114
2	32	18.3	3	11	42
1	25	14.9	4	15	48
			L	M	H

Table 1-3: Model input for Thickness, Porosity & Permeability (from Daniilidis et. al., 2016 [10])

The Net to Gross ratio (Net reservoir sand / Gross interval) were obtained from TNO's document

Parameter	Aanvrager		
	Laag	Verwacht	Hoog
Netto-bruto verhouding (%)	88	91	95

Table 1-4: Net-To-Gross for the Slochteren Reservoir (from TNO report "Advies aanvraag Garantieregeling AARDO4001 Aardwarmte ZernikeGeo", 2015 [11])

1.4.3 Best Case Forecast Scenario

The best case scenario represents an "optimistic case" (= low pressure differentials) i.e. if all input parameters and constraints come in positive or on the "high" side:

- reservoir properties such as permeability and NTG are on the "high" side i.e. average reservoir permeability 90 mD (over 250m reservoir section), NTG ratio 0.95
- all internal faults are not sealing
- the fault seal of the block boundary faults prevent the Zernike GS from significant impact from the Groningen depletion (10 bar depletion over 30 years assumed)
- "virgin" reservoir pressure of 383 bar @ datum (=3283 mSS) is encountered
- a sustainable injection rate of 200 m^3 / h

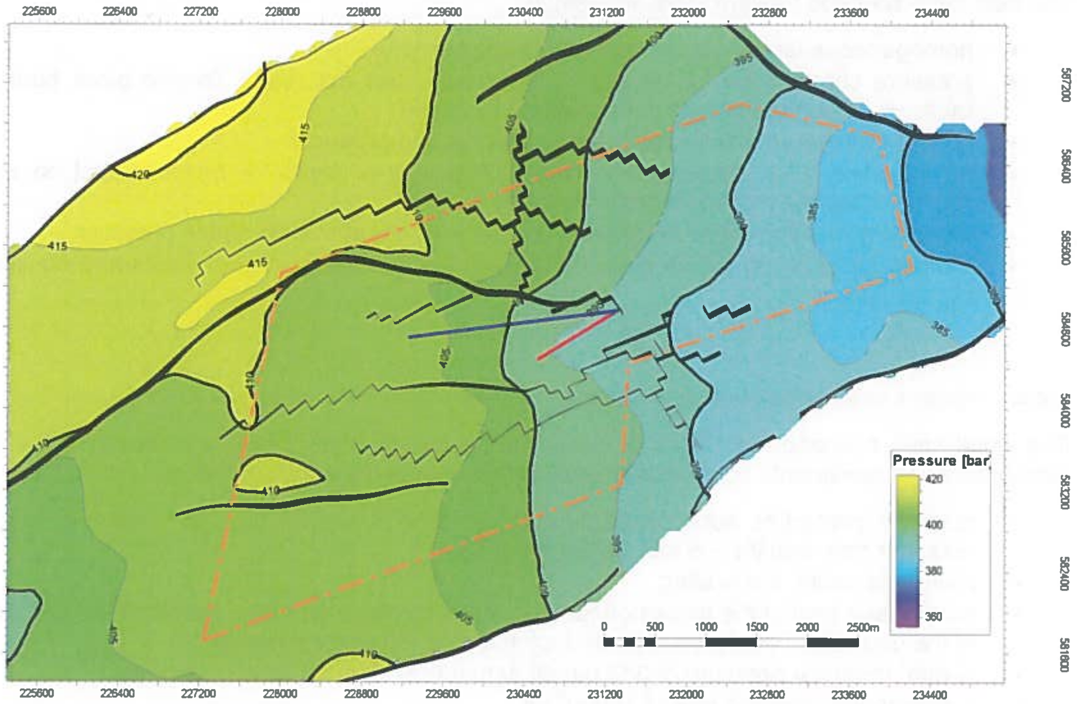


Figure 1-10: Best Case Scenario Pressure Distribution in Zernike GS after 30 Years of Operations

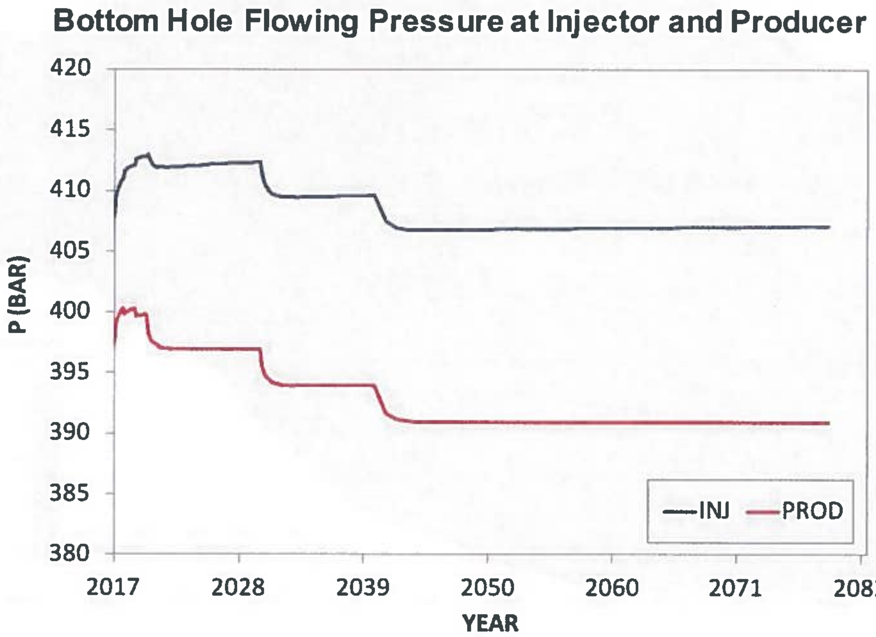


Figure 1-11: Best Case Scenario Bottom Hole Flowing Pressure versus Operation Time at Producer well GT01 and Injector well GT02

The best case scenario forward modeling results:

- homogeneous lateral pressure propagation over time
- pressure change due to injection / production does not reach Zernike block boundary faults → no change of fault stress regime triggered
- coherent pressure differential between injector and producer
- no induction of a pressure differential along internal faults → minor impact on stress regime along the internal faults anticipated
- Operating injection pressure reasonably low ~ 10 bar above formation pressure
- temperature cooling propagated around Injector and reach internal faults and equilibrate across fault

1.4.4 Worst Case Scenario

The worst case scenario represents a "pessimistic case" (= high pressure differentials) i.e. if all parameters and constraints come in at the low side or worse than anticipated:

- reservoir properties such as permeability and NTG are on the "low" side i.e. average reservoir permeability ~ 8 mD, NTG ratio 0.88
- all internal faults are sealing
- limited fault seal of the block boundary faults does not prevent the Zernike GS from impact of the Groningen depletion (50 bar depletion over 30 years assumed)
- "virgin" reservoir pressure of 383 bar @ datum (=3283 mSS) is encountered
- a sustainable injection rate of 160 m^3 / h

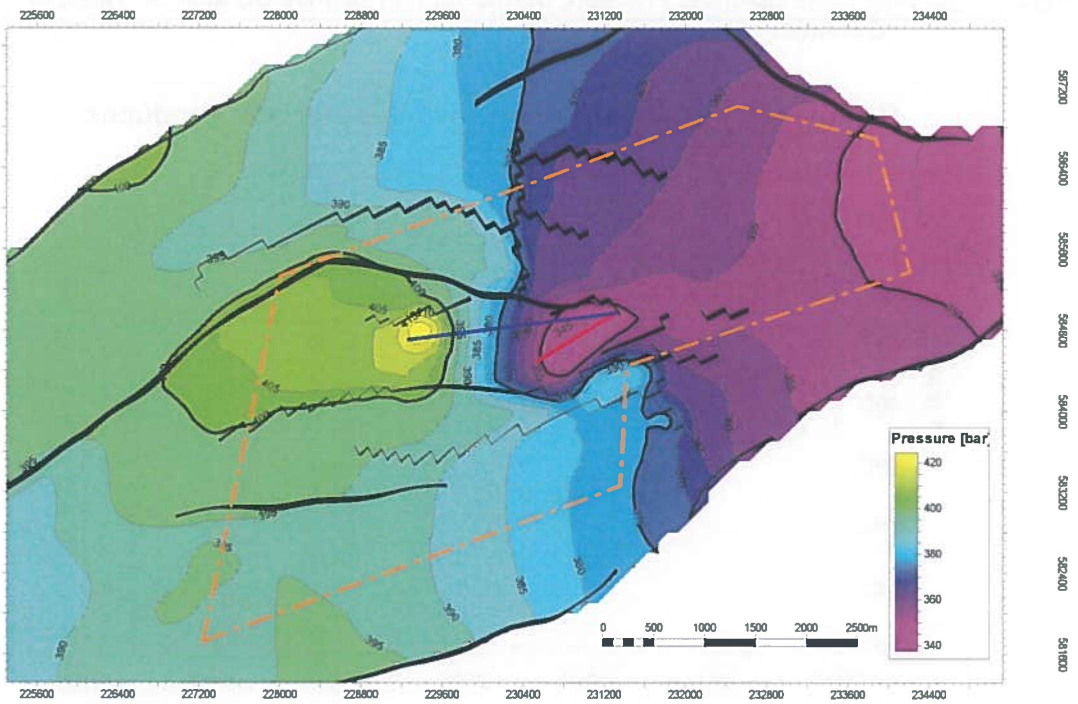


Figure 1-12: Worst Case Scenario Pressure Distribution in Zernike GS after 30 Years of Operations

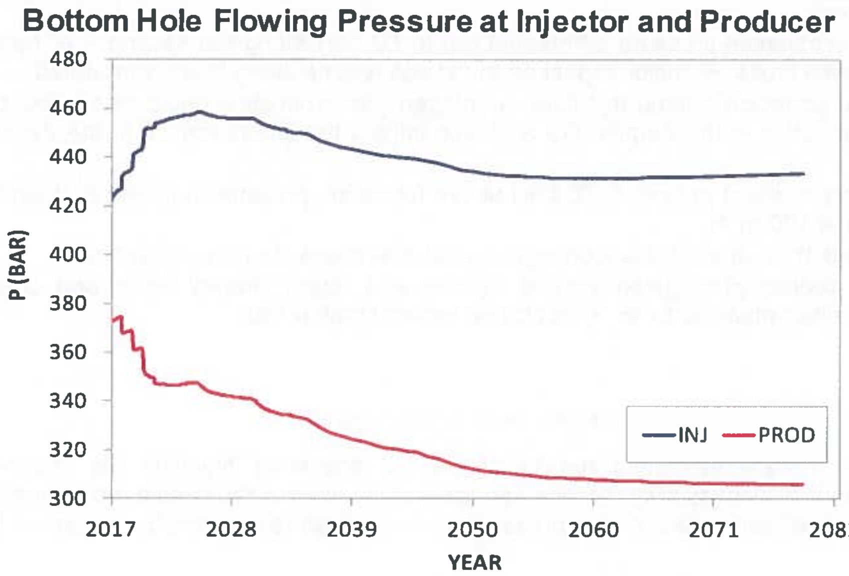


Figure 1-13: Worst Case Scenario Bottom Hole Flowing Pressure versus Operation Time at Producer well GT01 and Injector Well GT02

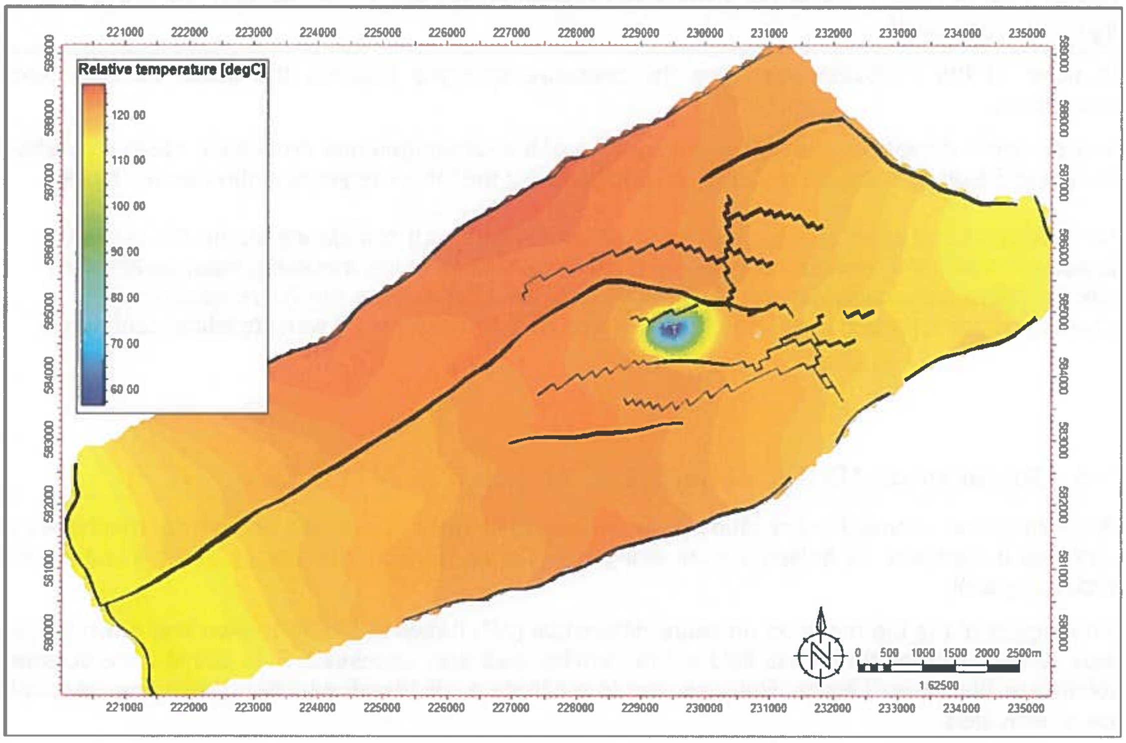


Figure 1-14: Worst Case Scenario Temperature Changes Related to Cooling by Injection

The worst case scenario forward modeling results:

- Large pressure differential between injector and producer i.e. 120 bar

- pressure change does not reach Zernike block boundary faults → no change of stress regime induced
- induction of substantial pressure differential (up to 50 bar) along the sealing – or partial sealing - internal faults → major impact on the stress regime along faults anticipated
- The pressure depletion related to future Groningen gas production could also affect the pressure distribution in the Zernike GS and also impact the stress regime in the Zernike block
- High operating injection pressure (80 bar) above formation pressure required to maintain injection rate of 160 m^3/h
- injection "break thru" at producer (cooling) beyond operations life time (30 years)
- temperature cooling propagated around Injector and reach internal faults and create temperature differentials up to 45 °C at closest internal fault (FA6)

1.4.5 Summary of Forward Modelling Results & Conclusions

The analysis of the forward modelling results of the 70 scenarios highlight the reservoir permeability and the fault transmissibility (sealing capacity) of the internal faults as the parameters, which have the most significant impact on the pressure and temperature propagation pattern in the Zernike GS.

Large pressure differentials at the internal faults as well as between the producer and injector – as modelled in the worst case scenario with sealing internal faults - could possibly have a major impact on the tectonic stress field in the area especially in the vicinity of faults.

The reservoir permeability not just influence the velocity of the pressure and temperature propagation but also controls the Zernike GS operation conditions, i.e. injection / production rates, injection pressure etc.

In none of the modelled scenarios the pressure changes reaches the major Zernike block boundaries

The pressure depletion related the continuation of the Groningen gas production could also affect the pressure distribution in the Zernike GS and impact the stress regimes in the Zernike block.

No "best technical case" (base case) could be established with confidence during this project phase predominantly due to the large uncertainties attached to the modelling input parameters since no data are available from the Zernike GS block. Furthermore the 70 realizations / scenarious are regarded insufficient to allow a best technical forecast with statistical confidence.

1.5 Results of 1D Geomechanical Analytical Modelling

A 1D analytical geomechanical study were performed in order to evaluate an order of magnitude of changes in stresses for selected point along the internal faults in the vicinity of the injection and producing well.

The impact of the the modeled pressure differential (ΔP) between the up-thrown and down-thrown side of the faults on the stress field in the Zernike area was assessed. Five points were selected located at the internal faults. Purpose was to estimate a ΔP threshold when faults possibly could be re-activated.

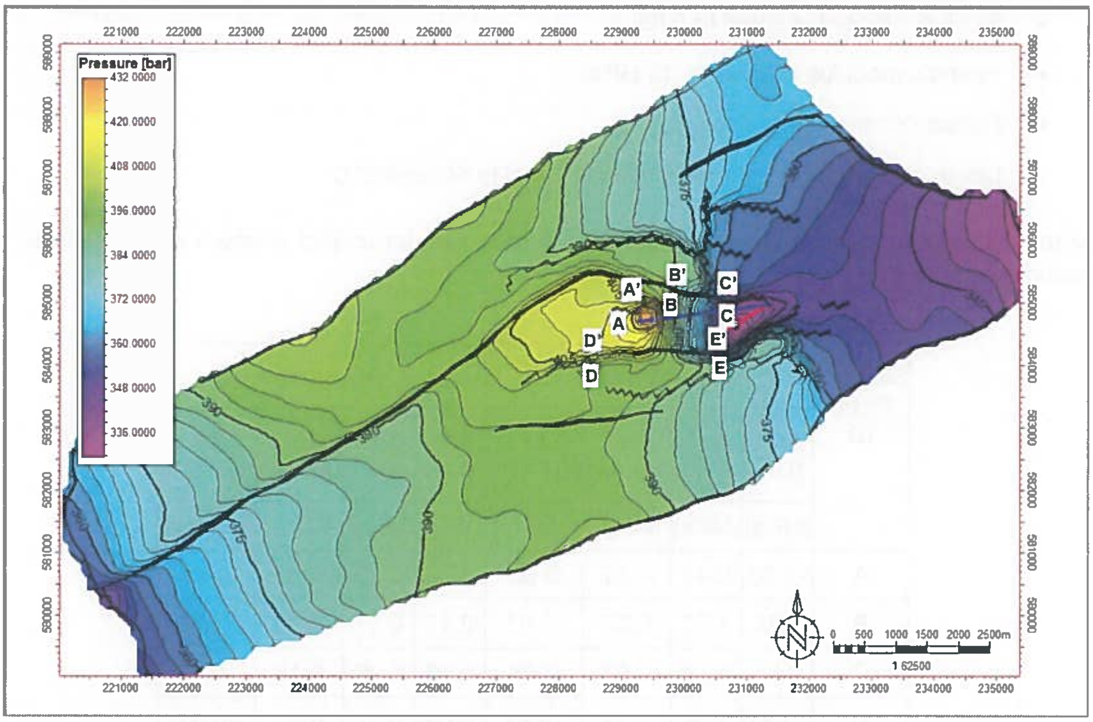


Figure 1-15: Location of sampling points for 1D numerical modeling of the stress fields

Pressures		A	A'	B	B'	C	C'	C''	D	D'	E	E'
Initial Status	P (BAR) @ 2017	405	405	403	408	401	405	404	407	410	397	397
Worst case (max)	P (BAR) @ 2047	425	400	388	388	368	384	357	411	394	330	382
Best Case (base)	P (BAR) @ 2047	404	404	401	406	398	402	401	406	408	392	393

Table 1-5: Pressure input data for stress calculation

Temperatures		A	A'	B	B'	C	C'	C''	D	D'	E	E'
Initial Status	T (oC) @ 2017	122	122	121	123	120	122	121	122	123	119	119
Worst case (max)	T (oC) @ 2047	77	120	121	123	120	122	121	122	123	119	119
Best Case (base)	T (oC) @ 2047	79	80	120	123	121	122	122	122	123	119	119

Table 1-6: Temperature input for stress calculation

Other parameter assumptions used in the computation are the following:

- Computations are performed under uniaxial strain conditions, i.e., it is assumed that no horizontal displacement occurs. This assumption is not fully true close to faults, especially when the fault is not fully permeable;
- No changes in total vertical stresses occur during the operations. This assumption is not fully true on the short term;

- Biot's coefficient is equal to 0.85;
- Young's modulus is equal to 15 GPa;
- Poisson's ratio is equal to 0.20;
- Linear coefficient of thermal dilation is equal to 10 µm/m/°C.

Note that performing finite element modeling as proposed for project phase 3 could alleviate the assumptions 1 and 3.

Sample Point ID	Worst Case				Best Case			
	$\Delta\sigma'_1$ (UT)	$\Delta\sigma'_1$ (DT)	$\Delta\sigma'_3$ (mean)	$\Delta\tau$ (UT-DT)	$\Delta\sigma'_1$ (UT)	$\Delta\sigma'_1$ (DT)	$\Delta\sigma'_3$ (mean)	$\Delta\tau$ (UT-DT)
	[MPa]	[MPa]	[MPa]	[mm/m]	[MPa]	[MPa]	[MPa]	[mm/m]
A	-1.70	0.43	-4.57	0.50	0.09	0.09	-7.95	0.02
B	1.28	1.70	0.37	-0.03	0.17	0.17	-0.05	0.02
C	2.81	1.79	0.57	0.08	0.26	0.26	0.16	-0.02
D	-0,34	1.36	0.13	-0.13	0.09	0.17	0.03	-0.01
E	5.70	1.28	0.87	0.35	0.43	0.34	0.10	0.01

Table 1-7: Results of Stress Field Calculation

Interpretation of results:

- A distinct relation between the simulated ΔP and the change of the stress fields across the faults has been observed
  - High ΔPs across fault → higher chance of fault re-activation
  - Higher ΔPs across faults appear to have most impact on σ'_1 (Sigma 1) i.e the vertical stress field
- No ΔP threshold for fault re-activation could be determined by the analytical quick look modeling
- The stress field calculation indicates that temperature changes probably have an impact on the stress field – predominantly on σ'_3 (horizontal stress)
  - Sealing faults in the vicinity of the injector, which are affected by cooling show significant higher changes in σ'_3 than sealing faults which are not reached by the thermal conduction front
  - No critical threshold or magnitude of the temperature differential, which could trigger fault re-activation could be established by the 1-D quick look modeling
- A reliable assessment of the impact of the pressure and temperature differentials on the stress fields of the faults as well as the establishment of a ΔP threshold for the fault re-activation can only be achieved in the course of a detailed finite element geomechanical and stress field 3D modeling. It is recommended to perform the geomechanical modeling when data from the Zernike GS wells become available and prior to the start of the GS operations.

1.6 Micro-seismic Events Related to the Zernike GS Operations

The results of the forward dynamic modeling of the pressure distribution in the Zernike block (Chapter 1.4) and the related possible changes of the local stress fields (Chapter 1.5) was assessed with respect to the potential of induction micro-seismicity trigger by the Zernike GS.

Five types of micro-seismic events can be distinguished based on the origin and/or trigger mechanism:

1. Natural Seismicity
2. Micro-seismicity induced by compaction
3. Micro-seismicity due to fault re-activation of major Zernike block boundary faults
4. Micro-seismicity induced by changes of the stress regime along internal faults (pressure differential across fault)
5. Micro-seismicity triggered by injection (cooling / cracking)

Ad 1) The effect of natural seismicity has not been observed in the Groningen region and thus has no implication for the Zernike GS.

Ad 2) Compaction (pore collapse) predominantly related to the pressure depletion is observed in the Groningen region with subsidence values up 30 cm in the central sector above the Groningen gas field. The Zernike GS is located at the edge of the Groningen "subsidence bowl" and a partial impact of the Groningen subsidence is assumed for the Zernike block, however to a much lesser degree (~ 6cm subsidence). The Zernike GS is planned as a "balanced" system with no net-volume withdrawal. Thus no impact of the Zernike GS operations on the subsidence of greater Groningen region is anticipated.

Ad 3) Micro-seismicity related to fault re-activation of the major block boundary faults is very unlikely to be triggered by the Zernike GS operation. All forward modelling scenarios indicate that the pressure increase and decrease caused by the injection and production respectively do not propagate to the boundary faults (closest boundary fault approximately 2.5 km distance from the wells) – see Figure 1-10 and Figure 1-12. The depletion of the neighbouring blocks due to continuation of Groningen gas field operations could have an impact on the fault stability; however this is out of the control of the Zernike GS.

Ad 4) Micro-seismic events induced due to the pressure differential along the internal faults are possible – provided the faults are sealing or partial sealing. The modelling indicate significant pressure differentials across the faults in most of the realizations where the transmissibility of the internal faults is 0.2 (partial sealing) or 0 (fully sealing). Most affected are the faults closest to the injector and producer i.e. faults FA6, FA5, FA3 and fault 11 (Figure 1-7). As shown in the worst case scenario pressure differentials along the internal faults could range from 0 to 50 bars.

The histogram below highlights that 65% of all model realizations generate pressure differentials (across the internal faults in the vicinity of the injector and producer), which are lower than 10 bar. The 1D geomechanical modelling presented in Chapter 1.5 provides only indications for potential changes of the stress regime at the particular points but cannot be used to establish a ΔP threshold when a fault is re-activated.

Micro-seismic events related to the induced pressure differential along faults cannot be ruled out during the operation time of the Zernike GS, however the chance to occur is regarded low especially since the internal faults are unlikely to be sealing.

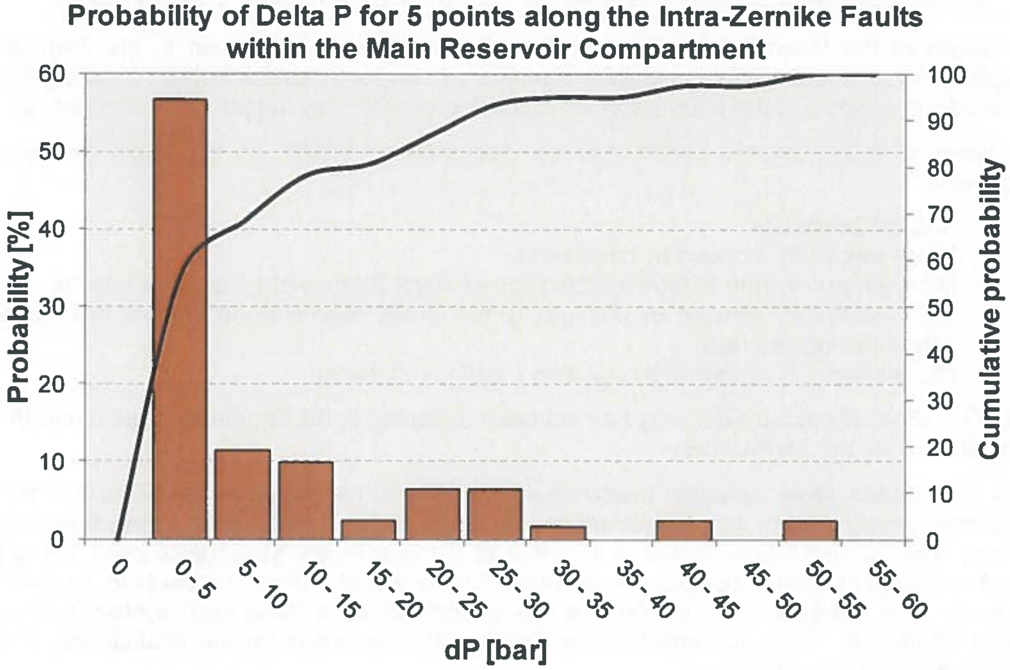


Figure 1-16: Probability of Occurrence of Delta P ranges modeled in all Scenarios

Ad 5) Micro-seismicity triggered by water injection or disposal are a phenomenon observed in several oil and gas field operations and has been described in several publications [12][13][22]. This occurs even in systems where water is injected below frac pressure. Similar observations are reported from several EGS and BGS systems in Europe and US [14],[23],[23] (discussed in Chapter 1.3). The reasons for the injection induced micro-seismicity are inter alia:

- changes of the local stress regime due to cooling
- pore collapse due to water weakening
- enhancement of micro-fracturing

In general those events are of low magnitude and beyond the resolution of the common surface monitoring technologies. The Gutenberg-Richter frequency-magnitude analysis of the Unterhaching geothermal site shown in Figure 1-4 (centre) is based on high resolution down-hole measurements, which are capable to capture events below the background noise level (magnitude < 0). Approximately 600 micro-seismic events were recorded in a period of 1200 days whereby the vast majority of the events have a magnitude of -1 to 1. Approximately 10 events above 1 magnitude have been recorded with a maximum event of magnitude 2. The Unterhaching events are interpreted to be induced by the injection.

Neither seismicity data nor operational data are available from Geothermal Systems operating in the Rotliegend Sandstone in the Netherlands, which would be the best analogues for the Zernike GS. Based on review of the publication, Unterhaching is considered as adequate analogue for the Zernike GS: similar depth, no natural seismicity region, low – moderate reservoir permeability – but different reservoir type (carbonate). The majority of micro-seismic events anticipated in the Zernike GS induced by the injection (cooling) are expected in the same order of magnitude as observed in Unterhaching i.e. < 1 magnitude. When assessing the magnitude of the potential maximum events, the regional geologic setting has to be considered (see also chapter 1.2 and 1.3). Following the Gutenberg-Richter concept, 3 - 3.5 M is the present estimate for the maximum magnitude of seismic events, which is similar to the maximum events recorded in the Groningen region.

2 FEASIBILITY OF THE ZERNIKE GS TRAFFIC LIGHT SYSTEM (TLS)

Based on the modelled sensitivities the feasibility of the design of a TLS system for the Zernike GS operation was assessed. Prior to implementation of a Traffic Light System (TLS) a description of the potential hazards and the analysis of the risks have to be performed. Based on the results of the risk analysis the TLS provide a checklist and protocol system (decision tree) for the ongoing operations with the purpose to trigger the appropriate mitigation activity. It is "best industry praxis" to implement the TLS prior to the start of the operational activities in order to provide a tool for operational decisions. In the course of the operations the TLS usually is adjusted to the local situation encountered in the GS.

The Figure below show an example of a flowchart for the hazard and risk analysis of potential induction of micro-seismicity as performed for the Zernike GS

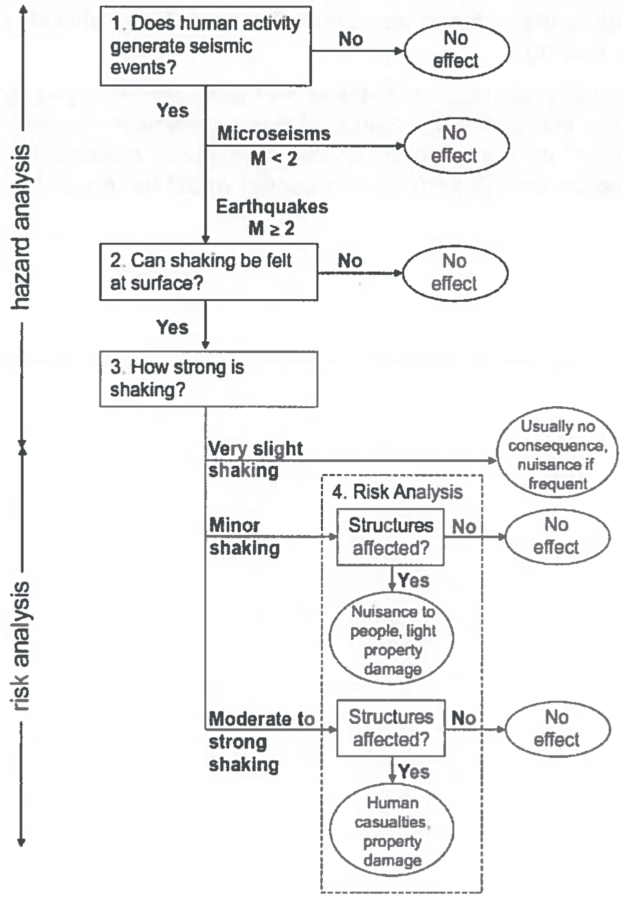


Figure 2-1: Example of Hazard and Risk Analysis Associated with Induced Seismicity for one well (from National Research Council, Induced Seismicity Potential in Energy Technologies, p. 141)[12]

Traffic Light Systems for Enhanced Geothermal Systems and other underground industrial activities are described in several publications [4][12][13]. The published checklists and protocols give a good overview of the relevant parameters to be acknowledged in a TLS. However any proposed TLS require adaptation to the local regulations and geological setting.

The establishment of a TLS for the Zernike GS is regarded feasible. The Zernike TLS describe the mitigation strategy and measures for critical parameters which have an impact on the pressure distribution in the Zernike GS. It will provide a decision tree for the GS operations with the purpose to minimize the risks of inducing micro-seismic events. The TLS implementation require a detailed analysis of the technical and geological hazards and subsequent assessment and quantification of risks related to the Zernike GS, which were out of the scope of this study phase.

As a result of the evaluation of the modelled sensitivity scenarios during this project phase, a ranking of the geological and operational parameters with respect to the potential of inducing micro-seismic events could be established.

Three parameters have been identified, which possibly play a significant role in context with induced micro-seismicity. It is recognized that those parameters have a significant impact on the Zernike GS operations and thus need to be included into the Zernike TLS:

- Status of pressure depletion in the Zernike Block → sealing capacity of boundary faults
- Reservoir properties - especially the permeability in the zones planned for injection
- Pressure differential induced along the internal faults (in unlikely case that the fault planes are partially sealing)

All 3 parameters will be measured / monitored and evaluated in an early status of the project i.e. from the results of the first well tests. Since all three parameter cannot be technically influenced only “indirect mitigation” by the adaption of the operational constraints (e.g. injection pressure / rate, selective completion of high permeability zones) would be feasible.

3 CONCLUSIONS

The analysis of the forward modelling results of the 70 scenarios highlight the reservoir permeability and the fault transmissibility (sealing capacity) of the internal faults as parameters, which have the most significant impact on the pressure and temperature propagation pattern in the Zernike GS.

The pressure distribution patterns in the Zernike block show significant differences, which are predominantly controlled by the reservoir permeability, the fault transmissibility of the internal faults (sealing / partial sealing or open) and the effect of future depletion in the Groningen field.

In the majority of the modelled scenarios with moderate to good permeability and high fault transmissibility (non sealing) the impact of the Zernike GS on the pressure distribution pattern is very homogenous and probably cause no or only minor changes of the stress field in the Zernike block.

Pressure changes as modelled in the worst case scenarios with low permeability, partially or fully sealing internal faults with large ΔP across the fault and significant impact of future Groningen depletion, could potentially cause changes of the tectonic stress field in the Zernike block. Subsequently micro-seismic events as a reaction of the stress changes in the block cannot be ruled out. However, the fault seal capacity of the internal minor faults is believed to be very limited. A relationship between the magnitude of ΔP across the a sealing fault to the frequency and magnitude of micro-seismic events is suspected. Unfortunately the methodologies applied in the course of this study phase trurned out to be inappropriate to establish a ΔP threshold, which could trigger fault re-activation and induce potentially micro-seismic events.

Micro-seismic events triggered by injection (cooling / cracking) in the course of the Zernike GS operation are regarded possible. From analogue geothermal operations the order of magnitude for the most frequent events is estimated to be below 1 (Richter). Based on an extrapolation applying the Gutenberg-Richter frequency / magnitude method, the estimate for the maximum possible magnitude of a seismic event will most likely be similar to the maximum events recorded in the Groningen region i.e. 3 - 3.5 – with a very low probability to occur.

The occurrence of micro-seismic events in the Zernike Block triggered by natural seismicity or compaction is very unlikely.

The Zernike Block boundary faults are assumed to be sealing (against the Groningen field). The changes of pressure distribution related to the Zernike GS activities do not reach the block boundary faults during operation life time (30 years) in all modelled scenarios. Thus it will be very unlikely that the Zernike GS could cause changes in the stress field along the Zernike Block boundary faults, which could trigger micro-seismicity along those faults. However, as observed in the past in the Groningen field the continuation of pressure depletion in the Groningen gas field could have an effect on the Zernike block boundary fault stability.

The establishment of a TLS for the Zernike GS is feasible. The TLS will provide a decision tree for the GS operations with the purpose to minimize the risks of inducing micro-seismic events. The implementation requires a detailed analysis of the technical and geological hazards and subsequent assessment and quantification of risks related to the Zernike GS. The assessment and quantification of the risks were out of the scope of this study phase. Further and more detailed reservoir modelling and the full 3D geomechanical modelling are recommended for the 3rd phase of the study in order to establish the operational thresholds required for the Zernike TLS.

4 REFERENCES

[1] "Hoofdrapport QS Seismic Hazard Analyse, Geothermie Warmtestad Groningen" IF Technology, 2016

a. Bijlage 1: "Reservoirmodellering, Warmtestad Groningen", IF Technology, 2016
b. Bijlage 2: "Geomechanische Evaluatie, Geothermie WarmteStad Groningen", IF Technology, 2016
c. Bijlage 3: "SHA Geothermal Project Groningen" Q-con GmbH, 2016

[2] "Geothermal Energy in Groningen Geological Investigation", Panterra, 2014. Including associated subsurface data: Petrel model and well logs (LAS files); no documentation / report available

[3] "Winningsplan Groningen 2016", NAM, 2016.

[4] A.G. Muntendam-Bos et al., "A guideline for assessing seismic risk induced by gas extraction in the Netherlands", The Leading Edge, 2015

[5] E. C. Robertson, "Thermal properties of rocks," USGS, 1988.

[6] L. Eppelbaum et al., "Applied Geothermics - Lecture Notes in Earth System Sciences", Springer-Verlag Berlin Heidelberg, 2014.

[7] S. Saeid et al., "A prototype design model for deep low-enthalpy hydrothermal systems", Renewable Energy, 2015.

[8] NLOG website: http://www.nlog.nl/

[9] KNMI Seismic Data: http://rdsa.knmi.nl/dataportal/about.html

[10] Daniilidis et. al. , Risk assessment of the Groningen geothermal potential: From seismic to reservoir uncertainity using a discrete parameter analysis in Geothermic 64 (2016) pp.271-288; 2016

[11] TNO report "Advies aanvraag Garantieregeling AARDO400 1 Aardwarmte ZernikeGeo", 2015

[12] National Research Council, Induced Seismicity Potential in Energy Technologies; The National Academies Press, 2013, ISBN 978-0-309-38708-8 | DOI 10.17226/13355

[13] National Research Council: 6 Steps Towards a "Best Practices" Protocol in Induced Seismicity Potential in Engergy Technologies. Washington, DC: The National Academies Press, 2013. Doi:10.17226/13355

[14] S.A. Shapiro, C. Dinske, and J. Kummerow, Probability of a given-magnitude earthquake induced by a fluid injection in GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L22314, doi:10.1029/2007GL031615, 2007

[15] E. L. Majer, R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith, H. Asanuma, Induced seismicity associated with Enhanced Geothermal Systems, publication of Lawrence Berkeley National Laboratory, 2006 Permalink: https://escholarship.org/uc/item/2568w6sn

[16] E. Majer, J. Nelson, A. Robertson-Tait, J. Savy, and I. Wong, Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems; U.S. Department of Energy Geothermal Technologies Program, 2012, DOE/EE-0662

[17] Dost et al. (2012) Dost, B., Goutbeek, F., van Eck, T., & Kraaijpoel, D., 2012, Monitoring induced seismicity in the North of the Netherlands: status report 2010, KNMI Scientific report WR 2012-03

[18] van Thienen-Visser, K. and J. N. Breunese, 2015, Induced seismicity of the Groningen gas field:History and recent developments, The Leading Edge, Vol. 34, Nr. 6, p. 664-671. www.knmi.nl/bibliotheek/knmipubWR/WR2012-03.pdf

[19] NLOG Website: http://www.nlog.nl/en/geothermal-energy-overview accessed on Wed Feb 1 17:06:05 CET 2017

[20] Király, E., D. Zechar, V. Gischig, D. Karvounis, L. Heiniger and S. Wiemer, Modeling and Forecasting Induced Seismicity in Deep Geothermal Energy Projects, Proc. Worls Geothermal Congress 2015, Melbourne, Australia, 10 pp, 2015.

[21] Evans, K. F., A. Zappone, T. Kraft, N. Deichmann and F. Moia, A survey of the induced seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe, Geothermics, No. 41, p. 30-54, 2012

[22] A.-P. Bois, M. Mohajerani, N.Dousi and S. Harms, Inducing Earthquake By Injecting Water In A Gas Field: Water –weakening Effect, SPE166430, 2013

[23] Dinske, C., C. Langenbruch, O.S. Krüger and S.A. Shapiro, Scaling of Frequency-Magnitude Distributions of Fluid Injection Induced Earthquakes and Implications for Seismic Hazard Assessment, Bochum Geothermal Day, Intl. Geothermal Center, September 3rd, 2014

[24] Dinske, C. and S. Shapiro, Seismotectonic state of reservoirs inferred from magnitude distributions of fluid-induced seismicity. Journal of Seismology, Vol. 17, p. 13-25, 2013

[25] Induced Seismicity Potential in Energy Technologies, 2013. The National Academies Press, Washington D.C., ISBN 978-0-309-38708-8: DOI 10.17226/13355, 262 pages