		Bijlage 2 Inventarislijst				
Nr.	**Datum**	**Onderwerp /inhoud document**	**Afzender**	**Ontvanger**	**Beoordeling**	**Art. Wob**
1.	08-01-2016	Email nauwkeurig heid positiebepaling	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art 10.2.e
2.	26-01-2016	Email vraag	FG (Nedmag)	D. en E, (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art. 10.2.e
3.	02-03-2016	Email Nedmag Wildervank	JP (KNMI	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art. 10.2.e
4.	03-03-2016	Email Ppt-presentatie met analyse van diepte bepaling van bevingen bij Veendam	JP (KNMI)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art. 10.2.e
5.	15-04-2016	Email Vraag Nedmag	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art. 10.2.e
6.	20-04-2016	Email Vraag Nedmag	BD (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
7.	09-05-2016	Email Vragen Nedmag	JS (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
8.	09-05-2016	Email Vragen Nedmag	FG (Nedmag)	JS (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
9.	26-07-2016	Email Vragen Nedmag	FG (Nedmag)	JS (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
10.	26-07-2016	Email Vragen Nedmag	JS (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
11.	26-07-2016	Email Vragen Nedmag	FG (Nedmag)	JS (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
12.	27-07-2016	Email Vragen Nedmag	JS (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
13.	27-07-2016	Email Vragen Nedmag	FG (Nnedmag)	JS (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
14.	08-02-2017	Email Analyse seismische activiteit 2017	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
15.	15-03-2017	Email Analyse seismische activiteit 2017	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
16.	17-03-2017	Email Analyse seismische activiteit 2017	BD (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e

17.	21-03-2017	Analyse seismische activiteit 2017	FG (nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
18.	01-05-2018	Seismic Activity in Veendam Area (20-04-2018)	EK (We-p)	LE (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
19.	09-05-2018	Seismic Activity	EK (We-p)	LE (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
20.	09-05-2018	Seismic Activity	LE (KNMI)	EK (We-p)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
21.	15-05-2018	Seismic Activity	LE (KNMI)	EK (We-p)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
22.	17-05-2018	Seismic Activity	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
23.	17-05-2018	Seismic Activity	WV (We-p)	LE (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
24.	24-05-2018	Seismic activity	WV (We-p)	LE (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
25.	25-05-2018	Seismic Activity	JDB (KNMI)	LE, GJvdH (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
26.	25-05-2018	Seismic Activity	ER (KNMI)	JDB, LE, GJvdH (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
27.	30-05-2018	Seismic Activity	BD (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
28.	30-05-2018	Seismic Activity	FG (Nedmag)	BD (KNMI)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e
29.	30-05-2018	Seismic Activity	BD (KNMI)	FG (Nedmag)	Openbaar, uitgezonderd gegevens persoonlijke levenssfeer	Art.10.2.e

1.

Van: [redacted] G[redacted]
Verzonden: vrijdag 8 januari 2016 10:45
Aan: 'D[redacted], B[redacted] (KNMI)'
CC: [redacted] (KNMI)'
Onderwerp: RE: Nauwkeurigheid positie bepaling aardbevingen

Geachte heer D[redacted],

Hartelijk dank voor de informatie zoals zojuist telefonisch besproken.

Hieronder even een korte samenvatting van ons gesprek met één concreet verzoek.

De in mijn mail van 16 december genoemde boorgatmeters zijn anders dan die bij Stedum en Zeerijp.
De meters bij Stedum en Zeerijp zijn op een 3 km diepte geplaatst en kunnen heel nauwkeurig de diepte van een beving bepalen.

Voor de vier genoemde boorgatmeter rond de Nedmag zoutwinning zijn live seismogrammen uit te lezen op de site van het KNMI.
Deze informatie is echter voor een leek lastig te interpreteren aangezien alleen een seismische activiteit is af te lezen.

Standaard wordt bij een beving de informatie automatisch verwerkt en is de nauwkeurigheid van plaats/diepte bepaling minder precies.
Bij een beving kan het KNMI een lokaal model gebruiken om de beving verder te analyseren.
Hiermee kan de plaats en diepte nauwkeurig bepaald worden.
De diepte kan in ieder geval tot op een paar honderd meter bepaald worden
Dit geeft voldoende nauwkeurigheid om het verschil naar oorzaak tussen gas- (3000 m) en zoutwinning (1500 – 1800 m) precies te kunnen bepalen.

Indien een dergelijke situatie zich voordoet kan Nedmag aan het KNMI vragen om met een lokaal model deze analyse uit te voeren.
Afhankelijk van de drukte heeft het KNMI hiervoor 1 a 2 weken voor nodig.
In dat geval bent u de contactpersoon voor Nedmag.
Mogelijk zijn aan deze analyse kosten verbonden.

Vanwege een specifieke klacht van een omwonende zou ik graag een nauwkeurige plaats en diepte bepaling ontvangen van de beving op 23 maart 2014 bij Sappemeer (M 1,6)
Ik hoor graag van u of hieraan kosten verbonden zijn.

Als een beving op een afstand van 1 km of in ieder geval 2 km van de zoutwinning is gelokaliseerd is het erg onwaarschijnlijk dat deze beving gerelateerd kan worden aan de zoutwinning

Nogmaals bedankt voor uw informatie en hoor graag van u of een nauwkeurige analyse van de beving bij Sappemeer beschikbaar is.

Met vriendelijke groet,

F[redacted] G[redacted]

2.

Op 26 jan. 2016 om 10:30 heeft F[redacted] G[redacted] <[redacted] het volgende geschreven:

Geachte heer D[redacted] en E[redacted]

Naar aanleiding van ons telefoongesprek en mijn van 8 januari ben ik even benieuwd of u de hieronder genoemde vraag binnenkort zou kunnen beantwoorden.

Vanwege een specifieke klacht van een omwonende zou ik graag een nauwkeurige plaats en diepte bepaling ontvangen van de beving op 23 maart 2014 bij Sappemeer (M 1,6)
Ik hoor graag van u of hieraan kosten verbonden zijn.

Is het mogelijk is om hierover maandagmiddag (1 februari) even kort van gedachte te wisselen (1/2 uurtje)

Ik ben namelijk 's morgens bij Deltares in Utrecht

Ik hoor graag van u

Met vriendelijke groet,

[redacted] **F G**[redacted]

3.

Van: S[redacted], J[redacted] (KNMI)
Verzonden: woensdag 2 maart 2016 13:01
Aan: D[redacted], B[redacted] (KNMI)
Onderwerp: NedMag: Wildervank op 20150203000222, magnitude: 1.6

Beste B[redacted],

Er was een beving dichtbij Veendam in 2015. De beving vond plaats in Wilkervank op 2015-02-03 00:02:22 en de magnitude was 1.6. Ik zal proberen de diepte van deze beving te bepalen. Voor bevingen bij Veendam voor 2015 geef ik het weinig kans de dieptes te kunnen bepalen gezien dat het uitgebreide netwerk er niet was voor 2015.

Jij krijgt morgen het resultaat van de diepte analyse.

Met vriendelijke groeten

J[redacted]

4.

Van: S[redacted], J[redacted] (KNMI)
Verzonden: donderdag 3 maart 2016 13:49
Aan: D[redacted], B[redacted] (KNMI)
Onderwerp: Ppt-presentatie met analyse van diepte bepaling van bevingen bij Veendam

Beste B[redacted],

Zie bijlage met ppt-presentatie met het resultaat van de analyse van diepte bepaling van bevingen bij Veendam.
Op basis van de huidige informatie en netwerk kan ik niet iets over de diepte van de bevingen bij Veendam zeggen.

Met vriendelijke groeten

J[redacted]

5.

Van: F[redacted] G[redacted] [[redacted]
Verzonden: vrijdag 15 april 2016 13:15
Aan: D[redacted], B[redacted] (KNMI)
Onderwerp: vraag Nedmag

Goedemiddag B[redacted]

Ik vroeg mij even af wanneer jij mij een korte reactie kunt geven op de afwezigheid van seismische activiteit rond Frisia (op basis van het lokale meetnet) en wanneer jij mij het concept artikel kunt geven mbt de evaluatie van het uitgebreide meetnet

Fijn weekend gewenst

Met vriendelijke groet,

F[redacted] G[redacted]

6.

Van: D[redacted], B[redacted] (KNMI) [[redacted]
Verzonden: woensdag 20 april 2016 13:08
Aan: F[redacted] G[redacted]
Onderwerp: RE: vraag Nedmag

Beste F[redacted]

Excuses voor mijn late reactie.

Over de seismiciteit in de omgeving van Harlingen kan ik zeggen dat het KNMI tot nu toe geen enkele aardbeving in de omgeving heeft geregistreerd waarvan de bron te koppelen is aan de zoutwinning ter plaatse. Tot nu toe zijn alleen wat verderaf gelegen bevingen geregistreerd in dit lokale netwerk rond Harlingen

Ik heb een powerpoint bijgesloten, die door J[redacted] S[redacted] bij het KNMI gemaakt is. Hij heeft gekeken naar de locatie van een recente beving. De beving waar jij oorspronkelijk naar vroeg (maart 2014) was nog enkel in het oude boorgat netwerk geregistreerd en had daarom een beperkte resolutie.

Ik ben de komende dagen in het buitenland, maar ben volgende week weer terug. Misschien is het goed om nog even telefonisch de presentatie toe te lichten.

Met vriendelijke groet
B[redacted] D[redacted]

7.

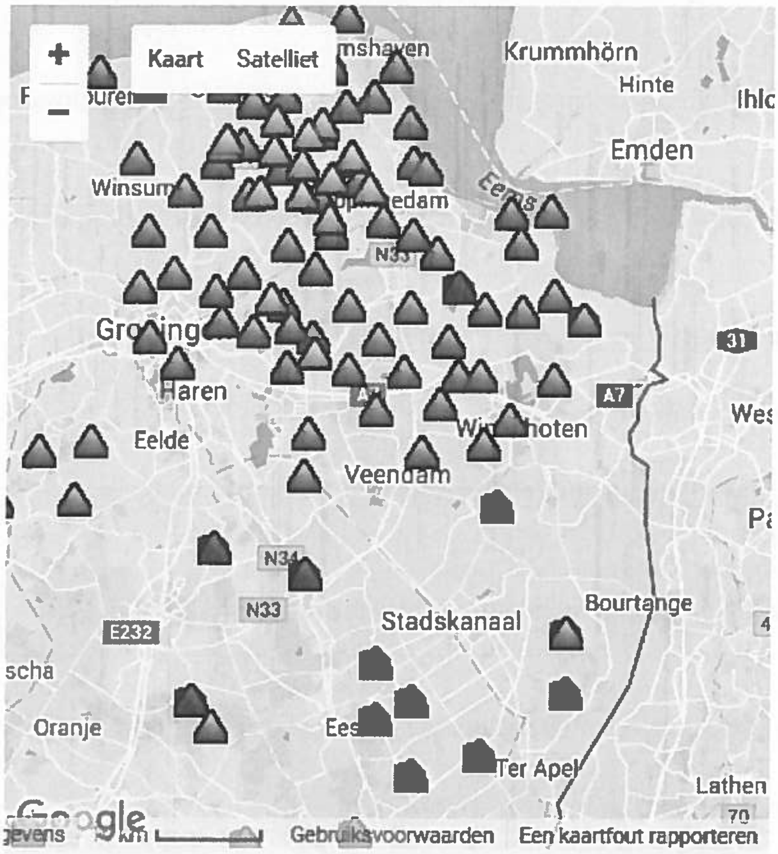
Van: S[redacted]r, J[redacted] (KNMI) [[redacted]
Verzonden: maandag 9 mei 2016 14:17
Aan: F[redacted] G[redacted])
Onderwerp: Vragen NedMag

Beste F[redacted] G[redacted],

Op mandag 2 mei heb u telefonisch contact met B[redacted] D[redacted] gehad. Ik zal hier antwoorden op uw vragen geven.

> 1] zou jij willen specificeren wat je nodig hebt van NedMag om in het geval van een nieuwe beving bij Veendam een goede diepte locatie te doen
> (Ik neem aan een Vp model of in elk geval een 3D lagen model van formaties, dat aansluit bij jouw snelheidsmodel van de NAM.)

Er zijn maar een paar geïnduceerde bevingen in de buurt van Veendam geweest. Ik heb eerder geprobeerd een diepte schatting te maken van een beving bij Wildervank (3 februari 2015) die op de KNMI aardbevingscatalogue staat, maar zonder succes. Er waren maar twee stations binnen 16 km van de epicenter. Het KNMI netwerk in het zuiden van provincie Groningen is niet zo uitgebreid als rond Loppersum, Hoogezand, Groningen stad, en het in noorden. Zie plaatje hieronder. Voor een goede schatting van de diepte van een beving is het juist van belang dat afstanden tussen stations niet langer zijn dan 4-5 kilometer. Het KNMI maakt gebruik van een 3D snelheidsmodel van Groningen. Deze model is afgekapt in het zuiden van provincie Groningen ergens op de hoogte van Veendam. Hier geldt ook dat een goede diepte schatting is sterk afhankelijk van de nauwkeurigheid van de ondergrond snelheidsmodel. Kortom voor bevingen tussen Winschoten en Veendam zou er een kans zijn de diepte te kunnen schatten, maar voor bevingen zuidelijker van Veendam wordt het gezien de huidige station configuratie en afgekapt snelheidsmodel veel moeilijker.



> 2] Zou jij alvast de laatste versie van ons paper dat gesubmit is bij GJI aan hem kunnen sturen? Lijkt mij geen probleem als hij het enkel voor intern gebruik > krijgt. Dat was overigens voor hem ook geen probleem)

Zie bijlage met pdf-file met artikel voor Geophysical Journal Internation.

J[redacted] S[redacted]

Senior scientist

Seismology and Acoustics
Royal Netherlands Meteorological Institute (KNMI)
PO Box 201
NL-3730 AE De Bilt
Netherlands

8.

Van: F[redacted] G[redacted] [[redacted]
Verzonden: maandag 9 mei 2016 16:39
Aan: S[redacted], J[redacted]r (KNMI)
CC: D[redacted], B[redacted] (KNMI)
Onderwerp: RE: Vragen NedMag

Goedemiddag J[redacted]

Hartelijk dank voor de informatie.

Ik stuur jou nog even een koppeling van een interessant artikel, het artikel zelf is te groot om op te sturen

Dit gaat over de studie die een PhD student van de Universiteit van Aken onder leiding van Janos Urai uitvoert.

Raith et al., 2015 (http://www.solid-earth.net/7/67/2016/se-7-67-2016.pdf)

De 3-D seismische informatie hebben wij van de NAM .

Wij hebben deze seismische data laten omzetten in Akoestische Impedantie op basis van de samenstelling (en Vsp) van de lagen

Dit zou specifiek rond de zoutwinning mogelijk een wat gedetailleerde beeld kunnen geven van de laag opbouw

Ik weet niet of dit relevant is voor de analyse of dat jullie liever zouden werken met 1 model

Als dit interessant zou ik even met Janos Urai moeten afstemmen

Als er binnenkort een beving rond onze locatie (zeg Sappemeer) zich voordoet is het voor ons belangrijk om na te gaan of deze goed gelokaliseerd kan worden

Nogmaals dank voor de informatie

Met vriendelijke groet,

F[redacted] G[redacted]

9.

From: F[redacted] G[redacted] [[redacted]
Sent: dinsdag 26 juli 2016 13:36
To: S[redacted], J[redacted] (KNMI)
Cc: [redacted] (KNMI)
Subject: FW: Vragen NedMag

Beste J[redacted]

Is dit publicatie die jij mij gestuurd hebt al openbaar en gepubliceerd ?, ik zal het nog niet op het internet of op jullie KNMI site

Nog even ten aanzien van het snelheidsmodel, ik zou verwachten dat voor onze situatie ook het NAM model gebruikt zou kunnen worden ?

Met vriendelijke groet, **F[redacted] G[redacted]**

10.

Van: S[redacted], J[redacted] (KNMI) [[redacted]
Verzonden: dinsdag 26 juli 2016 14:00
Aan: F[redacted] G[redacted]
CC: [redacted] (KNMI)
Onderwerp: RE: Vragen NedMag

Beste F[redacted],

Het artikel is nog niet publiek. Wij hebben het artikel opgestuurd naar een internationale tijdschrift (Geophysical Journal International), en
ook een antwoord teruggekregen. De reviewers zwaren positief, en hebben een aantal niet-te-moeilijk vragen. Als het artikel goedgekeurd is voor een publicatie, kunnen wij een beslissing nemen over het openbaar maken van deze werk.

Het NAM model wordt al gebruikt in het artikel. Helaas gaat de NAM model niet verder in het zuiden van Groningen dan ergens bij Veendam.

Met vriendelijke groeten

J[redacted] S[redacted]

11.

From: F[redacted] G[redacted] [[redacted]
Sent: dinsdag 26 juli 2016 14:17
To: S[redacted], J[redacted] (KNMI)
Subject: RE: Vragen NedMag

J[redacted]

Dank voor jouw snelle reactie.

Als een model ook voor het Nedmag gebied gebruikt zou worden welke informatie hebben jullie dan nodig ?

Ik kan Janos Urai vragen om die gegevens aan te leveren over bv laagopbouw en snelheidsprofielen ?
Kunnen jullie dit specificeren ?

Alvast bedankt

Met vriendelijke groet,

F[redacted] G[redacted]

12.

From: S[redacted], J[redacted] (KNMI)
Sent: woensdag 27 juli 2016 12:39
To: 'F[redacted] G[redacted]
Cc: [redacted] (KNMI)
Subject: RE: Vragen NedMag

Beste F[redacted],

Er zijn twee bevingen ietsjes noordelijker van Veendam geweest op 7 januari (magnitude 1.6) en 25 maart (magnitude 1.8) deze jaar. Uit de bron lokalisatie analyse komt de resultaten dat deze twee bevingen bij de reservoir of net daaronder plaats hebben gevonden.

Bevingen zuiden van Veendam zijn moeilijker te lokaliseren omdat er in de zuidelijke deel van Groningen (zuid van Veendam) weinig stations geplaatst zijn.

Met vriendelijke groeten

J[redacted] S[redacted]

13.

Van: F[redacted] G[redacted] [mailto:[redacted]
Verzonden: woensdag 27 juli 2016 13:59
Aan: S[redacted], J[redacted] (KNMI)
CC: [redacted] (KNMI)
Onderwerp: RE: Vragen NedMag

J[redacted]

Mooi dat je dit hebt uitgezocht.
Het is de laatste tijd erg rustig qua aardbevingen

Dank voor de informatie

Met vriendelijke groet,

F[redacted] G[redacted]

14.

Van: F[redacted] G[redacted]
Verzonden: woensdag 8 februari 2017 9:27
Aan: 'D[redacted], B[redacted] (KNMI)'
CC: [redacted]
Onderwerp: Analyse seismische activiteit 2017

Beste B[redacted]

Hoewel wij geen seismische activiteit verwachten van onze zoutwinning, krijgen wij van onze toezichthouder (SodM) voor het eerst de verplichting om jaarlijks te rapporteren over de al dan niet opgetreden seismische activiteit.

De letterlijk vraag is:
De jaarlijkse rapportage bevat tenminste een overzicht van de operationele status van het netwerk (de voor Nedmag relevante meetstations) gedurende het jaar, de daarbij gerealiseerde detectiecapaciteit ter plaatse van de winning, en een overzicht van alle waargenomen seismische activiteit.
Wanneer seismische activiteit wordt waargenomen verwacht ik een analyse hiervan in de rapportage of een separate analyse

Nedmag dient de rapportage voor 1 april 2018 op te leveren.
Ik zou dan graag de concept rapportage op 1 maart 2018 ontvangen

Het gaat dan om de analyse over het jaar 2017.

Mijn vraag heel concreet is kan het KNMI deze rapportage voor Nedmag maken en wat zijn de kosten.

Ik verwacht ook dat de andere zoutbedrijven met deze vraag komen.

Ben ik bij jou aan het goede adres voor deze vraag of moet deze aan iemand anders gesteld worden ?

Ik hoor graag van jou

Met vriendelijke groet,

[redacted]

15.

Van: F[redacted]s G[redacted] [[redacted]
Verzonden: woensdag 15 maart 2017 10:12
Aan: D[redacted], B[redacted] (KNMI)
CC: [redacted] (KNMI)
Onderwerp: RE: Analyse seismische activiteit 2017

B[redacted]

Zoals zojuist besproken bijgevoegd de eerdere mail met de vraag van het Staatstoezicht

Ik hoor graag van jou

Met vriendelijke groet,

F[redacted] G[redacted]

Van: F[redacted] G[redacted]
Verzonden: woensdag 8 februari 2017 9:27
Aan: 'D[redacted], B[redacted] (KNMI)'
CC: j[redacted]
Onderwerp: Analyse seismische activiteit 2017

Beste B[redacted]

Hoewel wij geen seismische activiteit verwachten van onze zoutwinning, krijgen wij van onze toezichthouder (SodM) voor het eerst de verplichting om jaarlijks te rapporteren over de al dan niet opgetreden seismische activiteit.

De letterlijk vraag is:
De jaarlijkse rapportage bevat tenminste een overzicht van de operationele status van het netwerk (de voor Nedmag relevante meetstations) gedurende het jaar, de daarbij gerealiseerde detectiecapaciteit ter plaatse van de winning, en een overzicht van alle waargenomen seismische activiteit.
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Ik zou dan graag de concept rapportage op 1 maart 2018 ontvangen

Het gaat dan om de analyse over het jaar 2017.

Mijn vraag heel concreet is kan het KNMI deze rapportage voor Nedmag maken en wat zijn de kosten.

Ik verwacht ook dat de andere zoutbedrijven met deze vraag komen.

Ben ik bij jou aan het goede adres voor deze vraag of moet deze aan iemand anders gesteld worden ?

Ik hoor graag van jou

Met vriendelijke groet, **F[redacted] G[redacted]**

16.

Van: D[redacted], B[redacted] (KNMI) [[redacted]
Verzonden: vrijdag 17 maart 2017 15:10
Aan: F[redacted] G[redacted]
CC: [redacted] (KNMI)
Onderwerp: RE: Analyse seismische activiteit 2017

Beste F[redacted],

Helaas hebben wij geen menskracht om op korte termijn een rapport te schrijven, maar ik heb wel een kaartje voor je gemaakt met de seismiciteit in Groningen voor 2016.

Jullie opereren zelf geen netwerk, dus je kunt m.i. volstaan met een verwijzing naar het KNMI netwerk,
waarvan de detectiecapaciteit voor de regio in elk geval M < 1.0 is en waarschijnlijk dichter bij M=0.5 ligt.

Aangezien er volgens mij geen seismiciteit in jullie winningsgebied is opgetreden, zou deze informatie voldoende moeten zijn.

Voor de exacte gegevens over de seismiciteit: de aardbevingscatalogus van het KNMI is te vinden op: http://www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus

Met vriendelijke groet
B[redacted]

17.

Van: F[redacted] G[redacted] [[redacted]
Verzonden: dinsdag 21 maart 2017 10:57
Aan: D[redacted] B[redacted] (KNMI)
CC: [redacted] (KNMI)
Onderwerp: RE: Analyse seismische activiteit 2017

Beste B[redacted]

Heel hartelijk dank voor de informatie.

Is het nog mogelijk om een legenda bij het kaartje te voegen ?
Ik ga deze informatie dan alvast bespreken met SodM

Mijn vraag aan jullie betreft de rapportage over 2017. Deze rapportage zou dan voor april 2018 klaar moeten zijn.
De vraag is dan of jullie dit voor begin 2018 kunnen inplannen

Alvast bedankt

Met vriendelijke groet,

F[redacted] G[redacted]

18.

Van: E[redacted] K[redacted]
Verzonden: dinsdag 1 mei 2018 14:47
Aan: E[redacted] L[redacted] (KNMI)
Onderwerp: Seismic Activity in Veendam Area (20-04-2018)

Good afternoon Mr. E[redacted],

My name is E[redacted], and I work as a Drilling Engineer for W[redacted] [redacted] P[redacted] in H[redacted]. We are currently evaluating a significant loss in pressure in one of our clients reservoirs. For an accurate evaluation, we are trying to gather all relevant data that might be helpful, including seismic activity.

Would it be possible for you to comment whether any seismic activity has been recorded in Veendam / Muntendam area in April 19 – 20th, 2018 (particularly, the night of 19th and morning of 20th)? Based on the overview of earthquakes, no activity has been reported. However, when I looked at the seismogram recordings in Muntendam (G554) from April 20th (See attached document), I notice some spikes early in the night (2 – 3 AM). Is there any information regarding these spikes? Is it possible to differentiate between surface and subsurface activities from the seismogram recordings?

Looking forward to your response.

Kind regards,
E[redacted] K[redacted]

[redacted]

19.

From: "E[redacted] K[redacted]
Sent: 9 mei 2018 13:52
To: "E[redacted], L[redacted] (KNMI)" <[redacted]
Subject: RE: Seismic Activity in Veendam Area (20-04-2018)

Good afternoon Mr. E[redacted],

Last week I have sent you a request regarding the seismic activities in the Veendam area on April 19 – 20, 2018 (see below for details).

Could you give me an indication whether my inquiry could be resolved or divert me to one of your colleagues who might help us identify the anomalies described and observed on the seismograms.

Should you have any questions, please do not hesitate to contact me.

Kind regards,
E[redacted] K[redacted]

[redacted]

20.

From: E[redacted]s, L[redacted] (KNMI)
Sent: Wednesday, May 9, 2018 1:56:08 PM
To: [redacted]
Subject: RE: Seismic Activity in Veendam Area (20-04-2018)

Dear E[redacted]

We will have a look at the recordings for the times you mentioned and get back to you next week.

Regards,
L[redacted]

21.

Delivered to you by KNMI Mobile environment
From: "E[redacted], L[redacted] (KNMI)" <[redacted]
Date: 15 May 2018 at 13:34:00 CEST
To: "[redacted]
Subject: Re: Seismic Activity in Veendam Area (20-04-2018)

Dear E[redacted]

We have looked at the data and found two events. These events are very small and hence difficult to localise. We retrieved:

knmi2018hrio: 2018-04-20 02:22:53 (UTC) - 53.117/6.842
knmi2018hrki: 2018-04-20 03:16:46 (UTC) - 53.121/6.837

They are too small assign a magnitude, which means that the magnitude is (much) smaller than 0.5 Richter scale.

Regards,

L[redacted]

22.

Van: F[redacted] G[redacted]
Verzonden: donderdag 17 mei 2018 10:21
Aan: 'D[redacted], B[redacted] (KNMI)'
CC: [redacted]
Onderwerp: FW: Seismic Activity in Veendam Area (20-04-2018)

Beste B[redacted],

Wij hebben in het verleden al eens gesproken over het meten van trillingen als gevolg van de zoutwinning.

Op 20 april hebben wij een ongewilde pekel lekkage gehad en is met het KNMI contact geweest of dit ook geleid heeft tot het meten van trillingen.

Uit de onderstaande reactie blijkt dat jullie zeer lichte trillingen hebben kunnen waarnemen vanaf onze zoutwinningslocatie bij Tripscompagnie.

Mijn vraag is of jullie huidige meetnet voldoende nauwkeurig is om lichte trillingen vanaf onze locatie(s) te meten ?

Zou het uitbreiden van het meetnet met één extra set standaard geofoons meerwaarde hebben voor de registratie en zo ja op welke ?

Het zou mooi zijn als jullie ons op korte termijn een reactie zouden kunnen geven

Alvast bedankt

Met vriendelijke groet/Kind regards,

F[redacted] G[redacted]
Technology & Business Development Director

23.

From: W[redacted] V[redacted]
Sent: donderdag 17 mei 2018 12:46
To: [redacted]

Cc: [redacted]
Subject: RE: Seismic Activity in Veendam Area (20-04-2018)

Dear L[redacted],

E[redacted] is the coming weeks offline.

Many thanks for the evaluation, based upon, what is the uncertainty on location and is it known at which depth the source might have been?

Met vriendelijke groet,

W[redacted] V[redacted]

24.

From: W[redacted] V[redacted]
Sent: Thursday, May 24, 2018 3:49 PM
To: E[redacted], L[redacted] (KNMI)
Cc: [redacted]
Subject: RE: Seismic Activity in Veendam Area (20-04-2018)

Dear mr L[redacted],

Could you help us on below question on the uncertainty.

We have to relay the answer to SODM in due time.

Met vriendelijke groet,

W[redacted] V[redacted]

25.

From: D[redacted] B[redacted], J[redacted] (KNMI)
Sent: Friday, May 25, 2018 1:20:41 PM
To: E[redacted], L[redacted] (KNMI); H[redacted] van den, G[redacted] (KNMI)
Cc: [redacted] (KNMI)
Subject: Re: Seismic Activity in Veendam Area (20-04-2018)

Hi L[redacted],

The solutions computed with Hypocenter have the following uncertainties:

Event 2018-04-20 02:22:53
errlon = 2.1 km, errlat = 1.9 km, errdep = 0.0 km

Event 2018-04-20 03:16:46
errlon = 2.0 km, errlat = 2.3 km, errdep = 0.0 km

Note that errdep = 0 because we fixed depth to 3km. The real depth uncertainty... I don't know. The same as the rest of induced earthquakes in Groningen?

In addition, the location of these events was difficult and we had to use a lot of S phases (usually not used at all). So I would say that the uncertainties are bigger. Maybe E[redacted] or B[redacted] can give more specific numbers?

Cheers,
J[redacted]

26.

From: R[redacted] E[redacted] (KNMI)
Sent: Friday, May 25, 2018 4:17 PM
To: D[redacted] B[redacted], J[redacted]i (KNMI); E[redacted] L[redacted] (KNMI); H[redacted] (KNMI)
Subject: Re: Seismic Activity in Veendam Area (20-04-2018)

Hi all,

Attached is a png file with a quick planning for a possible new station. The NEDMAG production location is in the middle, with orange lines radiating to our nearby stations and one possible new station within the cyan circle. Reasons to choose for a station location within the cyan circle are the following:
- To be close to the mine to improve the detection threshold. The nearest station now, G55, is 2.5 km away. The new station would be within 1 km.
- To fill the azimuthal gap SSE of the salt production site to improve the localization.
- to be at least a few hundred meters away from noisy sites (NEDMAG production site, Veendammerweg and Borgercompagnie)

Cheers,

E[redacted]

27.

Van: D[redacted], B[redacted] (KNMI) [[redacted]
Verzonden: woensdag 30 mei 2018 10:34
Aan: F[redacted] G[redacted]

CC: R[redacted], E[redacted] (KNMI)
Onderwerp: FW: Seismic Activity in Veendam Area (20-04-2018)

Beste F[redacted],

Hierbij onze analyse van het netwerk. E[redacted] stelt voor om een station in de aangegeven cirkel te plaatsen (zie onderstaande email). Dit is optimaal voor de monitoring van deze locatie.
Als het de bedoeling is om ook andere locaties van jullie operaties te monitoren, dan zou een locatie meer naar het ZZE een goede optie zijn, volgens de extensie van de oranje lijn die tot aan de cirkel loopt, maar niet verder naar het zuiden dan de Woortmanslaan.

Met vriendelijke groet
B[redacted]

28.

Van: F[redacted] G[redacted] [[redacted]
Verzonden: woensdag 30 mei 2018 11:54
Aan: D[redacted] B[redacted] KNMI)
CC: [redacted]
Onderwerp: RE: Seismic Activity in Veendam Area (20-04-2018)

Beste B[redacted],

Hartelijk dank voor jullie analyse.

Zou het ook mogelijk zijn om de geofoon op onze WHC-1 locatie te plaatsen (zie rode cirkel met adres Borgercompagnie 156a)

Op deze locatie wordt ook zout gewonnen en is een rustig gelegen locatie met geen activiteiten op de locatie zelf zoals vrachtauto bewegingen e.d.
Op deze locatie zijn namelijk voorzieningen aanwezig om de geofoon eenvoudig te plaatsen en aan te sluiten.

Indien er wordt overgegaan tot plaatsing van de geofoons dient Nedmag of het KNMI deze geofoon te financieren ?

Ik ga er vanuit dat na plaatsing van de geofoon deze in het KNMI meetnet wordt opgenomen, zijn hier nog kosten aan verbonden of wordt deze in de algemene analyse taken van het KNMI opgenomen ?

Alvast bedankt voor het beantwoorden van de vragen.

Met vriendelijke groet,

F[redacted] G[redacted]

Met vriendelijke groet,

F[redacted] G[redacted]

29.

Van: D[redacted], B[redacted] (KNMI) [[redacted]
Verzonden: woensdag 30 mei 2018 13:14
Aan: F[redacted] G[redacted]
CC: [redacted]
Onderwerp: RE: Seismic Activity in Veendam Area (20-04-2018)

Beste F[redacted],

De door jullie voorgestelde locatie heeft twee nadelen tov de door ons voorgestelde locatie

1] het azimut tov jullie zoutwinningslocatie valt samen met het azimut naar ZL2, zodat we niet de azimut-gap van ca 150 graden oplossen. Dit is van belang voor onze locatie bepaling van potentiele events
2] Als op de (rode) locatie ook zout wordt gewonnen, dan zal dit ook mogelijk storend kunnen werken op de metingen. Hoewel de locatie zelf geen vrachtauto bewegingen kent, is er wel een wat drukkere weg dichtbij (Borgercompagniester weg)

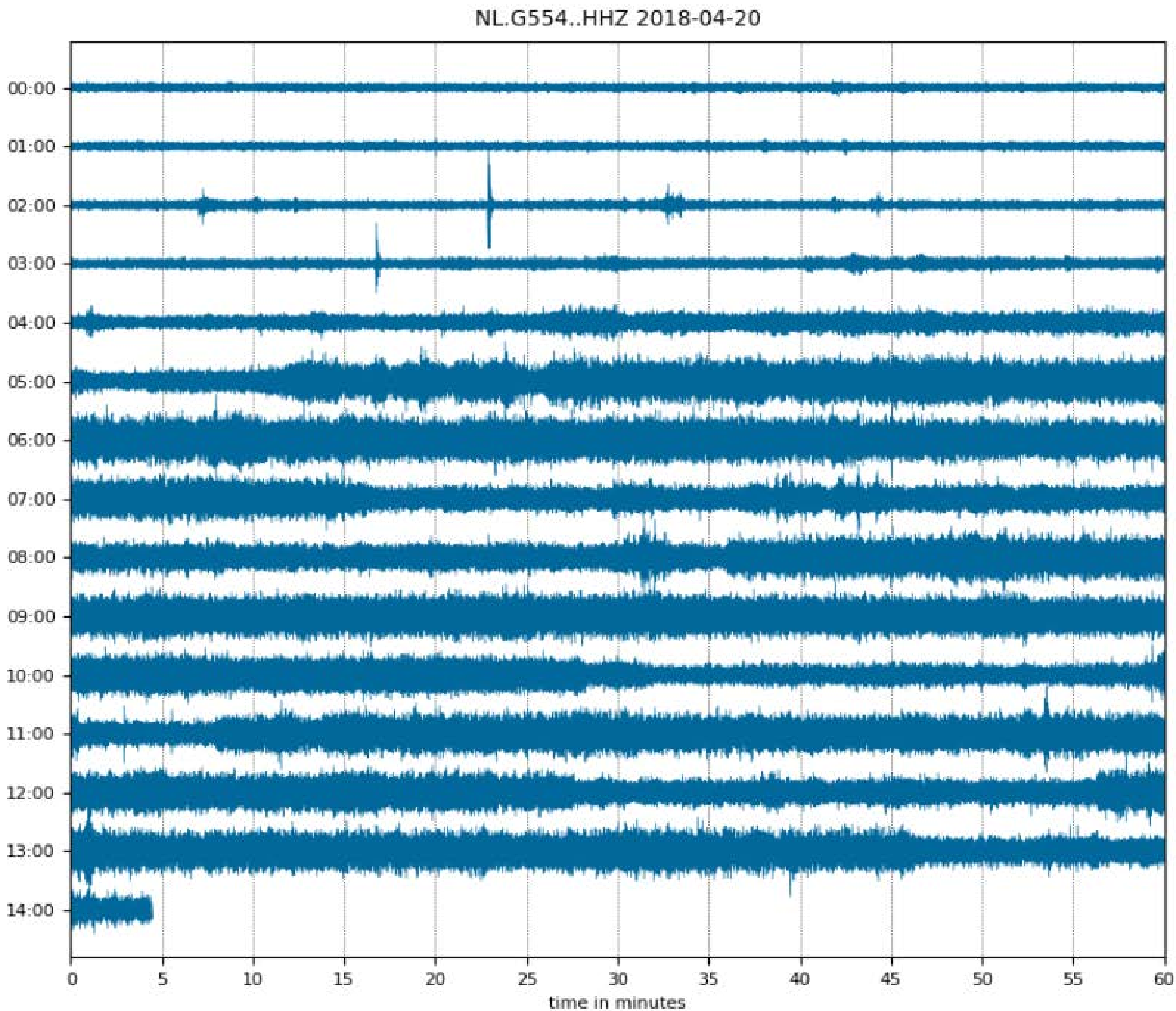
Voordeel is wel dat alle voorzieningen aanwezig zijn.

Over je financieringsvragen: NedMag dient de geofoon te financieren. Om snel te kunnen handelen is het verstandig als NedMag zelf de opdracht aan bv Antea kan geven.
Wij nemen de geofoon vervolgens graag in ons netwerk op. De kosten van communicatie en onderhoud en beheer zijn ook voor NedMag. In de praktijk zijn deze kosten voor 1 boorgat niet hoog

Met vriendelijke groet
B[redacted]

Live seismogram per station

Stations G554 - Muntendam Dag Friday Apr 20, 2018 Toon



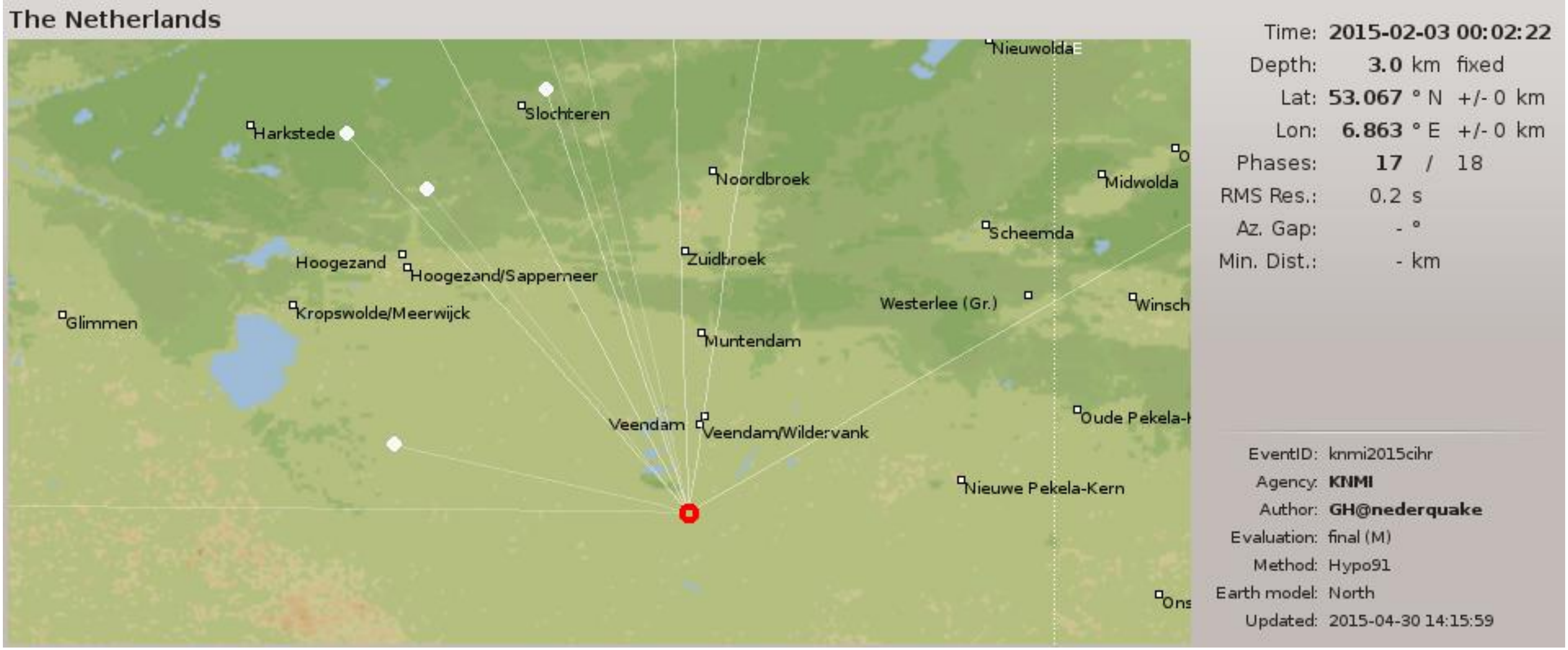
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Analyse van de mogelijkheid voor diepte bepaling van bevingen dichtbij VeenDam

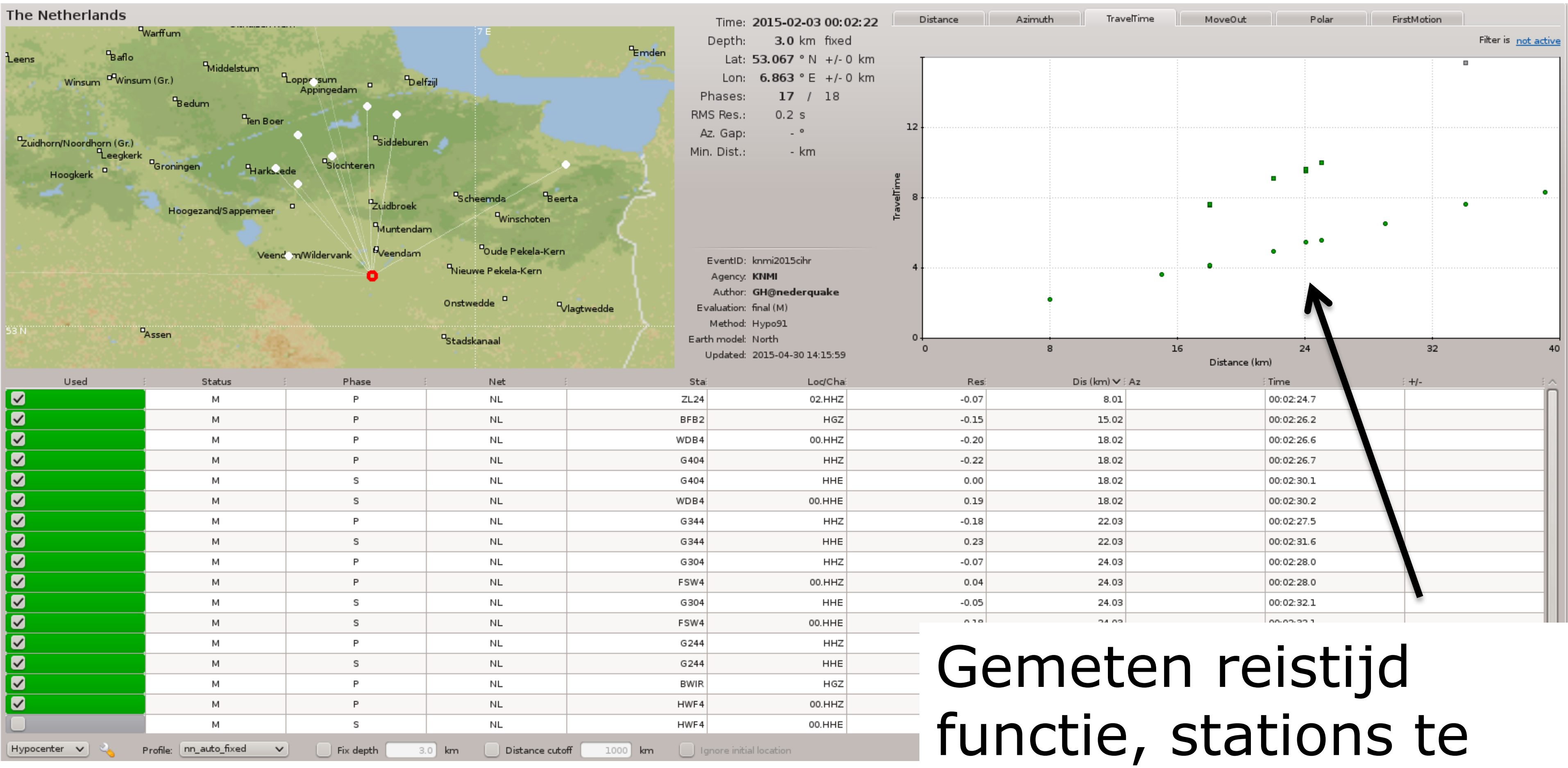
Bron localisatie van beving bij Veendam

- Analyse met seiscomp
- Misfit functie berekend op epicenter locatie
- Conclusies

Scherm plaatje van de epicenter van de beving op 3 februari 2015 bij Veendam



Scherm plaatje met de analyse van reistijden van epicenter naar stations.



Gemeten reistijd functie, stations te ver van elkaar

Range van gedetailleerde ondergronds model van Groningen

```
/ x and z are RD coordinates

    qreal xmin = 228512.5; // unit: [m], DO NOT CHANGE!
    qreal xmax = 267512.5; // unit: [m], DO NOT CHANGE!

    qreal zmin = 569312.5; // unit: [m], DO NOT CHANGE!
    qreal zmax = 613712.5; // unit: [m], DO NOT CHANGE!
```

De epicenter ligt buiten de model gebied, de epicenter is 4-5 km van de rand van de model.

Vertical misfit functie op locatie van epicenter

Diepte

Misfit functie

```
oem@Akabanga ~/Documents/Focus_Estimation $ focus_estimation_Groningen
The misfit function =
2000   12.1795
2050   12.1688
2100   12.5866
2150   12.7667
2200   13.0939
2250   13.5931
2300   13.6774
2350   13.8031
2400   14.2034
2450   14.3029
2500   14.5314
2550   13.9187
2600   14.0004
2650   14.5949
2700   14.3067
2750   14.5534
2800   14.7332
2850   10000
2900   10000
2950   10000
3000   31.9906
3050   30.966
3100   31.9494
3150   31.9416
3200   29.1664
3250   32.7841
3300   28.399
3350   27.9522
3400   32.8086
3450   35.0793
3500   26.8398
```

De waarden van de misfit zijn ongeloofwaardig wegens de afstanden van stations en een verkeerd model voor Groningen

Conclusies

- De afstanden tussen de epicenter en stations zijn te groot.
- Veendam ligt een een gebied van Groningen met een beperkte dekking van stations
- Veendam ligt buiten de model van de gedetaillerde model van de ondergrond van Groningen
- Het bepalen van de diepte van bevingen bij Veendam is niet mogelijk op basis van de huidige toegangbaar informatie en metingen

submitted to *Geophys. J. Int.*

Hypocenter Estimation of Induced Earthquakes in Groningen

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SUMMARY

Induced earthquakes due to gas production have taken place in the province of Groningen in the North-East of the Netherlands since 1986. In the first years of seismicity, a sparse seismological network with large station distances from the seismogenic area in Groningen was used. The location of induced earthquakes was limited by the few and wide spread stations. Recently, the station network has been extended significantly and the location of induced earthquakes in Groningen has become routine work. Except for the depth estimation of the events. In the hypocenter method used for source location by the Royal Netherlands Meteorological Institute (KNMI), the depth of the induced earthquakes is by default set to 3 km which is the average depth of the gas-reservoir. Alternatively, a differential travel time for P-waves approach for source location is applied on recorded data from the extended network. The epicenter and depth of 37 induced earthquakes in 2014 and 2015 have been estimated. The newly estimated epicentres are close to the induced earthquake locations from the current method applied by the KNMI. It is observed that most induced earthquakes take place at reservoir level. Five events with roughly the same magnitude are found near a brittle basalt-anhydrite layer in the overburden of mainly rock salt evaporites.

1 INTRODUCTION

Induced earthquakes due to gas production occurred in the North of the Netherlands over the last 30 years (Dost & Haak 2007; Bourne et al., 2015). The first events were felt near small gas fields in production, followed by activity that could be related to the Groningen gas field, one of the largest onshore gas fields in the world. Seismicity rate of the Groningen field gradually increased over the years until 2003. Since then activity rate increased more strongly, coinciding with an increase in annual gas production.

Observed magnitudes of the induced earthquakes in Groningen are usually in the lower range of the Richter scale (ML $<$ 3.5) except for a few stronger events in 2006 and 2012. An event with magnitude 3.5 took place on August 8 2006, while the largest event recorded was the magnitude 3.6 on Augustus 16, 2012 (Dost & Kraaijpoel 2013). The epicenters of these two events were close to the small town of Huizinge. Many people were shocked by the sudden feeling of strong ground motion and a substantial amount of building damage was reported, due to the shallow depth, around 3 km, of the events

In 1995 the KNMI realized a sparse regional borehole network with average distance between stations of 20 km. The network geometry, covering a heterogeneous shallow crustal structure, limited the resolution of the location of induced earthquakes to 0,5-1 km. The network was gradually extended over time, with the aim of covering a larger region. After the magnitude 3.6 event in 2012, it was decided to increase the number of stations significantly with the result that currently the average interstation distance is reduced to 3-4 km.

Originally, the KNMI used the traditional P- and S-wave arrival time difference method to locate induced earthquakes with the sparse network using the hypocenter method (Lienert, 1986) and an average 1D velocity model for the region. It has proven difficult to resolve the depth of the events, which is set by default to 3 km, the average depth of the gas reservoir in Groningen. Nevertheless, a good estimate of the depths of the induced earthquakes in Groningen would add valuable information that is useful for hazard analysis (Bommer et al., 2016).

In 2013 two deep downhole arrays have been installed in the most active region near the village of Loppersum with the aim to record microseismicity at reservoir level and determine the depth extend of the seismic activity. Arrival time inversion using a grid search location algorithm (Pickering 2015) was applied and it was concluded that all events processed occurred at a depth of the reservoir. Since the deep arrays only cover a small region of the Groningen field and larger events saturate the geophones used, it is a challenge to improve the depth estimation using the improved shallow borehole network set-up in Groningen.

A popular method to relocate earthquakes is the double difference method (Waldhauser & Ellsworth 2000; Zhang & Thurber 2006). In the double difference method, travel time differences of recorded waveforms at one station for several earthquakes are used to reposition the epicenters. A different method, more suitable for real-time and off-line relocation of individual events is the differential travel time method where waveforms from one specific event are measured at several stations (Font et al., 2004; Lomax 2005; Satriano et al., 2008; Theunissen et al., 2012). The travel time shift of the recorded waves between stations is used to find the focus of the earthquake. In Lomax (2005) and Theunissen et al., (2012), the differential travel time method between stations is known as equal differential time EDT. The differential travel time approach is insensitive to the depth-origin time trade-off. On the contrary, the hypocenter method is based on the minimisation of traveltime residuals, where information about the origin time (e.g., related to the depth of the event) is important.

The hypocenter method for P-wave arrivals (Lienert et al., 1986) is implemented in the automatic routine for source location at the KNMI. The addition of stations to the network and the use of a detailed local velocity model did not lead to a more accurate depth estimation of induced earthquakes in Groningen. The event depth is still by default set to 3 km.

In the present paper, we will explore how the rapidly growing data set with picked P-wave arrivals for induced events in Groningen can best be used to determine reliable depth estimates of induced events in the region. The extended station network guarantees that an event will always be relatively close to at least 3 stations. In addition, NAM, who exploits the gas field, has made available a detailed 3D elastic model of the complex sub-surface structure of Groningen. Theunissen et al., (2012) conclude that the more accurate the velocity model is the better the estimation of the hypocenter of an event is. Altogether, more data and accurate information about the complex heterogeneous of Groningen is becoming available.

We will give an outline of the geological model and the seismological station network in Groningen and a short introduction of the slightly adapted differential travel time method for P-waves. A 2D synthetic experiment with two stations over a constant half-space velocity model is used to illustrate how to estimate the hypocenter of an event. Results of the differential travel time method applied on earthquake data from 2014 to 2015 are presented and compared to the KNMI hypocenter solutions. Finally, conclusions are drawn.

2 GEOLOGICAL SETTING OF GRONINGEN

One of the largest onshore gas fields is located in the province of Groningen in the North-East of the Netherlands. Figure 1 shows the location of Groningen in the Netherlands (Bourne et al., 2015; Dost & Haak 2007). The surface area of Groningen is about 1000 km^2. A lithological setting of sedimentary layers dominates the geology of the area (Dalfsen et al., 2006; Duin et al., 2006; van Gent et al., 2011; www.nlog.nl). The black dotted lines in Figure 1 indicate the positions of two cross-sections of the stratigraphy in Groningen. The two cross-sections for north-south and east-west directions of the velocity field are shown in Figure 2. The Dutch RD coordinate system is used in all figures in this paper except for Figure 1. The cross-sections of the velocity field in Figure 2 have been extracted from a 3D detailed elastic model for Groningen. A vast geophysical data set of 3D seismic reflection data and several deep well log data going down to the carboniferous layer below the gas reservoir were used to produce the 3D elastic model.

The stratigraphic setting is explained from the surface and down to the underburden below the gas-filled reservoir. The top layer is the North Sea (NS) group containing clays, silts and sandstone. The thickness of the North Sea group varies between 600 m and 1000 m. The North Sea layer is subdivided into an upper and lower part. The transition from upper North Sea to lower North Sea is at 400 m depth. The velocity in upper North Sea is significantly lower than in lower North Sea. The next layer is the Chalk (CK) group which is made of mainly limestone. The thickness of the Chalk layer is between 500 m and 800 m. A sequence of three thinner sedimentary layers are found below the Chalk group. These layers are the Rijnland (RN) group, the Altena (AL) group and the Trias (TR) group. The Zechstein (ZE) group is a layer of rock salt evaporites. In general, the Zechstein layer is referred to as the impermeable salt layer above the gas reservoir. The Zechstein layer is thickest in the central area of the gas field near Loppersum (see Figure 1) and tends to get thinner at the north, south and east flanks of Groningen. Notice the lateral variations in the Zechstein layer with horst and graben structures. To complicate matters, two thin layers of basalt-anhydrite (www.dinoloket.nl) are present in the Zechstein group: One anhydrite layer in the upper section of Zechstein and another one right above the gas reservoir (van Gent et al., 2011). These two stiff, brittle layers in the soft Zechstein group give rise to strong reflected and refracted waves. The reservoir (RO) is composed of a porous sandstone in the upper-Rotliegend group. The depth of the gas reservoir is on average 3 km, but varies laterally over Groningen. The sedimentary layer below the Rotliegend group is part of the Limburg group from the late carboniferous age. The carbon layer (DC) is the rock source for the gas which has been pushed upward into the Rotliegend layer and is prevented from migrating further upward by the impermeable Zechstein group. Faults are present mainly in the Rotliegend gas reservoir layer due to extensional stress conditions. The faults do not extend vertically into the Zechstein layer because of the ductile and malleable behaviour of rock salt under high pressure. The faults are generally aligned NW-SE (Kraaijpoel & Dost 2013). Several of the faults have been reactivated during the production of gas in Groningen in the past 40 years.

3 SEISMOLOGICAL NETWORK

A borehole network of geophones was installed in 1995 with the aim to detect and locate induced seismicity in the North of the Netherlands. The network was intended to cover an area of 60 by 80 km and designed to record all events in the region of magnitude 1.5 and larger. The station separation was on average 20 km and due to the sampling of a heterogeneous upper crust, location accuracy was limited to 0.5-1 *km* in the horizontal plane. The resolution in the vertical plane was even more limited, at least 1-2 *km*. In 2014 and 2015 the network was extended over the Groningen area, resulting in an average station separation of 4 *km*, which opened the possibility to use detailed velocity models and new location algorithms.

The monitoring network developed over time from 11 borehole geophone stations in 1996 to 15 stations in and outside of Groningen with the addition of 17 accelerometers deployed at the surface until 2014. In 2015, another 60 borehole stations divided equally over Groningen were added to the network. The location threshold value of the network has been reduced from 2.3 in 1991 to 1.5 in 2008 and currently to about 0.5.

The current network of seismological stations by February 2016 is illustrated in Figure 1. Each station location is indicated with a triangle. The stations are either 3-component instruments in 4-level boreholes, accelerometers and broad-band stations. The 4-level boreholes are 200 m deep and four levels of instruments separated by 50 m have been installed. The deepest instruments have the best S/N ratio. An accelerometer is placed at the surface of each new borehole. Other accelerometers are located at the surface. A screen snapshot of waveform data and first arrival time picks of the event on July 21st, 2015 is shown in Figure 3. In general, the first arrival times for P-waves are always picked and used in the automatic location method. Travel time picking is done for the first arriving S-waves only if the events are clearly observable. S-wave picks are never used in the automatic routine, but may later be added to the data base of travel times and used in a relocation of the original epicenter.

4 DIFFERENTIAL TRAVEL TIME METHOD

The concept of the differential travel time for P-waves (dtP) method for source location is illustrated in Figure 4. Lomax (2005); Theunissen et al., (2012) apply the same principle in the construction of their source location method. An earthquake is located at the position $\mathtt{s}$. The seismological network stations record the earthquake. For example, the two stations in Figure 4 are at positions $\mathbf{r}_1$ and $\mathbf{r}_2$. Let the unknown onset time for an earthquake be written as T_0. In general, the onset time for an earthquake can be determined after the focus of the earthquake has been estimated. The recorded arrival time for a wave to travel from the source position $\mathbf{s}$ to receiver $\mathbf{r}_1$ is given by

$$T(\mathbf{r}_1, \mathbf{s}) = T_0 + \int_{ray} \frac{1}{V(\mathbf{r})} dr, \tag{1}$$

where the integration along the ray path in a heterogeneous velocity field V between the earthquake $\mathbf{s}$ and station $\mathbf{r}_1$ yields the travel time of the wave (Aki & Richards 1980). Similarly for receiver $\mathbf{r}_2$, the recorded arrival time is given by

$$T(\mathbf{r}_2, \mathbf{s}) = T_0 + \int_{ray} \frac{1}{V(\mathbf{r})} dr. \tag{2}$$

To eliminate the unknown onset time, the recorded arrival time in Eq. (1) is subtracted from Eq. (2). The differential travel time is obtained as

$$\Delta T(d) = T(\mathbf{r}_2, \mathbf{s}) - T(\mathbf{r}_1, \mathbf{s}), \tag{3}$$

where $d = \|\mathbf{r}_2 - \mathbf{r}_1\|$ is the epicentral distance between the two receivers. Expression (3) demonstrates that the differential travel time method is insensitive to the depth-origin time trade-off.

To find the focus of an earthquake, an objective function is defined. The earthquake location is determined by minimising the objective function. We follow the differential travel time approach by Font et al., (2004); Lomax (2005); Satriano et al., (2008). The observed differential travel times ΔT_{obs} between stations in Eq. (3) are compared with the calculated travel time differences ΔT_{calc} for an earthquake at an arbitrary depth. The advantage of working with time shifts between two stations is not only that the onset time of the earthquake cancels out (Satriano et al., 2008), but also that errors due to inaccuracy in the reference velocity model and modelling limitations and artifacts may be eliminated. The difference between the observed - and calculated differential travel times are squared and summed up for all station pairs. Two additional steps are carried out. 1) The sum of squared differential travel times is multiplied by the depth z to enhance the depth resolution of the objective function. This step is not a strict requirement, but is helpful to emphasise the depth resolution. 2) The average objective function is calculated by dividing with the number N of available station pairs to account for the fact that not all stations have an epicentral distance within the maximum distance of a pre-calculated travel time function. Hence, the depth-dependent objective function $L(z)$ is given by

$$L(z) = \frac{z}{N} \sum_{i}^{N} (\Delta T_{obs} - \Delta T_{calc})^2. \tag{4}$$

The addition of the linear depth term z and the averaging over the number of stations pairs is specifically introduced in this paper. However, the summation of the differential travel time residuals over all available station pairs is as well applied by Lomax (2005); Theunissen et al., (2012). The earthquake focus is obtained at the minimum point of the objective function in Eq. (4).

The maximum number of station pairs can be calculated from the number of available stations denoted N_r. The number of combinations of station pairs (each pair counting one time) is given by

$$N = \sum_{i=2}^{N_r} (i-1). \tag{5}$$

Expression (5) is valid for 3 or more stations. For example, 3 stations results in 3 station pairs, 4 stations yield 6 combinations and so on.

For an example of the use the objective function in Eq. (4), consider a homogeneous half-space model with the constant velocity v = 2000 m/s. An illustration of the setup of the earthquake and stations can be found in Figure 5. The earthquake is located at 7000 m to the right of station $\mathbf{r}_1$ and depth h = 2600 m. For convenience, station $\mathbf{r}_1$ and $\mathbf{r}_2$ have the surface coordinates 0 m and 11000 m, respectively. The time for the recording of the earthquake at station $\mathbf{r}_1$ is calculated with Eq. (1), hence for the homogeneous velocity field with $x =$ 7000 m,

$$T(\mathbf{r}_1, \mathbf{s}) = T_0 + \frac{\sqrt{x^2 + h^2}}{v} = T_0 + 3.734s. \tag{6}$$

In similar veins, the recording time of the earthquake at station $\mathbf{r}_2$ equals

$$T(\mathbf{r}_2, \mathbf{s}) = T_0 + \frac{\sqrt{(L-x)^2 + h^2}}{v} = T_0 + 2.385s, \tag{7}$$

where $L - x$ = 4000 m. The observed differential travel time between station $\mathbf{r}_1$ and $\mathbf{r}_2$ equals

$$\Delta T(d = 11000m) = T(\mathbf{r}_1, \mathbf{s}) - T(\mathbf{r}_2, \mathbf{s}) = 1.349s. \tag{8}$$

Notice that the unknown onset time of the earthquake is eliminated in the equation above. Combining the expressions for the travel times in Eq. (6) and Eq. (7) and the observed differential travel time in Eq. (8), we explicitely obtain for the homogeneous velocity field the objective function

$$L(x, z) = z\left[\Delta T(d = 11000m) - (\frac{\sqrt{x^2 + z^2}}{v} - \frac{\sqrt{(L-x)^2 + z^2}}{v})\right]^2, \tag{9}$$

where an arbitrary earthquake is located at (x, z). A global search method applied on the objective function results in the minimum point at the coordinate point (7000 m, 2600 m) which is the theoretical location of the earthquake in the synthetic experiment. The horizontal - and vertical cross-section of the objective function are shown in Figure 6. Theunissen et al., (2012) carries out an extensive sensitivity analysis of the dtP method in terms of an inadequate velocity model and a poor station coverage. It is concluded in Theunissen et al., (2012) that the dtP method in most cases does a much better job in estimating the focus of an event than the hypocenter method (Lienert et al., 1986). The hypocenter method tends to overestimate the depth parameter because of the depth-origin time trade-off.

The presented synthetic example is constructed for a 2D half-space model and only two stations are strictly required to estimate the focus of an event. The induced earthquakes in Groningen take place in a 3D regional area. Like the general requirements for seismological focus estimation using the difference between P-wave - and S-wave travel times (Aki & Richards 1980), at least three stations must be available in the dtP method. Estimation of the onset time is not the scope of this paper, but would of course possible to estimate.

The Royal Nederlands Meteorological Institute applies the hypocenter method (Lienert et al., 1986) for the location of induced earthquakes in Groningen. The hypocenter method is strongly dependent on the depth-origin time trade-off. According to Lienert et al., (1986), the onset time is defined as the mean arrival times minus the mean travel times. The travel times can only be calculated assuming a given depth of an event. Second, the 1D velocity profile in Figure (7) for the KNMI hypocenter method is an average model for the northern part of the Netherlands. The detailed structures of the overburden, the Zechstein group and Carboniferous group in Groningen are not well-represented in the hypocenter velocity model. Travel time functions based on this velocity structure are calculated with a taup method for epicentral distances to 120 km. Modifications of the 1D velocity model in the hypocenter method did not improve the depth resolution.

5 METHODOLOGY FOR FOCUS ESTIMATION OF INDUCED EARTHQUAKES IN GRONINGEN

Induced earthquakes in Groningen are believed to be caused by a reactivation of existing faults due to compaction after the production of gas was initiated in the late 1960. To get an idea about how compressional - and shear wave energy propagate in the Zechstein group dominated subsurface, a full elastic waveform study was carried out. Naturally, waves in the Groningen subsurface propagate in a 3D half-space. However, the waveform modelling experiment was limited to 2D media to reduce calculation time. The main difference in results between 2D and 3D waveform modelling is the behaviour of the geometrical spreading factor (Aki & Richards 1980; Snieder 2004) which affects the amplitude of wavefields. Hence, it is expected that amplitude effects may be different in observed data compared to synthetic waveforms in the 2D full elastic wave modelling experiment. On the other hand, the phase information in the propagating elastic waves will be identical for 2D and 3D media.

The east-west cross-section in Figure 2 was used as elastic model input in a 2D finite-difference (FD) program (Robertson et al., 1994). The dimensions of the input model was 30 km horizontally and 10 km vertically. The central frequency in the FD modelling was set to 5 Hz which is equivalent to the dominant frequency of recorded induced earthquake data in the shallow boreholes in Groningen. A Q-value equal to 200 is representative for Groningen (Bommer et al., 2016) and was accordingly applied. The top boundary acts as a free surface. The gridsize and temporal step length were adjusted to satisfy the Courant number (Robertson et al., 1994). A proper taper was implemented to reduce boundary reflections.

A simulation of wave propagation in the Groningen subsurface is shown in Figure 8 for a source at 3 km depth. The epicentral distance from the surface coordinate of the source is given in kilometers. Three dominant wave directions are observed. There is the direct wavefield ($\mathbf{1}$) from the source towards the surface. The reservoir has a lower velocity compared to the Zechstein group and the Carboniferous layer and therefore acts as a strong wave guide giving rise to high amplitude waves ($\mathbf{2}$). The underburden with the Carbon group is characterised by a linear gradient velocity. Wave energy propagating downward ($\mathbf{3}$) from the source will be redirected upward in the underburden and eventually be recorded at the shallow borehole stations close to the surface. Finally, internal multiples and interface conversions between compressional - and shear wave energy are part of the propagating wavefield. These latter waves will have longer travel times due to the longer propagation paths and will have low amplitudes because of reflection/transmission effects at layer interfaces (Kraaijpoel & Dost 2013; Aki & Richards 1980; Kennett 1993). Especially, free surface reverberations are clearly visible in the upper part of the waveform snapshots in Figure 8.

The dtP method would be rather time inefficient if the travel time for a wavefield from a given source depth to a station at a certain epicentral distance was repeatedly calculated in a 3D heterogenous velocity model. Instead, a local 1D velocity profile is used to compute a series of travel time functions for a wide range of source depths and epicentral distances. A 1D velocity profile with the RD-coordinate point (Dutch coordinate system: 246877, 593444) from the Loppersum area (i.e., seismic active zone) was extracted from the 3D elastic model. The velocity profile is shown in Figure (7). A narrow moving average window has been used to smooth the velocity profile. Still, the fine structures of the Groningen subsurface are well-preserved. The velocity smoothing was introduced to facilitate the calculation of travel time functions by means of a ray tracing algorithm. A direct solver for the eikonal equation is the workhorse to calculate ray paths for a given source depth and epicentral distance to a station. The travel time between the source and station is calculated using the path integral in Eq. (1). Calculated ray paths and travel time curves are shown in Figure 9 and 10, respectively, for source depths at 2500 m, 3000 m and 3500 m. In general, the direct wavefield is dominant for source depths above the reservoir. On the other hand for source depths at reservoir level or in the underburden, the propagating wavefield consists of direct up-going waves until an epicentral distance about 10-12 km (depending on the source depth) is reached. For longer epicentral distances, diving waves will arrive at the stations. Several examples of direct- and diving waves in event gathers recorded in the dense network have been observed. We refer to the KNMI webpage (http://www.knmi.nl/nederland-nu/seismologie/aardbevingen.html) for examples of events gathers in Groningen.

A regular 3D grid is used to parametrise the misfit function used in the source location. The number of cells in the grid is 100x100x31 (Area$x$Depth). The coordinates for the surface area in RD-coordinates is limited to [228512; 267512] and [569312; 613712], respectively. The depth range is between 2 km and 3.5 km which is where the Zechstein group, Rotliegende gas reservoir and Carboniferous underburden are found.

The dtP method to determine the source location in section 4 consists of two-steps. The first step is the same for all events in Groningen: 1) An imaginary earthquake is located at the center of a cell in the 3D grid. Travel time curves for the general 1D velocity profile in Figure (7) near Loppersum are used to produce estimated differential travel times which are compared to the observed data in the misfit function in Eq. (4) for all possible station pairs. The minimum point of the misfit function is determined with a global search method (Tarantola 1987) resulting in the first iterative estimate of the event focus. 2) The 1D velocity model in Figure (7) is considered to be a too general velocity model for Groningen. The depth resolution of the event in the first iterative focus may therefore still be too inadequate. A second iteration is carried out to get a better idea about the depth of the event. The second step is similar to the first step, except that a new travel time function is calculated for the local velocity profile at the epicenter coordinates found in the first iteration.

To quantify the improvement of the focus estimation of an event, the root mean squared (rms) value of differential travel times is calculated with

$$rms = \sqrt{\frac{1}{N}\sum_{i}^{N}\left[\Delta T_{obs} - \Delta T_{calc}\right]^2}. \tag{10}$$

The rms formula in expression (10) is identical to Eq. (7) in Satriano et al., (2008).

6 RESULTS OF DEPTH ESTIMATION OF INDUCED EARTHQUAKES IN GRONINGEN

Before 2014 the original borehole network was not capable to accurately determine the depth of induced events in the region, due to a large average interstation distance (20 km) and a strong lateral variation of the P- and S- velocities in the upper 4 km of the crust which required the use of average regional velocity models. For the largest recorded event, the 3.6 magnitude induced earthquake on August 16, 2012, only 3 stations were operational within an epicentral distance of 15 km. The epicenter of this event estimated by the dtP method is close to the location reported in the KNMI earthquake catalog. However, it is rather difficult to give a reliable estimate of the focal depth based on these three data points. For many other events for which the determinination of the event was unreliable, the azimuthal coverage was too poor. The depth of events in the KNMI earthquake catalog is by default 3 km. The station density over the Groningen gasfield started to improve in 2014 when new geophone stations were installed. In 2015, the station network was further improved, with about 60 borehole stations in Groningen in the second part of the year. Currently, there are about 80 locations with instruments (i.e., 3-component geophones and accelerometers) from the old and new network.

A total of 37 events from February 2014 to December 2015 were processed with the two-step dtP method. Three events on March 15th, 2014, June 6th, 2015 and July 18th, 2015 are presented and discussed below. These events were selected based on their location at three different depth intervals. The setup is the same in all figures. The error on the depth is obtained by propagating the discrepancy between observed and calculated traveltime differences for each station pair into the misfit function. Hereby, the total misfit function curve get shifted in the vertical direction. The shift of the minimum point of the misfit function is an indication of the error of the depth. The epicenter location is much less sensitive to errors between the observed - and calculated travel times.

Results for the first event, March 15, 2014, are shown in Figure 11. All stations used in the procedure are located to the western side of the epicenter. The distance between epicenters calculated with the hypocenter - and dtP method is about 1.5 km. The "petal" pattern of the misfit function illustrates the lateral variability of stations due to the maximum epicentral distance of the pre-calculated travel time functions. The average over the number of station-pairs in Eq. (4) takes into account the effect of a variable number of station pairs. The misfit function indicates a depth of the induced earthquake about 2850 $m \pm 100$ m. Notice the vertical cross-section of the misfit function is similar to the vertical profile of the misfit function in the synthetic experiment in Figure 6. The east-west cross-section of the detailed 3D elastic model together with the estimated focus of the induced earthquake shows that the event took place in the Rotliegend gas reservoir. This result applies to most of the processed events. The depth of the second event on June 6th, 2015 (Figure 12) is calculated at 3150 $m \pm 100$ m. This is in the lower part of the gas bearing sandstone reservoir or in the underburden. Similar to the second event, the estimated epicenter of the third event on July 18th, 2015 (Figure 13) is well-surrounded by stations. The distance between the epicenters determined by the two methods is less than 500 m. The misfit function indicates that the depth of the event is about 2200 $m \pm 150$ m. The event location coincides with the upper aanhydrite and a graben structure in the Zechstein group. The upper anhydrite layer in the Zechstein layer is much closer to the Rotliegend gas reservoir compared to the neighbouring structure. The anhydrite layers are made of stiff, brittle material. The magnitude of this event is 0.7 according to the KNMI earthquake catalog. A few more events (i.e., June 30, 2015; November 9, 2015; November 10, 2015; December 8, 2015) with magnitudes in the range [0.5; 0.8] have also been located in the upper anhydrite layer. Information about the depth, rms-values and errorbars on the depth of induced earthquakes is available in table 1. From this table, one can see that the epicenter estimated by the hypocenter - and dtP method are comparable. The depth range of the events is between 2200 m and 3200 m with the majority between 2700 m and 3100 m (i.e, reservoir depth). The error on the depth is often between 100 m and 200 m. Figure 14 shows the resulting event depth distribution related to the number of events (A), the magnitude (B) and the structural information (C). Most events are centered around 2700 m with five shallow events in the anhydrite layer and others in the underburden. It does seem possible to have induced earthquakes in the overburden with the Zechstein group and in the carboniferous underburden.

With respect to the magnitudes, the trend is clear. Induced earthquakes at the shallow anhydrite layer within the Zechstein group have a small magnitude less than 1.0, while events at reservoir level can be weak as well as stronger. One possible explanation for the overburden events in the upper stiff anhydrite layer, which has a limited vertical dimension of 30-50m (van Gent et al., 2011), is that the layer simply breaks. An alternative explanation may be the increase in horizontal stress above the compacting reservoir, which may lead to movements along existing fractures in the anhydrite layer.

The structure of the Rotliegend gas reservoir in Groningen varies laterally. For an illustration of the gas reservoir structure, we refer to Figure (2). At the reservoir boundaries (i.e., north, east, south and west), the reservoir is deeper, while close to Loppersum in the central part of Groningen the reservoir is somewhat more shallow. By visual inspection, the structural location (i.e., upper anhydrite layer, top reservoir and lower reservoir/underburden) of all 37 events was determined. The histogram in Figure 14 shows the distribution of the structural location of the 37 induced earthquakes. The majority of the events are found at reservoir level, with about half and half in the top reservoir and in the lower reservoir/underburden, respectively. A small number of induced events (about 10 $\%$) are located in the upper anhydrite layer (i.e., top floater).

In 2014, the mining company (NAM) installed two deep boreholes at 3 km depth in the reservoir in the Loppersum area near the villages Stedum and Zeerijp. The wells are equipped with 3-component geophones at reservoir level. The lateral distance between the two wells is 3 km. Local micro seismicity is reported and analysed by the mining company. Focal depth estimates of recorded induced earthquakes are ranging between 2400 m and 3200 m with a cluster of events at reservoir level between 2800 m and 3100 m (Pickering 2015). By visual inspection of the magnitude distribution, it can be seen that events with a magnitude above one are mainly between 2800 m and 3000 m (i.e., reservoir depth).

A comparison of the epicenters calculated using the hypocenter - and dtP method of all the processed induced earthquakes is shown in Figure (15). The fault structure and a background image of the province of Groningen are included in the figure. The estimated epicenters by both methods seem to follow two main lines on the NW-SE aligned fault system. One trendline of events is more towards to the city Delfzijl and the other one is shifted towards the city Groningen. The epicenters by the hypocenter - and the dtP method are often located on or near a fault. We are well aware of the possibility that there are mapped - and unmapped faults in the current fault model. For several events, the epicenter estimated by the two methods may not necessarily correlate with the same fault. Most epicenter solutions for the same event differ less than 1 km.

7 CONCLUSIONS

Due to the installation of a new dense borehole network, a sub-set of the hydrocarbon induced earthquakes recorded in the province of Groningen (Netherlands) have been relocated. Especially the depth of the events, which was fixed in the original location procedure, could be calculated with an average resolution of 100-200 m. Besides the new network, the availability of a detailed 3D velocity model and new location methods were essential to obtain these results

A differential travel time approach similar to the EDT method (Lomax 2005; Theunissen et al., 2012) was applied to the hypocenter estimation of the induced earthquakes in Groningen. Instead of defining a misfit function based on the travel time residuals for single stations, the residual of differential travel times between stations is used in the objective function. The total misfit function is obtained by summing the contributions of differential travel times residuals from all station-pairs for one event. By minimising the misfit function by means of a standard global search method, the hypocenter of the event and the uncertainty in the depth parameter are calculated. As a rule of thumb, at least 3-4 stations with epicentral distances shorter than 5-8 km must be available in order to obtain an estimate of the event depth. The epicenter is much easier to measure even when applying stations located farther away or the azimuthal coverage is poor.

The dtP method was applied to 37 induced earthquakes between 2014 and 2015. For earlier events recorded before 2014, the station network was too sparse. Most of the located events are found at the reservoir level. Five events with a magnitude about 0.5-0.8 are found near a stiff basalt-anhydrite layer in the Zechstein group. It is observed that the magnitude of the events is weaker in the overburden while a range of weak to stronger events take place in the reservoir compartment and uppermost part of the underburden. A possible explanation can be the increase in horizontal stress above the compacting reservoir, which may lead to movements along existing fractures in the anhydrite layer The estimated epicenters for events at reservoir level correlate well with the mapped fault system in Groningen.

The developed method for hypocenter location of induced earthquakes will be applied to future recorded events in Groningen. It is expected that the dtP method will soon be implemented as a module in the automatic location program (seisComP3 by Gzf and Gempa). The database of induced events is an essential ingredient for hazard and risk studies (Bommer et al., 2016).

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Table

Event date	**Magnitude**	**Hypocenter method** x (m)	y (m)	**dtP method** x (m)	y (m)	z (m)	RMS (s)	Vertical error (m)
20140213021314	3.0	247804	597489	246842	596840	3100	0.005	100
20140218050332	1.7	239854	595190	238652	595064	3200	0.008	100
20140315190924	1.9	254023	591918	252692	592844	2850	0.0035	100
20140318211518	2.1	236868	600981	237872	599948	2750	0.034	200
20141230023736	2.8	244601	581022	244502	581300	2700	0.02	100
20150106065528	2.7	247027	593926	246842	593732	3150	0.041	150
20150204223447	1.1	251236	594509	250742	595064	3300	0.059	300
20150225100256	2.3	252914	593969	255252	594620	2700	0.067	200
20150516141449	1.6	252285	592100	252302	591956	2700	0.017	100
20150606233915	1.9	245771	595702	246062	595952	3150	0.035	100
20150610022607	1.8	245963	596151	245672	595952	3250	0.03	250
20150610142127	0.8	243297	596212	243722	596840	2800	0.028	250
20150630005300	0.5	241571	588500	241772	588848	2400	0.055	200
20150704180758	1.1	242019	596857	242162	596840	2700	0.016	200
20150718073714	0.7	253595	587841	253472	587516	2200	0.019	150
20150718234729	0.5	246816	579358	246842	579524	2500	0.007	100
20150721021804	1.3	249319	594880	249572	594620	2900	0.004	100
20150730153452	0.7	247571	578371	248402	579524	2650	0.03	100
20150818070612	2.0	246365	578459	246062	579080	2850	0.024	100
20150822001230	1.4	246365	578459	244892	584852	3050	0.08	100
20150828080727	1.3	251120	581446	250352	582188	2800	0.05	100
20150905033430	0.5	244594	576645	244892	577304	2850	0.01	100
20150909200151	1.2	242754	582176	244112	583076	2550	0.03	200

Table 1. Source locations obtained with the KNMI hypocenter - and the dtP method. RD coordinates are used for the epicenter location. The rms value and errors for the depth estimate in the dtP method are indicated.

		Hypocenter method		**dtP method**				
Event date	**Magnitude**	x (m)	y (m)	x (m)	y (m)	z (m)	RMS (s)	Vertical error (m)
20150930180537	3.1	251603	584016	251522	584408	3200	0.02	200
20151009002719	0.3	251531	590916	251522	590180	3050	0.002	100
20151010055148	0.2	249281	586641	250352	586628	2950	0.029	200
20151011044142	0.3	253016	576920	253082	577304	2700	0.021	100
20151027154628	1.2	245818	593254	246452	594176	3150	0.032	300
20151030160718	1.7	247535	590615	247232	590180	2600	0.045	250
20151030184901	2.3	257224	589810	255812	588848	2700	0.012	100
20151109131737	0.7	259445	585850	258932	585296	2300	0.033	300
20151110163223	0.6	249130	584078	251522	584852	2500	0.034	100
20151112123009	0.6	243045	580846	244892	582188	2800	0.02	100
20151202064002	1.6	251725	584575	251132	585296	2750	0.04	200
20151208035422	0.8	240451	595159	240212	594620	2200	0.055	200
20151215000150	1.6	255247	595000	255032	595508	2550	0.004	100
20151215074355	1.7	236168	588406	235922	589292	3250	0.039	250

Table 2. Cont. table 1. Source locations obtained with the KNMI hypocenter - and the dtP method. RD coordinates are used for the epicenter location. The rms value and errors for the depth estimate in the dtP method are indicated.

Figures

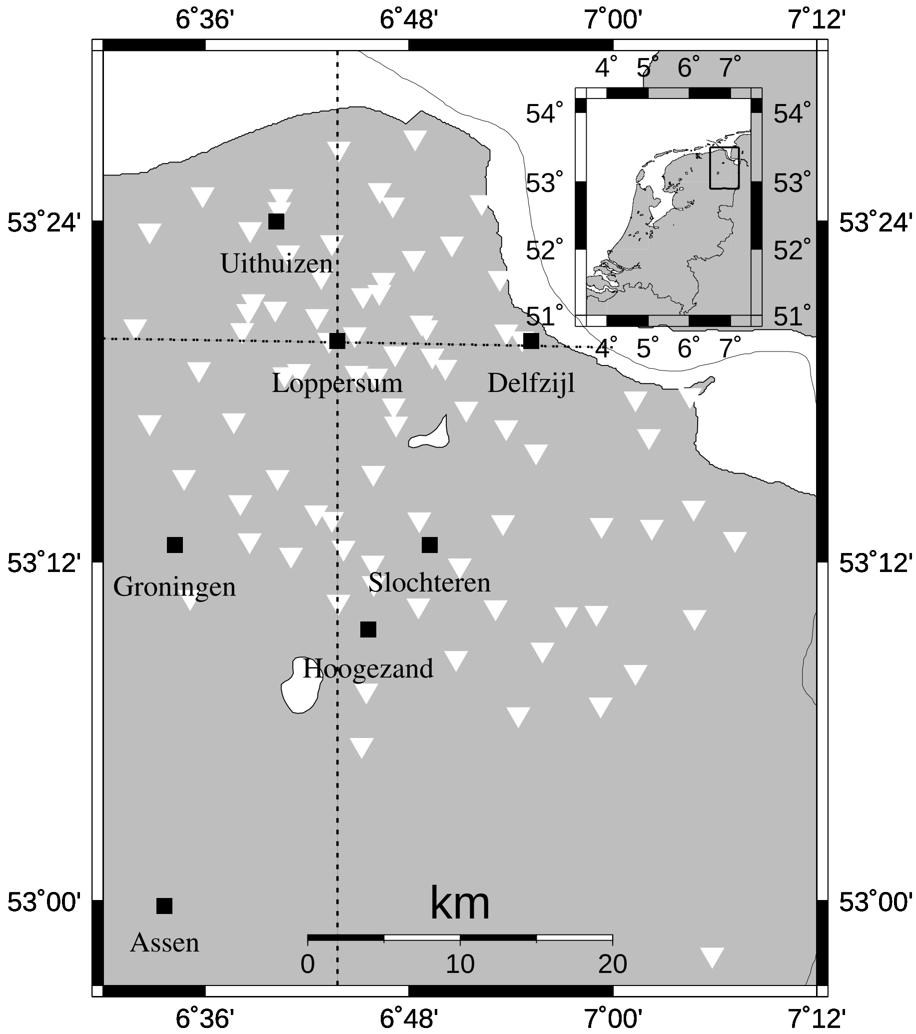

Figure 1. Location of the province of Groningen in the north-east of the Netherlands. Larger cities in Groningen are indicated with a square, while station locations are shown with white triangles.

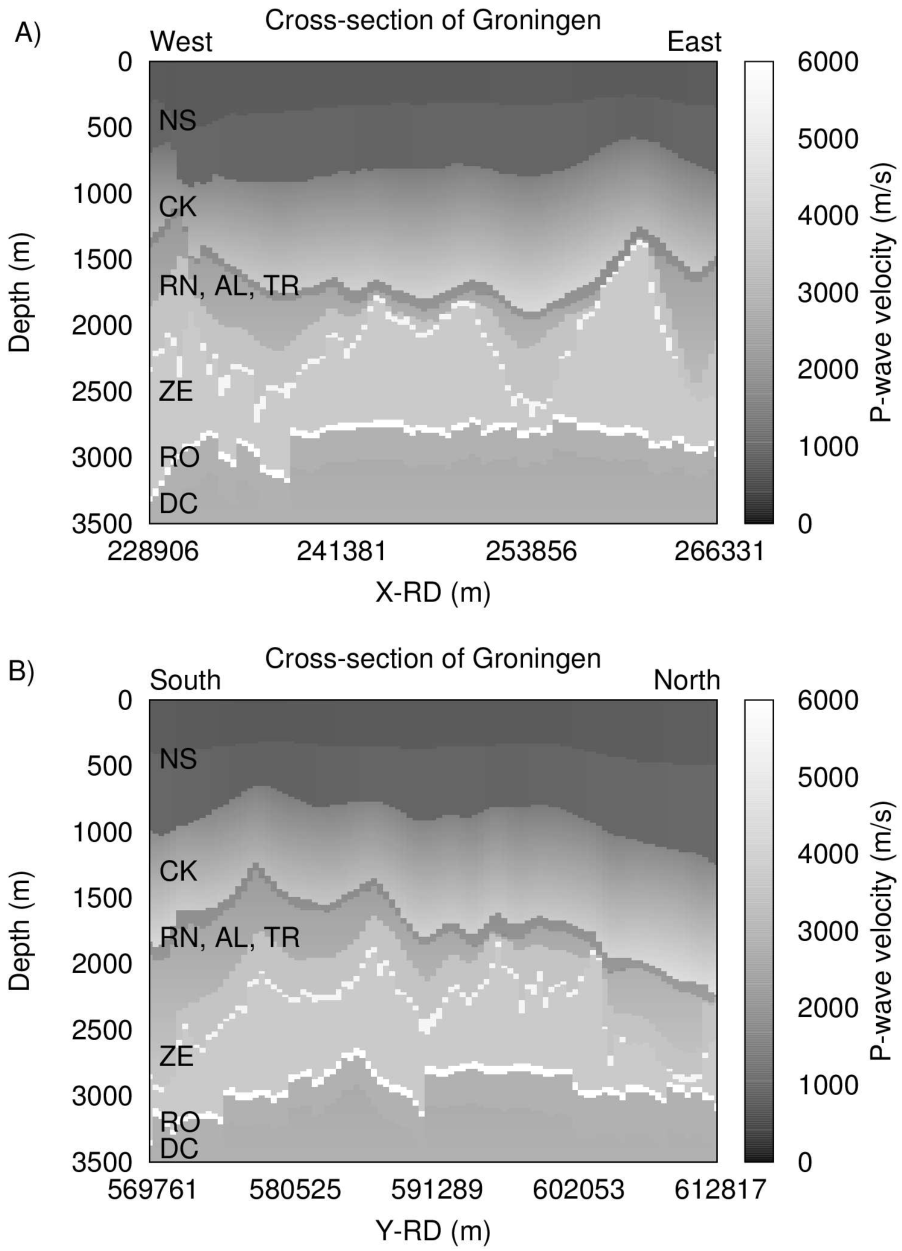

Figure 2. The 3D velocity field of Groningen. The crossing point for the two perpendicular cross-sections is located in the central field. A) West-east cross-section. B) South-north cross-section. The scaling factor between the horizontal and vertical direction is 13. Data courtesy of NAM.

A)

B)

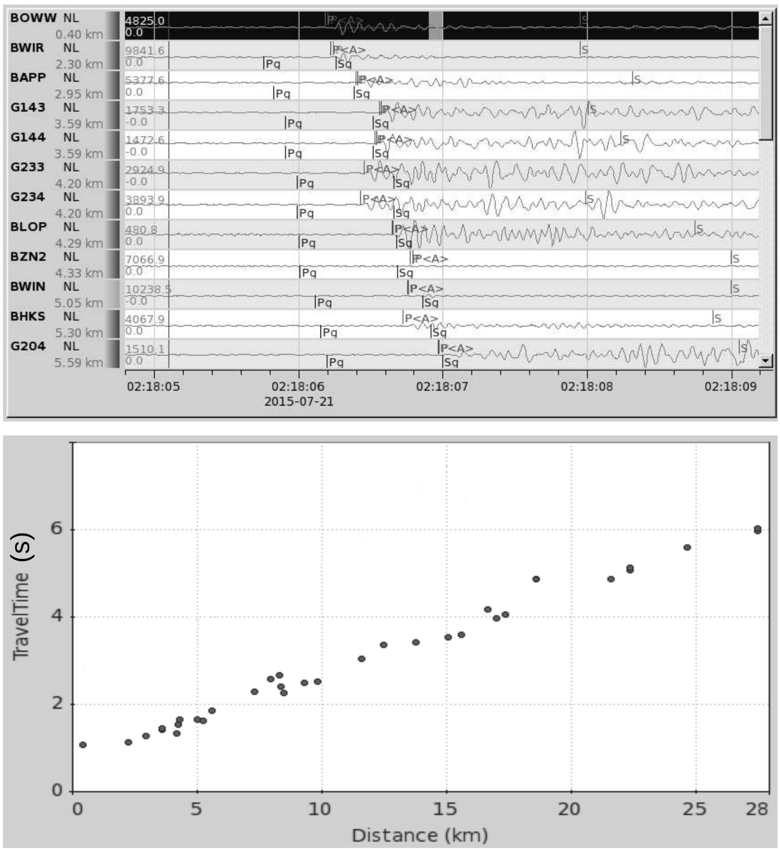

Figure 3. Example of recorded waveforms and an observed travel time curve for an induced earthquake on July 21st, 2015.

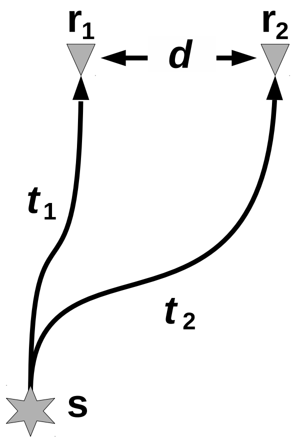

Figure 4. Concept of the differential time for P-phase method. Body waves propagate from an earthquake indicated with the grey star to the two receivers $\mathbf{r}_1$ and $\mathbf{r}_2$. The receivers are illustrated with the grey triangles. The epicentral distance between the receivers is denoted by d. The travel time for the waves is t_1 and t_2 for the first and second station, respectively.

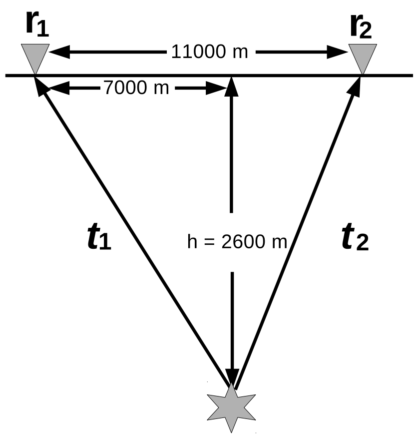

Figure 5. Synthetic example of depth estimation of an earthquake. The arrival times t_1 and t_2 of the propagating waves from the earthquake are recorded at the two stations $\mathbf{r}_1$ and $\mathbf{r}_2$, respectively.

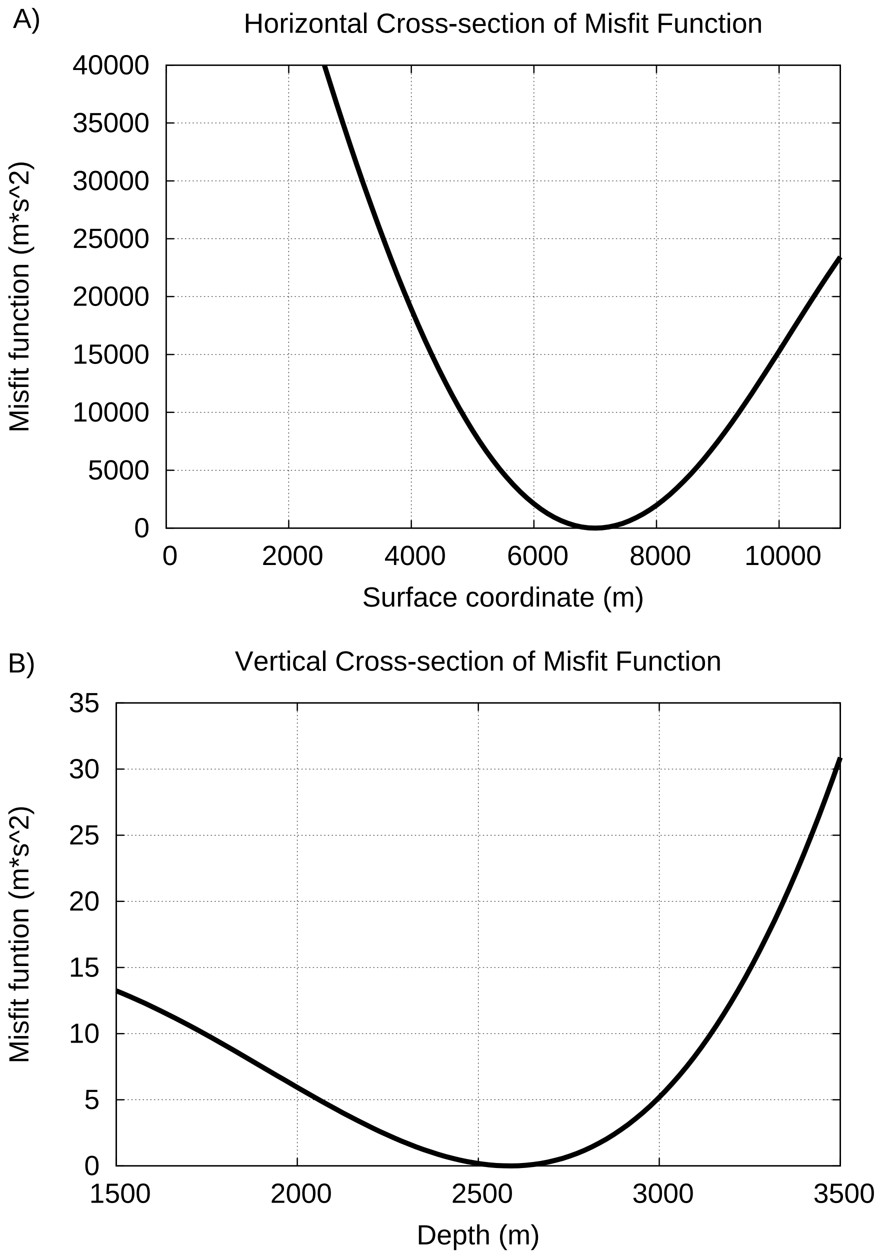

Figure 6. Misfit function for the synthetic example with a homogeneous velocity field. A) The horizontal cross-section for fixed depth value, $h = 2600\,m$. B) The vertical cross-section for fixed value of the surface coordinate, $x = 7000\,m$.

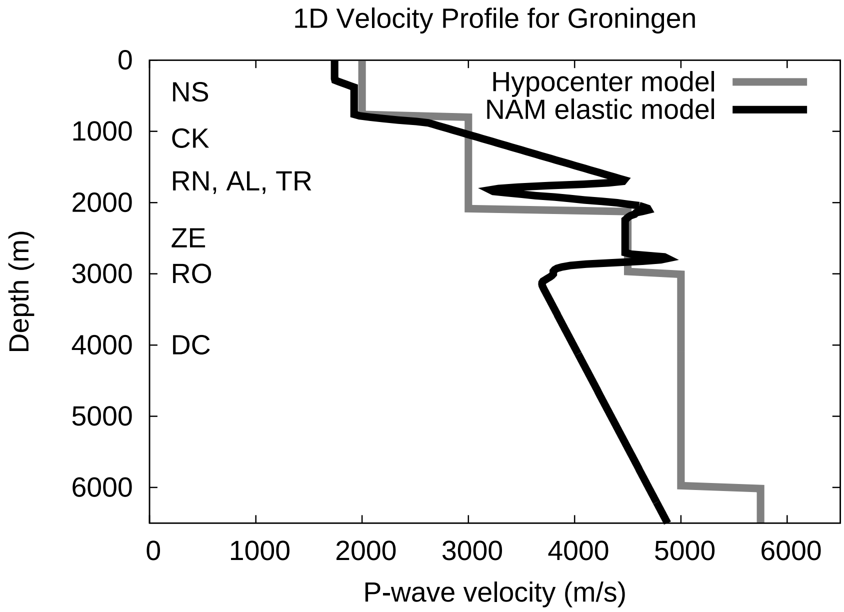

Figure 7. Example of the 1-D P-wave velocity profile (black solid line) that is used to calculate depth-dependent travel time curves. The grey solid line shows the 1D velocity model applied in the hypocenter method.

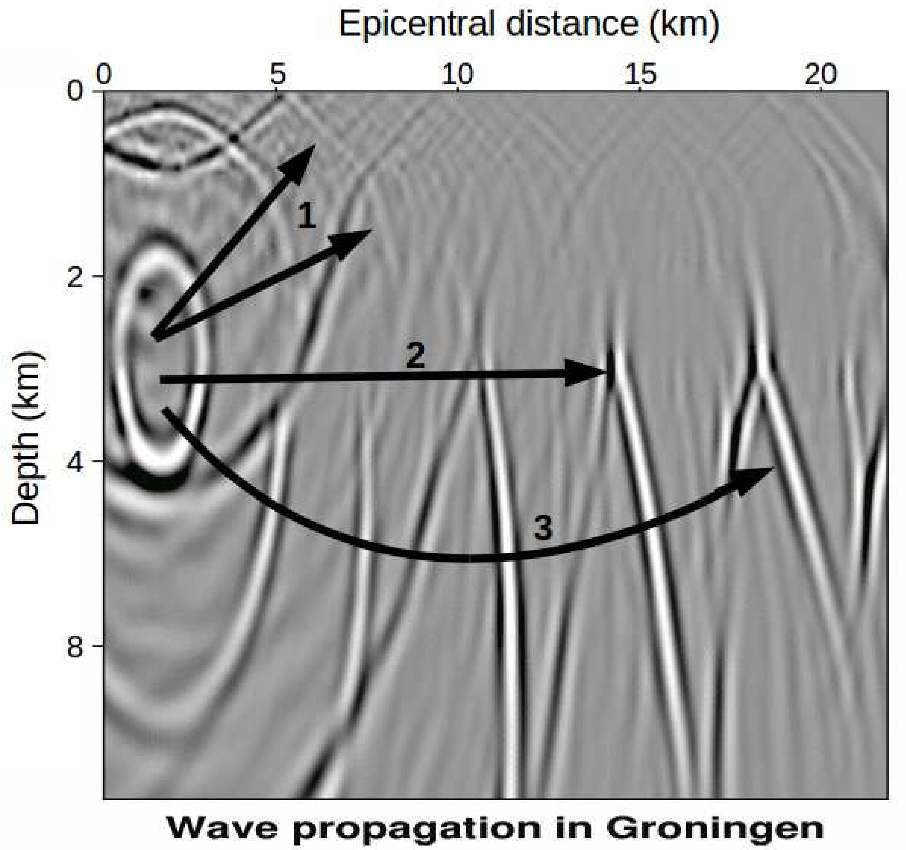

Figure 8. Illustration of principle components of wave propagation in the complex Groningen subsurface. The source depth is 3 km

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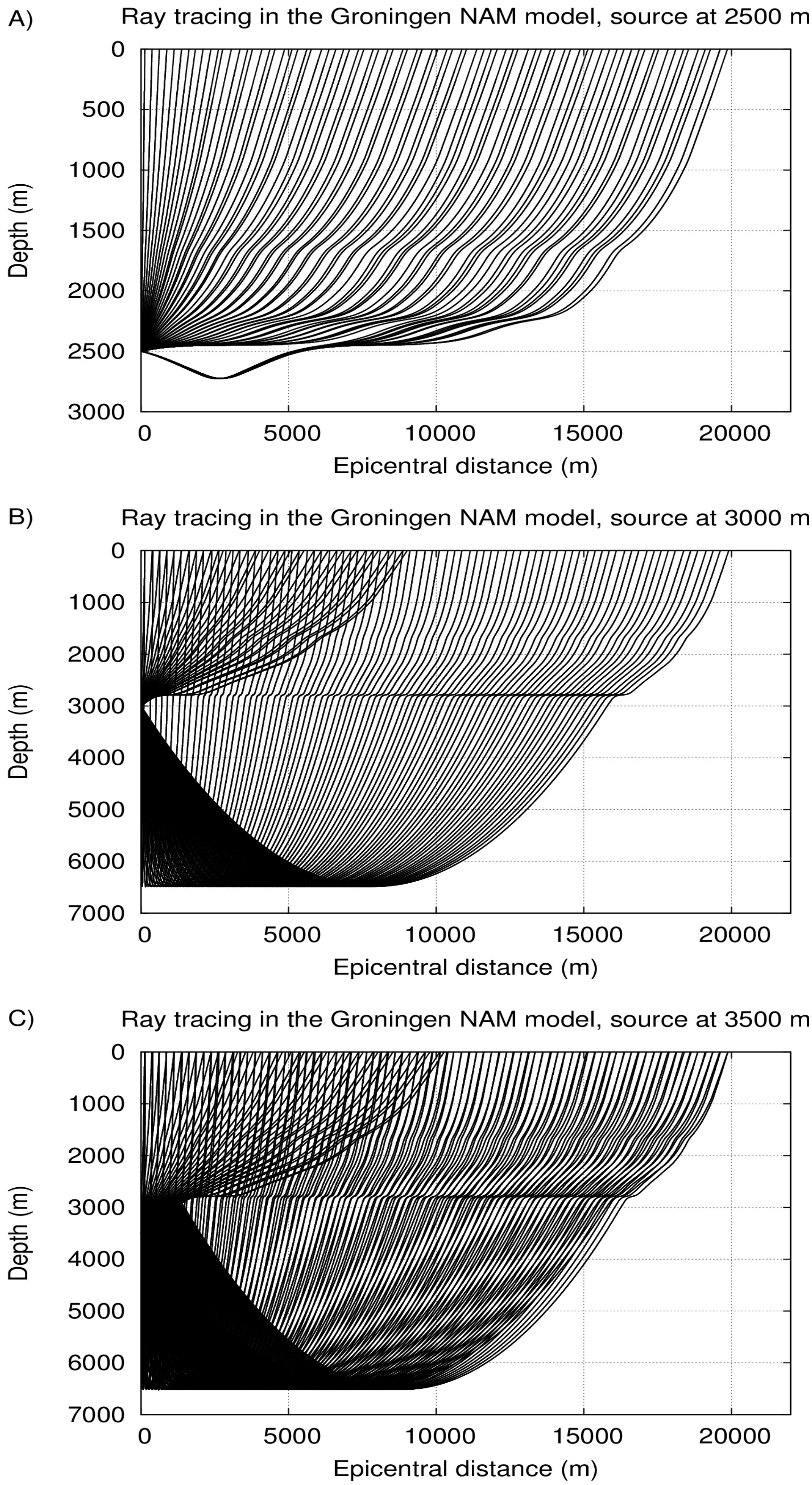

Figure 9. Ray tracing in the complex Groningen subsurface. A) The source depth is 2500 m. B) The source depth is 3000 m. C) The source depth is 3500 m.

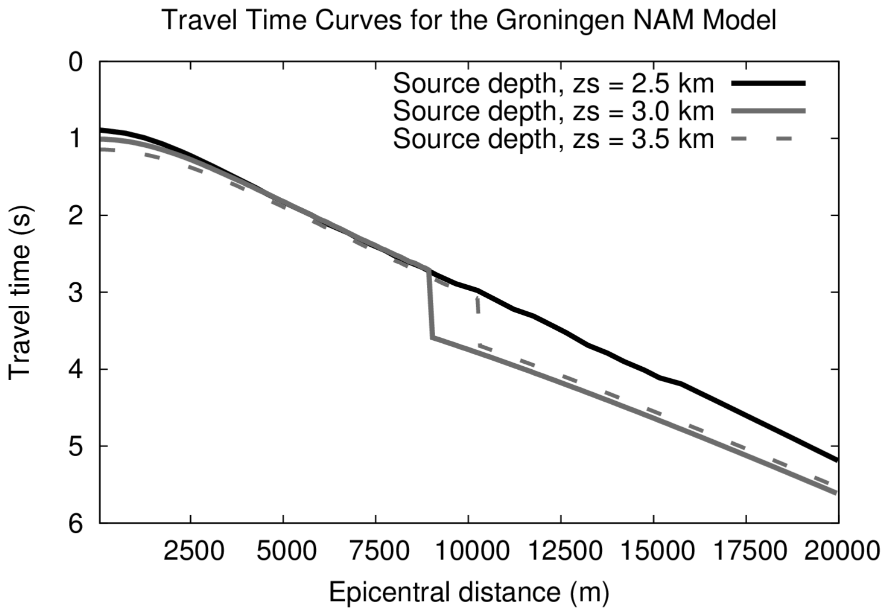

Figure 10. Travel time curves for a source depth at 2500 m, 3000 m and 3500 m.

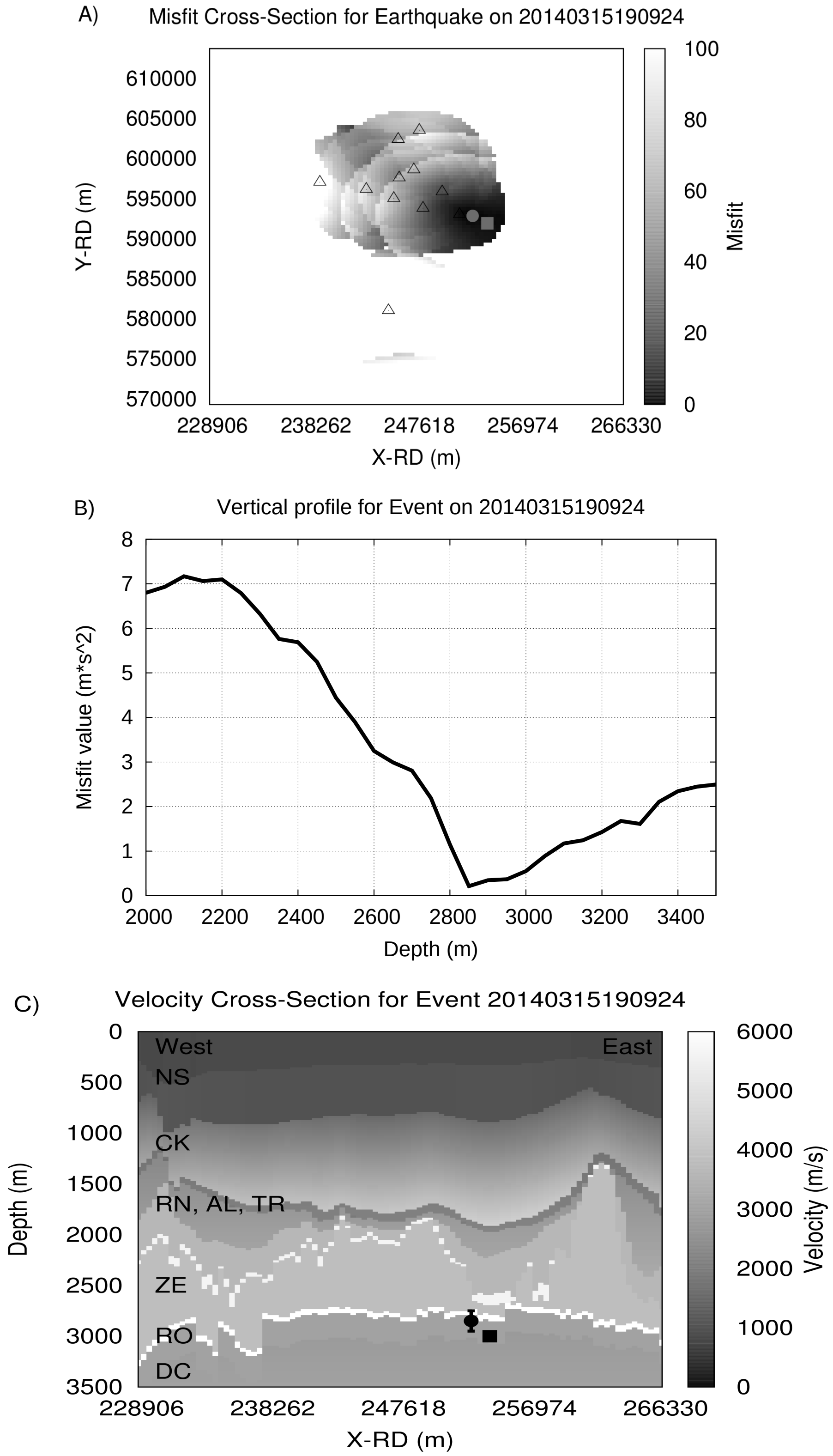

Figure 11. Focus estimation of the event on March 15th, 2014 at the time 19h09m24s. A) The horizontal cross-section of the misfit function at estimated source depth. Stations are plotted with triangles. B) The vertical cross-section of the misfit function at the estimated surface coordinate. C) West-east cross-section of the 3D NAM elastic model with the location of the earthquake. The KNMI hypocenter location is indicated with the filled square while the estimated focus in the differential time method is shown with the filled sphere and vertical errorbar.

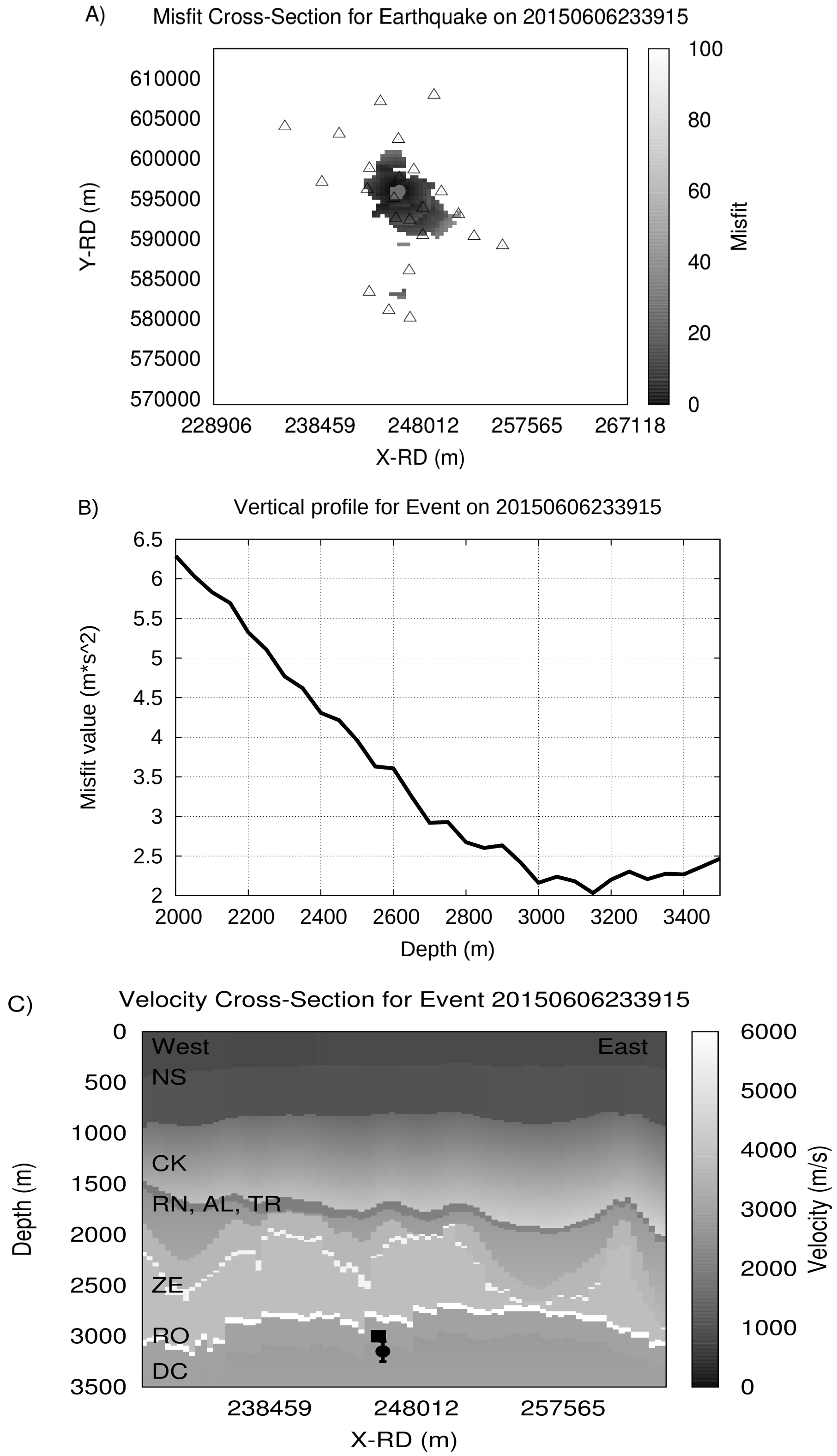

Figure 12. Focus estimation of the event on June 6th, 2015 at the time 23h39m15s. Identical setup as in Figure (11.

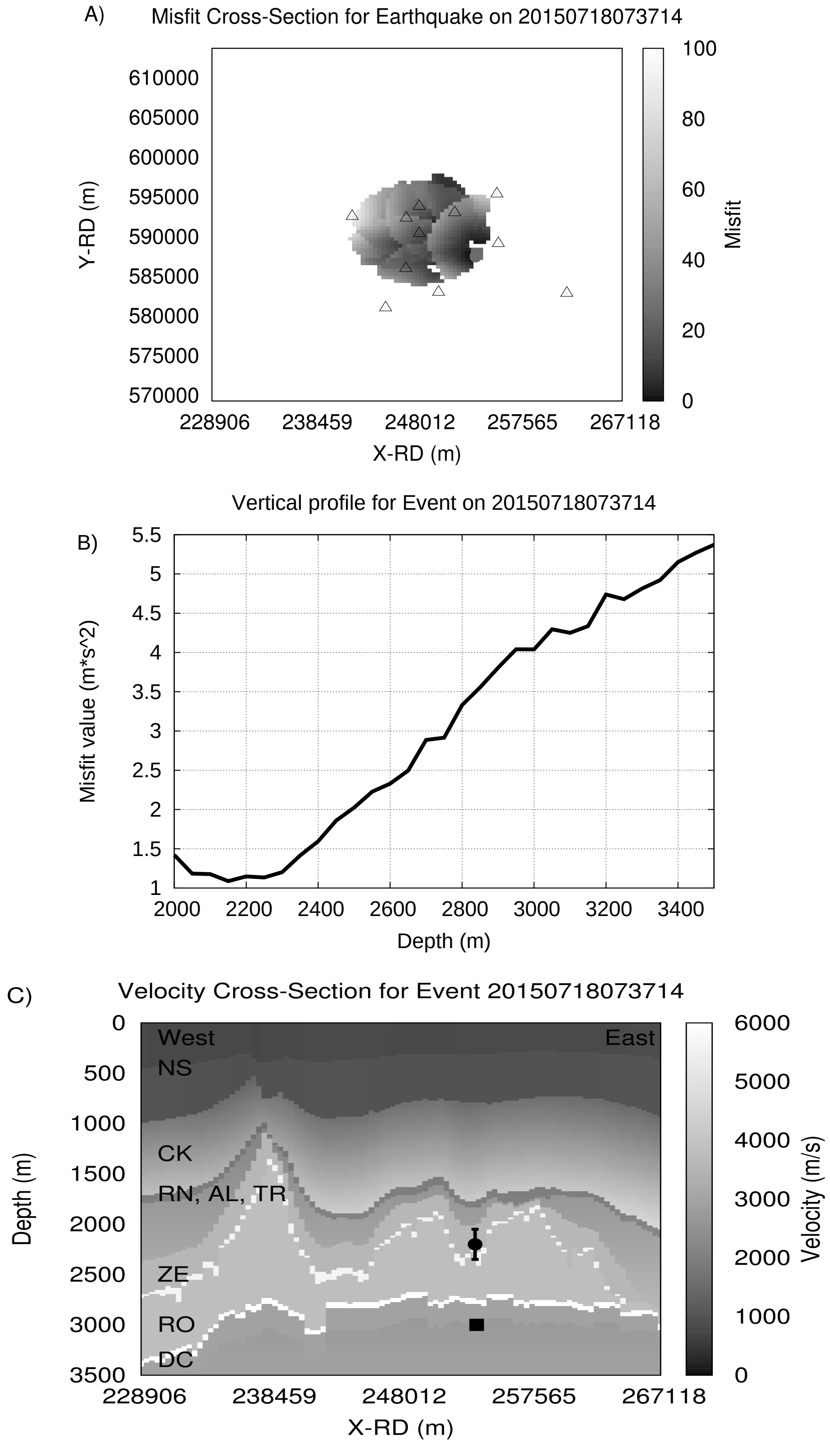

Figure 13. Focus estimation of the event on July 18th, 2015 at the time 7h37m14s. Identical setup as in Figure (11.

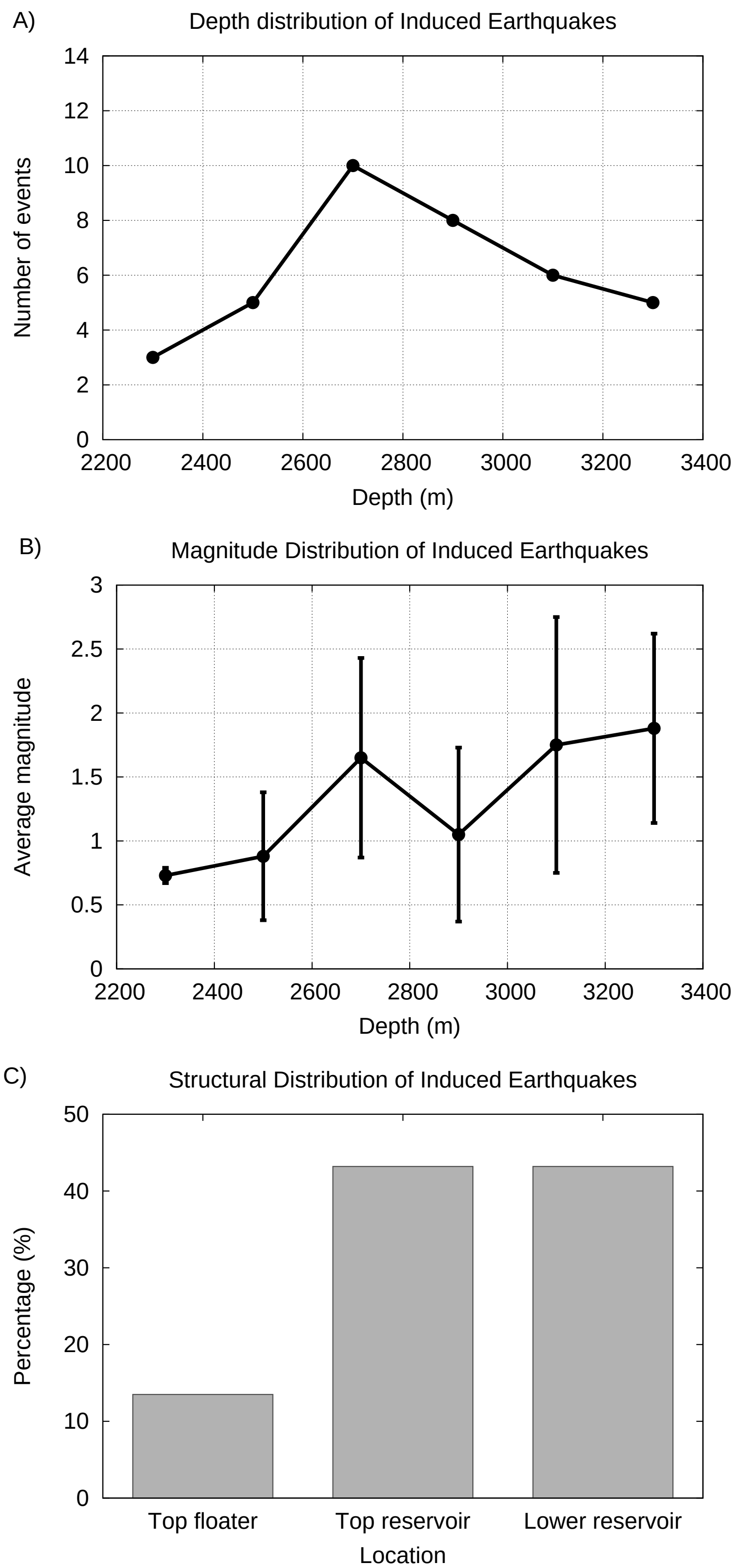

Figure 14. Simple statistical analysis of the assessed induced earthquakes A) Depth distribution. B) Magnitude distribution. C) Structural distribution.

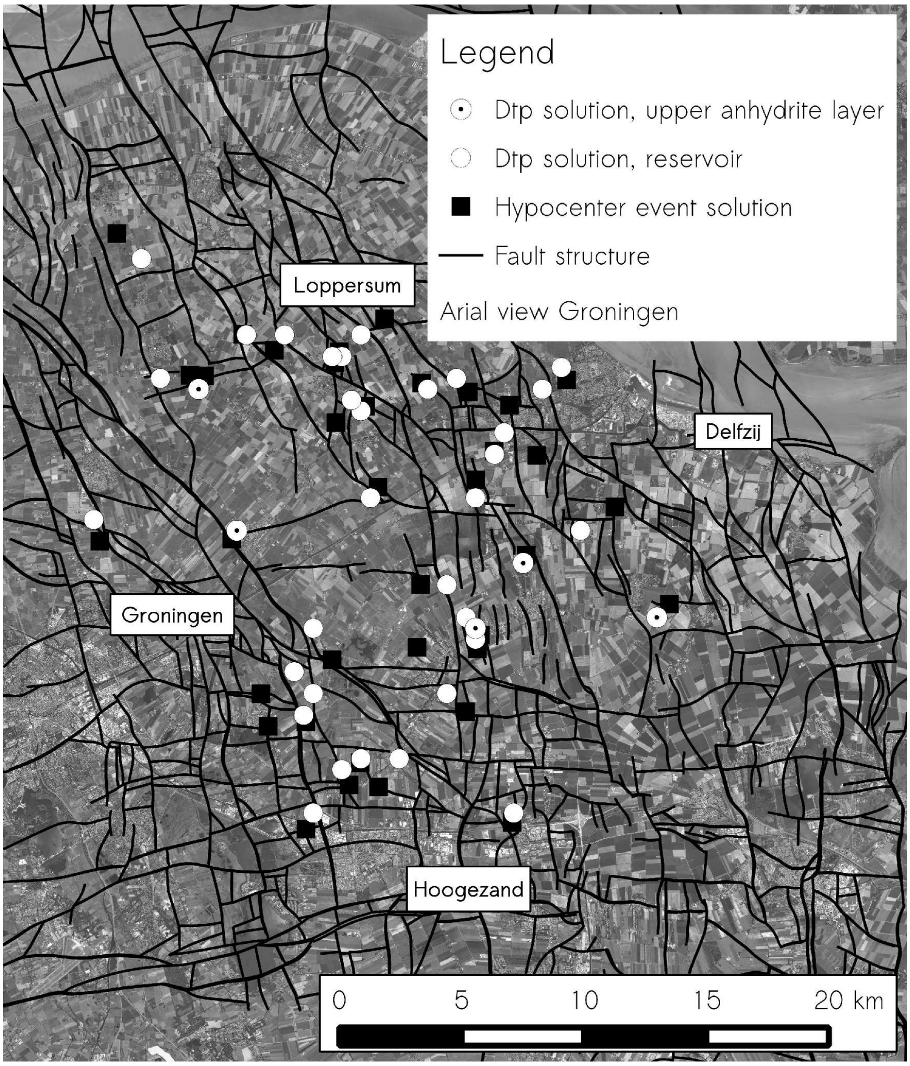

Figure 15. Map of the province of Groningen with epicenters estimated with the hypocenter method and the differential travel time approach for selected events in 2014 and 2015. The black squares and white circles indicate epicenters from the hypocenter method and the differential travel time method, respectively. The square and circle closest to each other are derived from the same induced earthquake. The NW-SE aligned fault system is illustrated with black lines.


6 E
6.5 E
7 E
7.5 E
53.5 N
53 N
Aurich
Uithuizen Kern
Emden
Delfzijl
Appingedam
Bedum
Zuidhorn/Noordhorn (Gr.)
Groningen
Leer (Ostfriesland)
Leek
Winschoten
Drachten
Oude Pekela-Kern
Papenburg
Assen
Musselkanaal
Ter Apel
Hoogeveen
Meppen


6 E
6.5 E
7 E
7.5 E
53.5 N
53 N
Aurich
Uithuizen Kern
Emden
Delfzijl
Appingedam
Bedum
Zuidhorn/Noordhorn (Gr.)
Groningen
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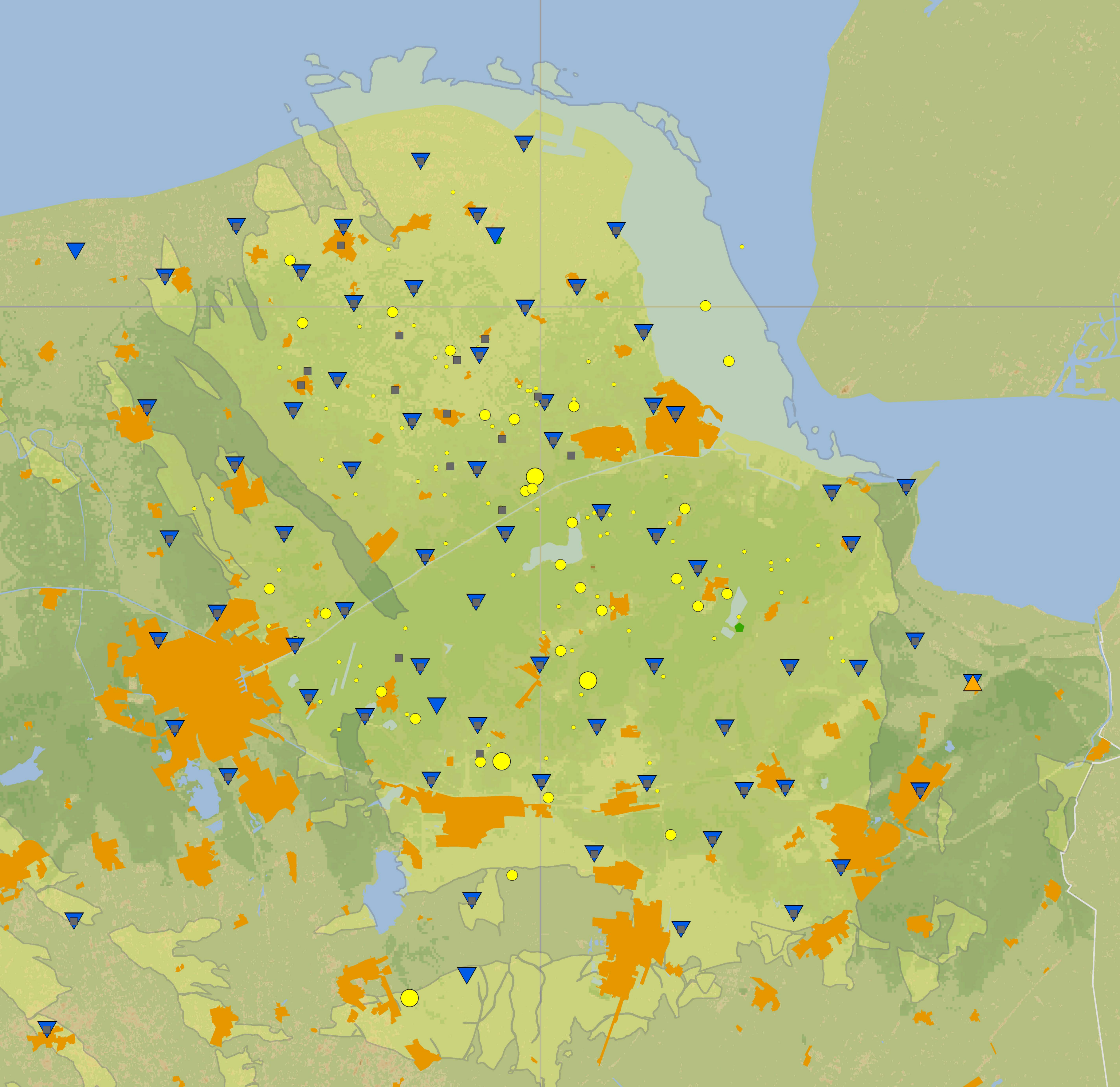
Leek
Winschoten
Drachten
Oude Pekela-Kern
Papenburg
Assen
Musselkanaal
Ter Apel
Hoogeveen
Meppen



G550
Nieuweweg
Het Loeg
Borgercompagniesterweg
G540
N962
Middenweg
Egypteneinde
Benedenoosterdiep
G580
Veendammerweg
Lloydsweg
N963
Borgercompagnie
Kielsterachterweg
Dorpsstraat
Sorghvlietlaan
Boven Oosterdiep
N366
Provincialeweg
ZL21
Woortmanslaan


G550
G540
G580
ZL21
N962
N963
N366
Nieuweweg
Borgercompagniesterweg
Borgercompagnie
Kielsterachterweg
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Veendammerweg
Het Loeg
Middenweg
Egypteneinde
Beneden Oosterdiep
Boven Oosterdiep
Lloydsweg
Sorghvlietlaan
Provincialeweg