Microseismic pilot study in the Bergermeer field
Summary of results

10.2.e.

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Introduction This report summarizes the results from the pilot study for microseismic monitoring in the Bergermeer field from January 15 to February 24 2010. This gas field is being developed as gas storage facility.

The KNMI was asked to give independent expert advise on the analysis carried out by the contractor, Magnitude. The monitoring consisted of the operation of a downhole tool at reservoir level, 2 km depth, for a period of five weeks. The test was designed to include two weeks of inactivity and three weeks of active gas injection.

The downhole tool consisted of a string of six three-component geophones, with a spacing of 15 meter between the sensors. Data was stored continuously and made available to the KNMI, where analysis was carried out using the NORSAR MIMO software.

The reason for independent analysis is the occurrence of four seismic events in the past during the gas production from the Bergermeer field. The magnitudes of these events were between 3 and 3.5 on the Richter scale and caused damage (*KNMI* (1994a) and *KNMI* (1994b);*Haak et al.* (2001)). The events have been associated to a central fault in the gas field (see *Dost and Haak* (2007)), but no smaller events were recorded.

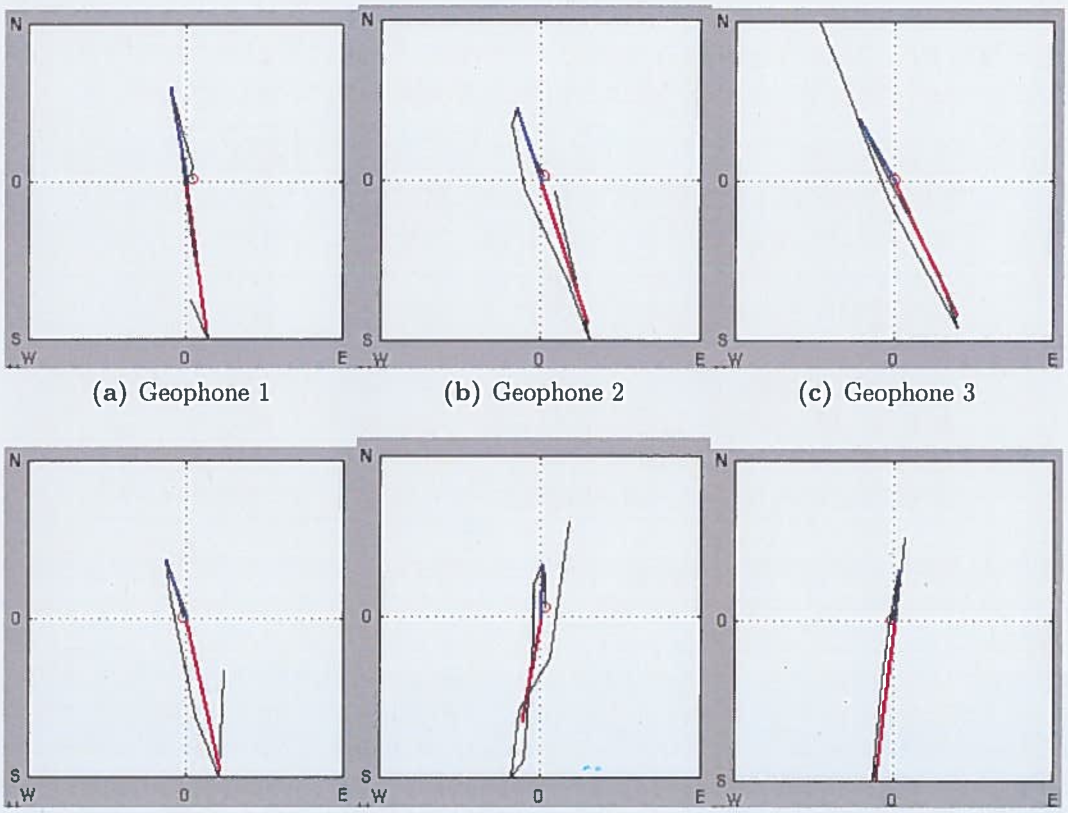
Microseismic monitoring is expected to give new insights in the re-activation of existing faults, opening the possibility to adapt the injection strategy in case of an increase in microseismic activity.

In this summary the highlights are presented, where first the results of the analysis of the sensor orientation are reported, which is essential for the location of events, and secondly the locations.

Sensor orientation Each sensor measures ground motions in three orthogonal components (X,Y,Z), in a left-handed configuration. After initial deployment of the tools, the absolute orientation (azimuth and tilt) of the sensors is unknown. Two check-shots from borehole BGM3A, at a distance in the order of 500m, have been used to constrain the orientations. The initial ground motion due to an explosion is expected to be away from the source. Therefore the polarization direction of the first arriving waves gives an indication of the direction of the source with respect to the sensor components.

The transformation of the ground motions from the left-handed sensor coordinates to the right-handed coordinates (East, North, Up) used in the seismic analysis we refer to as sensor calibration. This calibration basically involves a polarity-flip of a single component and a rotation. The Y-component has been flipped to obtain a right-handed coordinate system. Next, the azimuthal rotation has been determined for each sensor with use of the test shots.

In their initial analysis Magnitude made an error in the calibration procedure, leading to erroneous orientation estimates and locations. Our results led them to review and revise their results as reported in *Fortier* (2010). With regard to the azimuthal rotations there is still a discrepancy between our results and theirs. It seems that sensors 4 and 5 are flipped in the tool orientations obtained by magnitude with respect to our analysis. The ground motions from the check-shots are rather weak and the interpretation of the polarization of the initial arrivals may be debated. However, the much stronger motions due to the event on Feb. 18 (see next Section) and the hodograms for the test shot (Figure 1) confirm our interpretation.



(a) Geophone 1 (b) Geophone 2 (c) Geophone 3

(d) Geophone 4 (e) Geophone 5 (f) Geophone 6

Figure 1: Hodograms of the calibration shot for each different geophone in a map view. The blue line indicates the relative direction of first movement and the red line indicates the relative direction of the calibration shot.

In conclusion: As a result of our re-analysis of both polarity and orientation of the sensors, the original results of the contractor had to be revised, resulting in a correction of the locations of the microseismic events.

Microseismic event locations In this analysis a simple homogeneous model is used, characterized by a P-velocity of 4500 m/s and a corresponding S-velocity of 2580 m/s using Castagna's relation (*Castagna et al.*, 1985).

During this pilot project on the Bergermeer field nine microseismic events are detected. P- and S-wave onset times are picked for each of these events and polarizations are determined automatically in a 0.01 s time window after the P-onset. These onsets and the polarization are inverted for the source location. Result are shown in Table 1 and Figure 2 to 4. The waveforms of each event are plotted in Figures 5 to 13. Errors in the locations have been analyzed. However, we do not feel that the procedures used by MIMO give satisfactory results. It is recommended to discuss this with the MIMO developers. It should be noted that all of these events are detected in the period of injection, starting only one day after the first injection. Magnitudes determined are between the -2.5 and -2.0 and the location of most events is near the central fault, which is assumed to be reactivated.

Event time	East(X)	North(Y)	Depth(Z)	Mw
2010-02-02 14:15:29.5019	108813.9	518787.8	-2565.6	-2.0
2010-02-02 14:30:58.2141	108710.3	518841.2	-2399.7	-2.0
2010-02-05 12:30:24.7202	108835.4	518973.0	-1972.7	-2.0
2010-02-06 16:23:53.7658	108875.4	518688.5	-2229.3	-2.2
2010-02-09 21:03:48.8901	109009.2	518328.9	-2153.3	-2.4
2010-02-13 18:29:10.9153	109441.1	518360.4	-2200.3	-2.3
2010-02-14 00:57:39.7234	108732.7	519023.9	-2251.9	-2.1
2010-02-15 03:39:37.8415	109048.2	518749.5	-2348.1	-2.5
2010-02-18 05:30:30.8943	108892.4	518877.3	-2103.9	-2.0

Table 1: Events with their origin time (date and time), locations (meters) and magnitude.

The contractor, Magnitude, came to similar conclusions after re-analysis. The difference in location between both analyses are in the order of 100m, which may partly be explained by a difference in velocity model. Magnitude used a more detailed 3D velocity model, which is not yet possible in the MIMO package we used. On the other hand, a difference in azimuth is also observed, which may be attributed to a difference in orientation of geophone 4 and 5.

Two events, processed by Magnitude, were not located by the KNMI, since P- and S-waves could not clearly be picked during processing. However, four other events (not studied by Magnitude) were studied in this report (first four events in Table 1).

For future analysis e intend to use a better velocity model and a rigorous error analysis.

Conclusions Analysis of the downhole monitoring data from the Bergermeer field with independent methods and procedures has resulted in a new, consistent pattern of microseismicity that is agreed upon by all research parties. Results from the pilot project will form the basis for future monitoring.

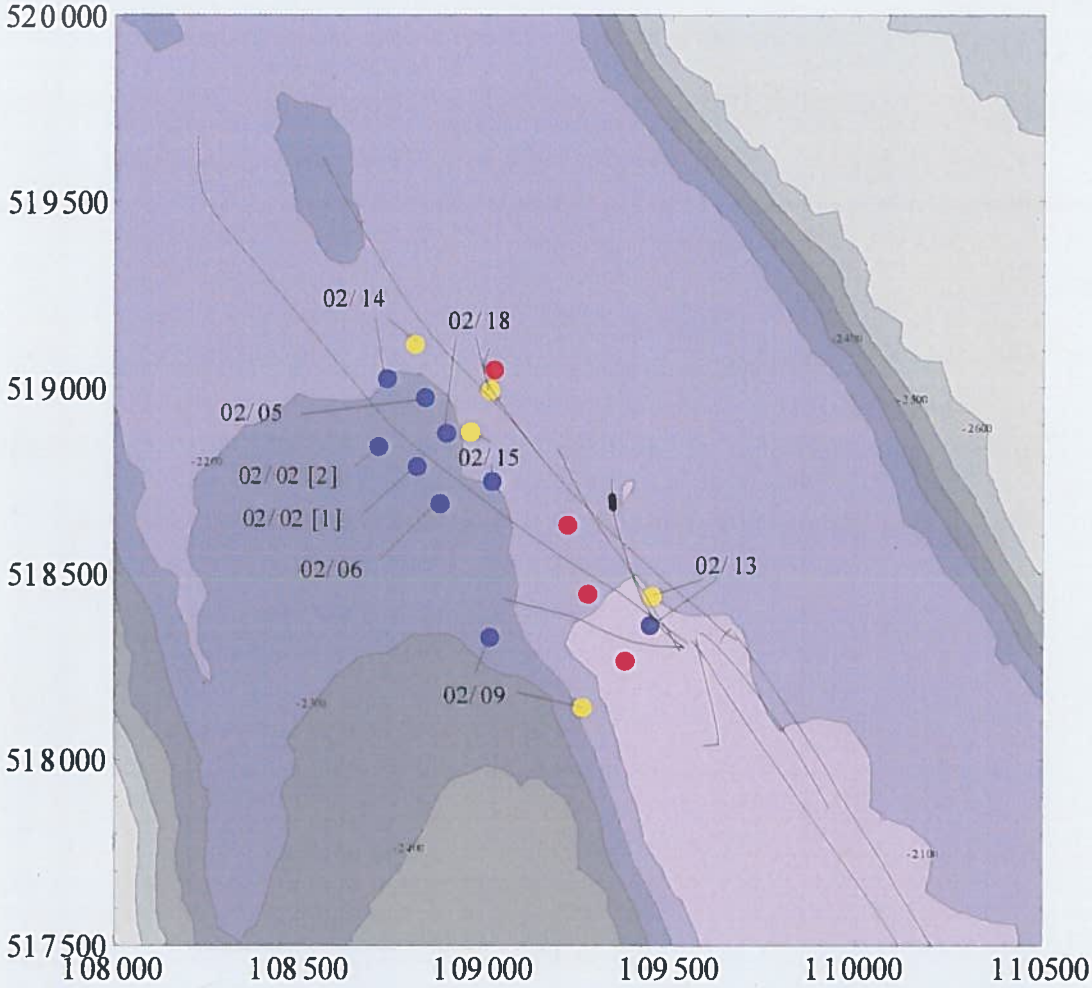


Figure 2: The locations plotted on map view. Blue points are the results obtained by the KNMI, the yellow points show the results of Magnitude and the red points show the former macro-quakes. The boreholes are plotted in black and the geopones are indicated with small black dots. The depth of the top of the Rotliegend reservoir is plotted on the background.

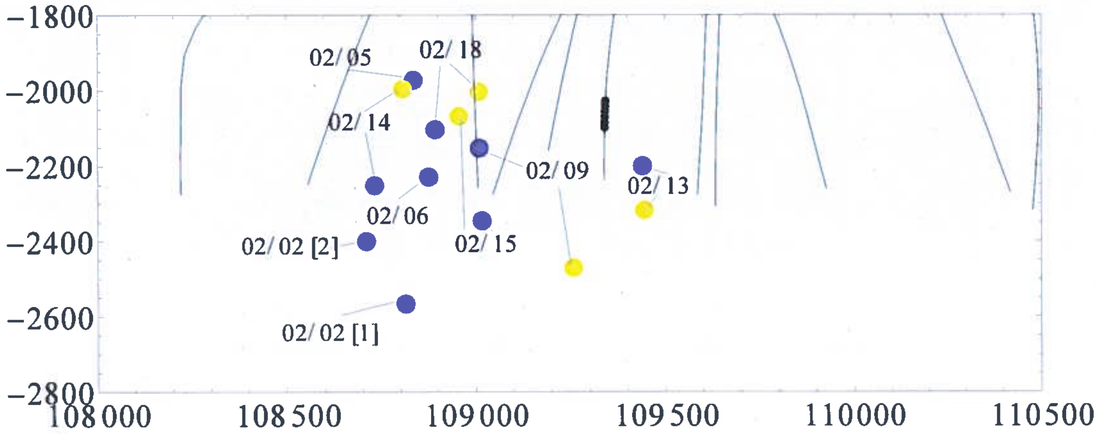


Figure 3: The locations plotted on a cross-section (Easting vs Depth).

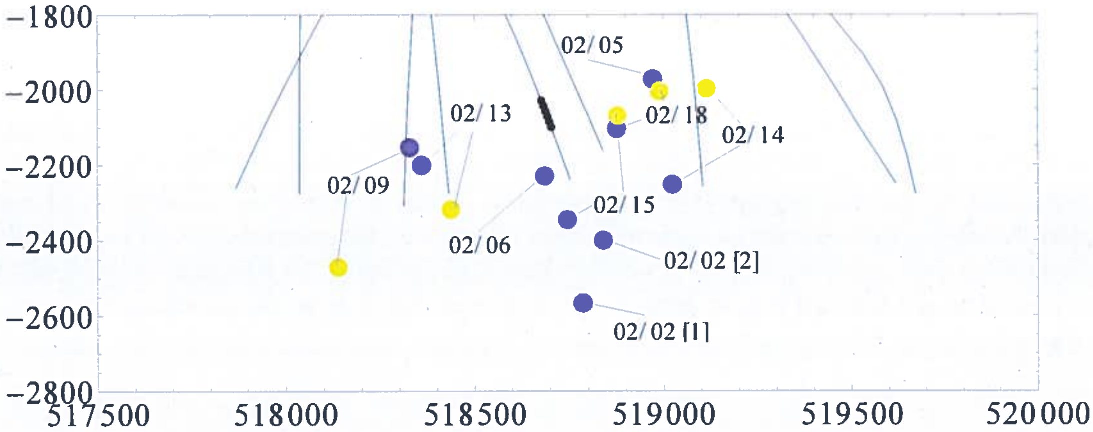


Figure 4: The locations plotted on a cross-section (Northing vs Depth).

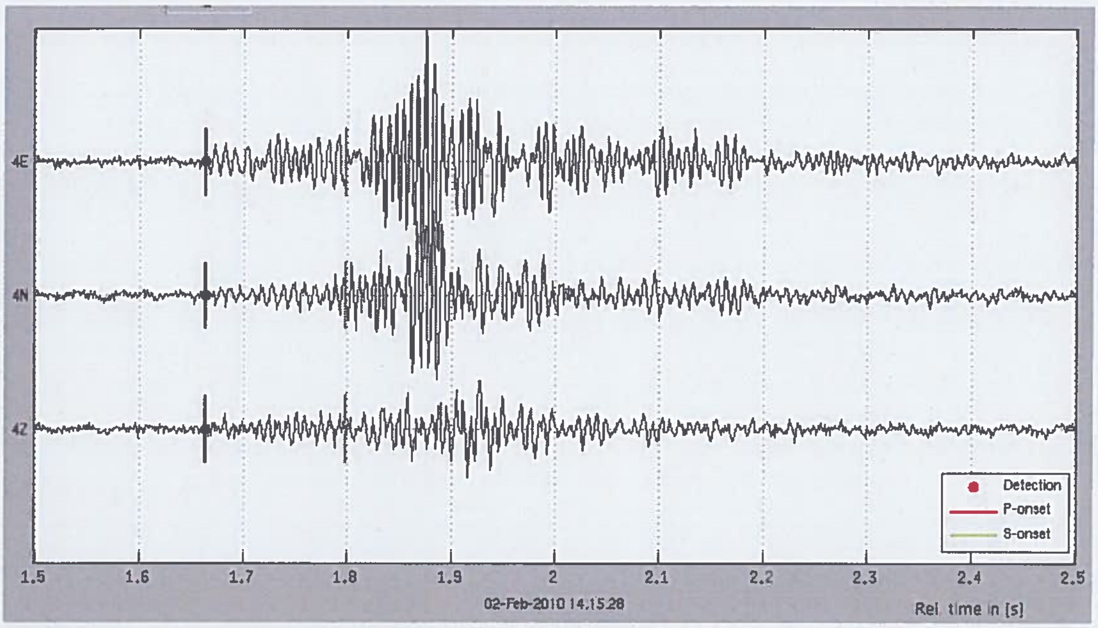


Figure 5: The waveforms for each component (E,N,Z) of the third geophone. All waveforms (figure to are filtered with bandpass filter (20-450Hz).This is the waveform for the first event on 02/02.

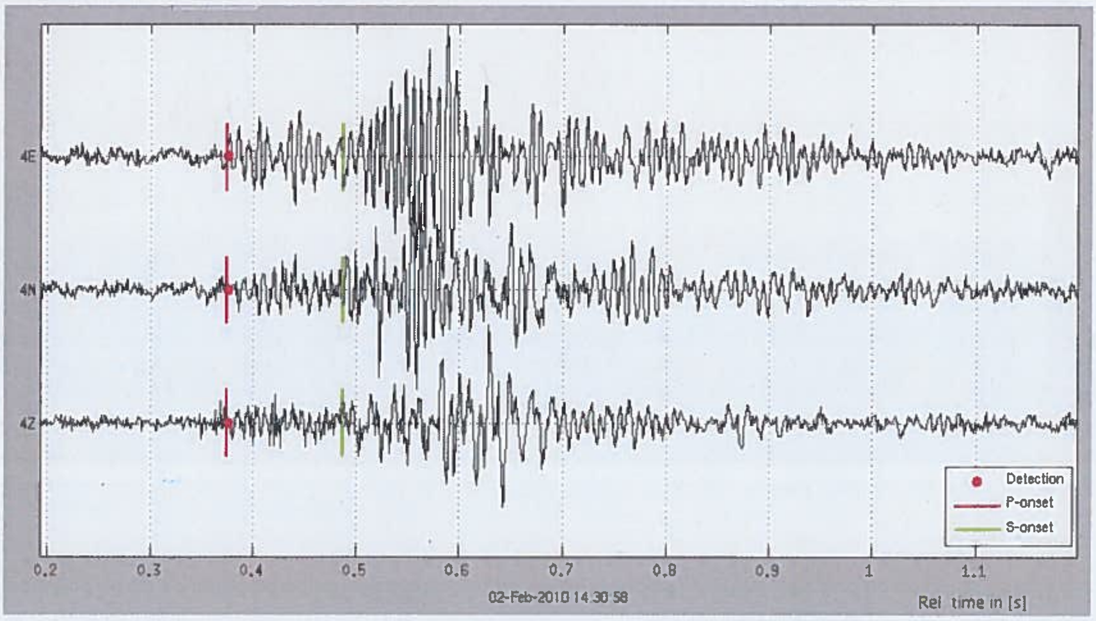


Figure 6: The waveforms of the second event on 02/02.

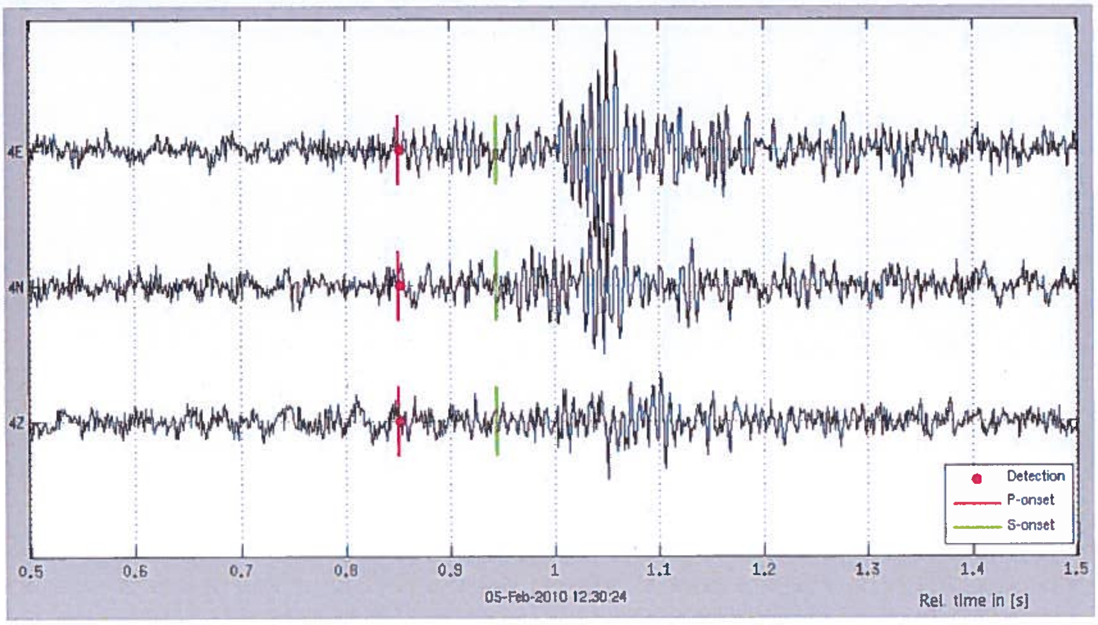


Figure 7: The waveforms of the event on 05/02.

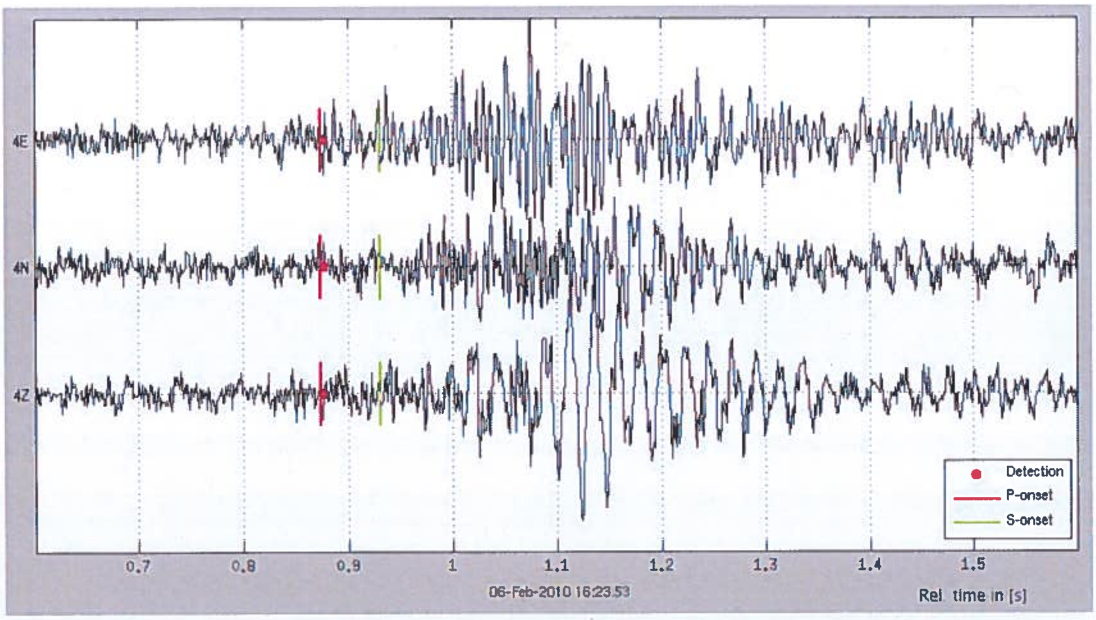


Figure 8: The waveforms of the event on 06/02.

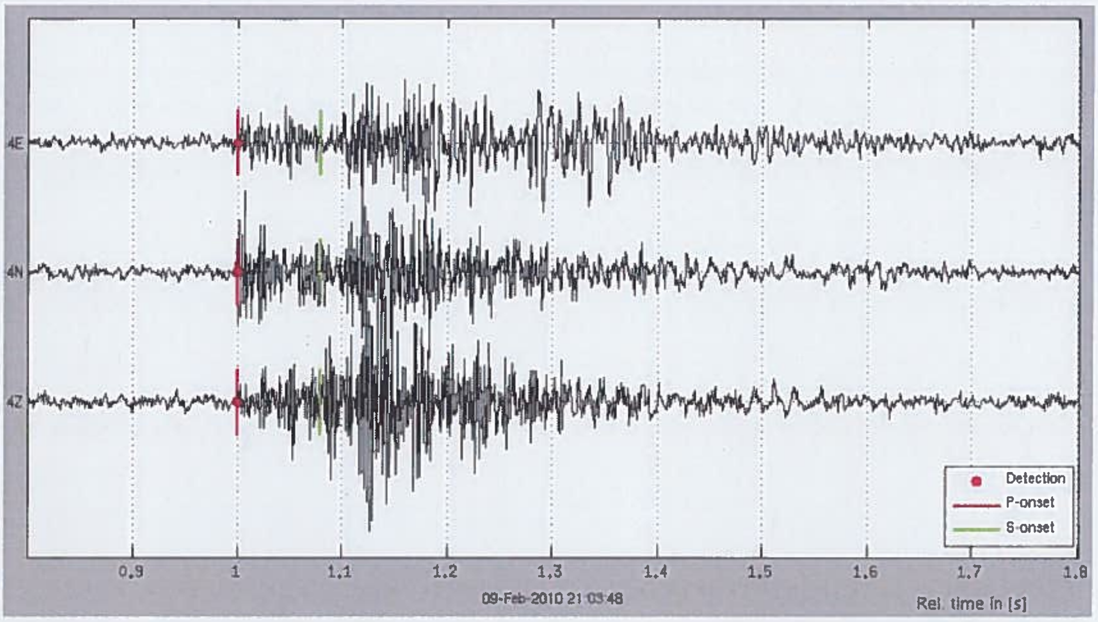


Figure 9: The waveforms of the event on 09/02.

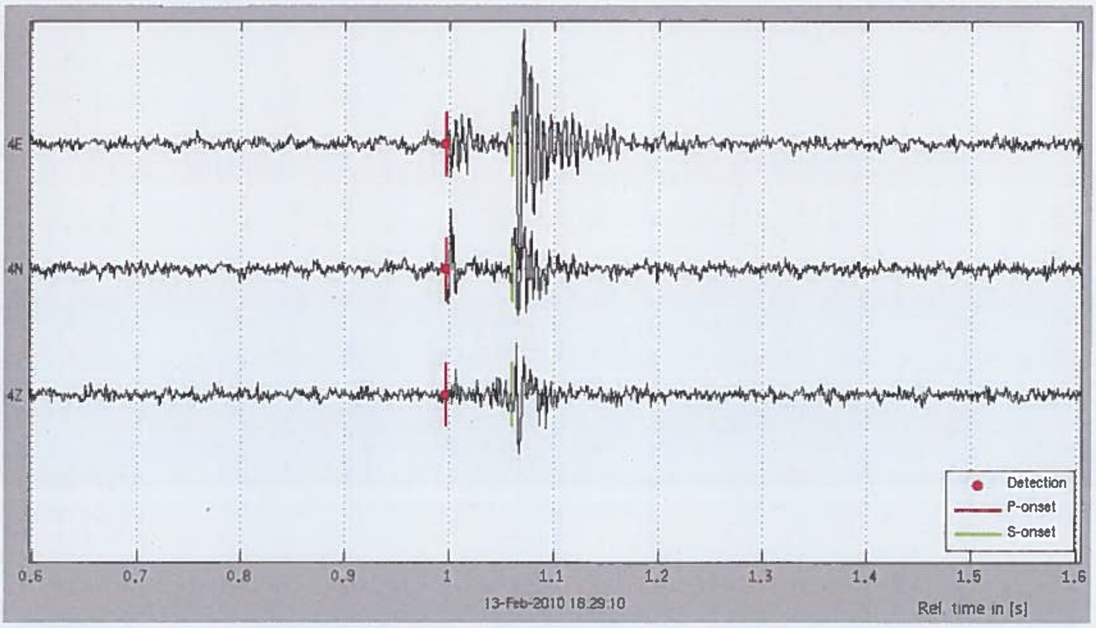


Figure 10: The waveforms of the event on 13/02.

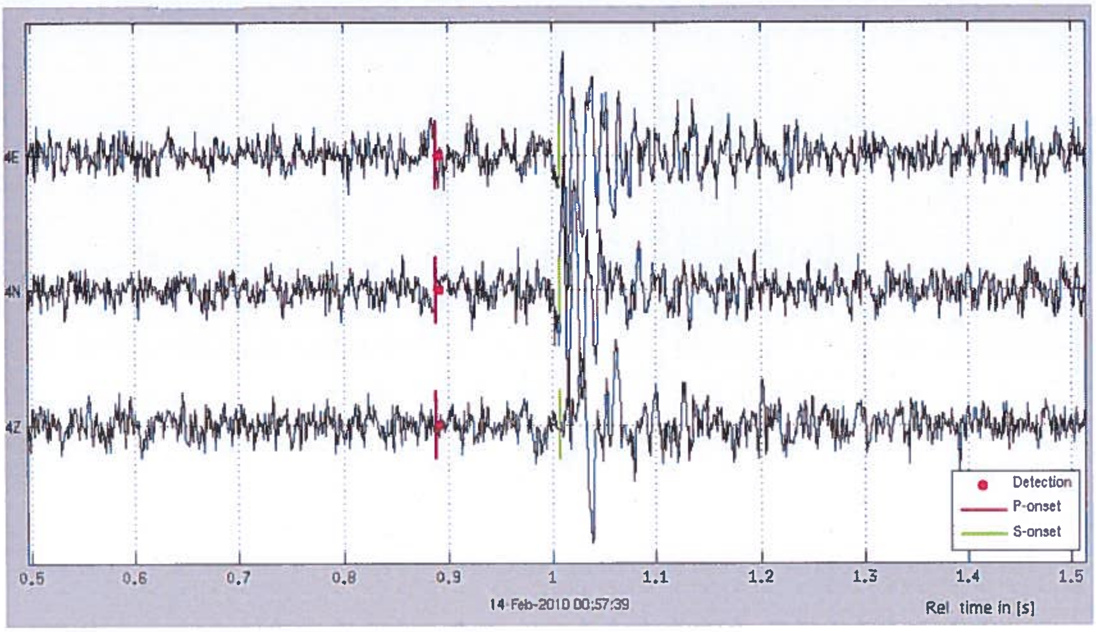


Figure 11: The waveforms of the event on 14/02.

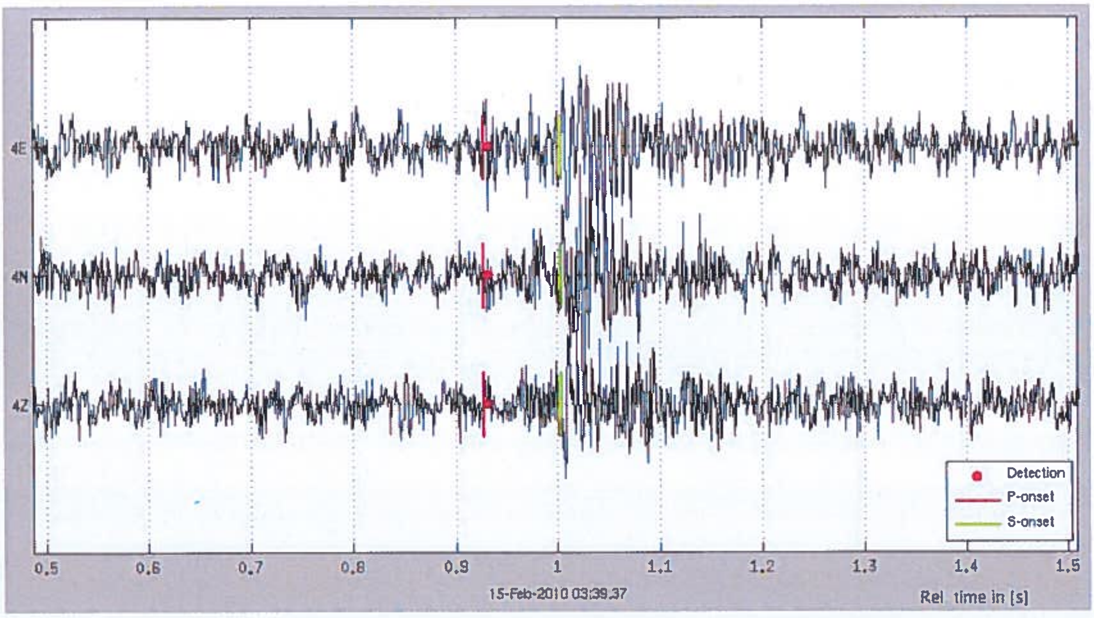


Figure 12: The waveforms of the event on 15/02.

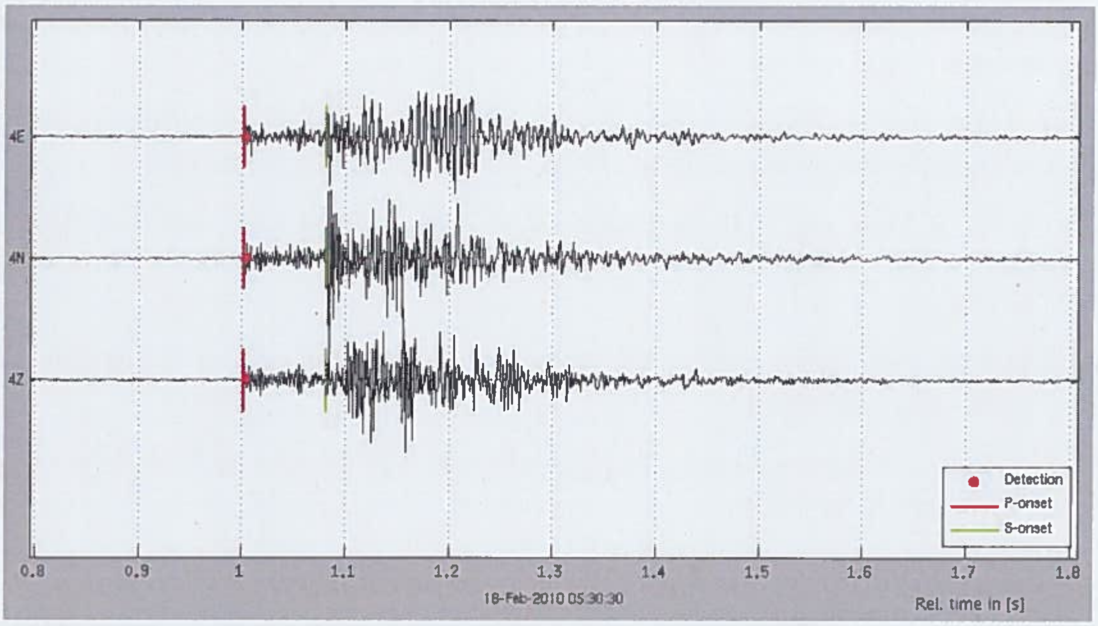


Figure 13: The waveforms of the event on 18/02.

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Structural Geometry of the Bergermeer Gas Field:

Implications for induced earthquake magnitudes.

10.2.e. [redacted] and 10.2.e. [redacted], TAQA Energy, January 2011.

Objective

The objective of this brief description of the structural geometry of the Bergermeer field is to support the ongoing 3D geo-mechanical modelling and pressure modelling work. The structural geometry defines the physical boundaries of the structure as well as the internal baffle formed by the central fault.

Summary

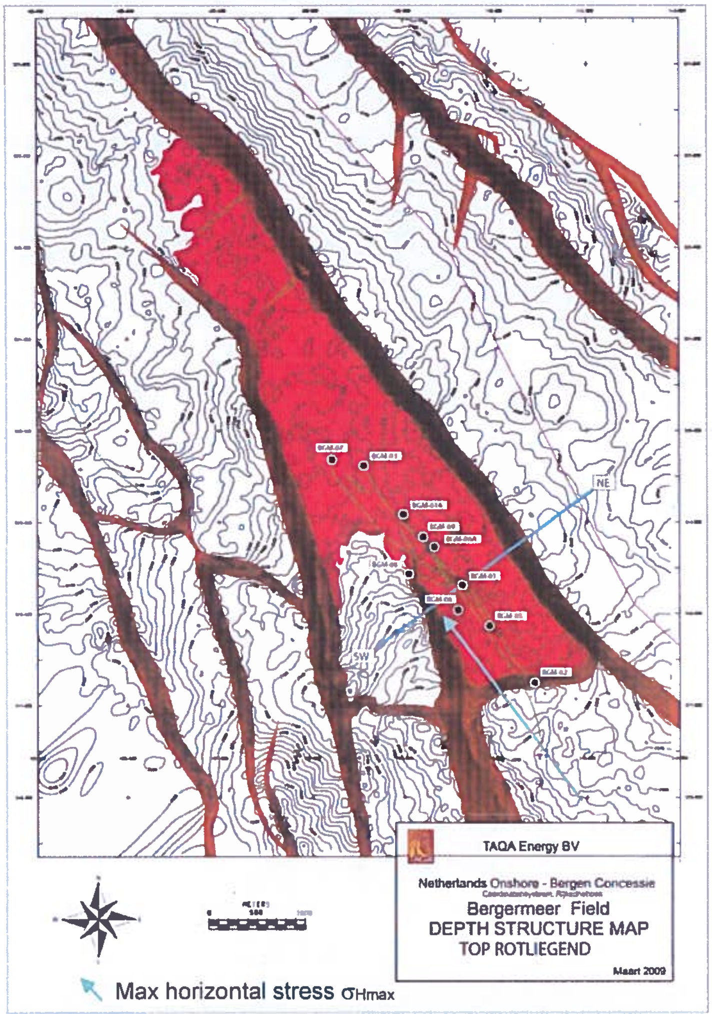
The Bergermeer gas field is mainly defined by two NW-SE striking boundary faults, an E-W striking southern boundary fault and in part also by dip-closure. A central fault separates the field in two blocks (East and West) that are partly pressure separated; the central fault is a baffle that slows gas and water flow across it, but not a complete seal. The faults and their characteristics are not only essential for trapping gas in the structure, but the central fault also represents a potential location for induced seismicity resulting from gas production and, during the gas storage project, resulting from pressure variations associated with the injection and production cycles.

This report presents a structural and geo-mechanical summary of the Bergermeer fault system, the fault properties and consequences for ground movement and induced seismicity.

Fault properties

The faults bounding the Bergermeer gasfield and the internal faults of the field are all normal faults (Fig. 1). The fault planes are relatively steep and the main movement is downthrown. A small strike-slip component is common for many normal faults. This can not always be visibly detected, but may be derived by other means such as regional tectonic analysis or seismic source determination. The maximum principle stress in a normal fault system is vertical, gravity being the main driving force of the faulting mechanism. The top seal for Bergermeer also provides a passive fault seal by juxtaposition. The Rotliegendes Aeolian sandstone reservoir of the Slochteren Formation is sealed by the overlying Zechstein evaporates consisting of anhydrite, limestone and dolomites, intermingled with halite, halite also forms the top of the evaporate series (Fig. 2).

The trapping mechanism across the bounding faults is juxtaposition, whereby the porous Rotliegendes sandstone reservoir is juxtaposed to the tight lithologies of the Zechstein top seal. The internal fault is only partly juxtaposed to the Zechstein and limited flow is possible between the lower part of the Rotliegend in block I (the eastern block) and the Weissliegend (upper part of the reservoir) in block II (Fig. 3).



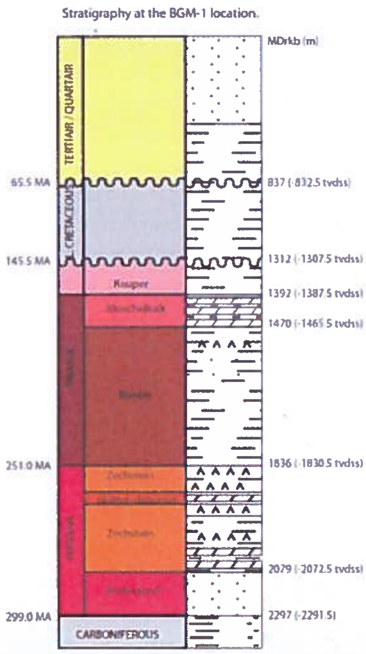


Fig. 1. Structural depth map of the Bergermeer gasfield.

Fig. 2. Stratigraphy at the BGM-1 well.

The Rotliegendes reservoir sandstone is relatively clean and almost free of clay or feldspars. The overlying Weissliegendes is less clean and less permeable. However, in both Rotliegend and in the Weissliegend soft clay layers that could contribute to the formation of a clay gouge by clay smearing are not present. Consequently the dominant deformation process in the fault zones cutting the Weissliegend and the Rotliegendes, will be cataclasis. This is the process whereby grains are crushed by the combination of shear movement (along the fault plane) and normal stress on the fault plane.

Internal faulting

The Bergermeer structure is internally deformed by a central normal fault splitting the southern part of the reservoir in two. This is a commonly occurring geometry called relay structure, which in this case represents a soft link, meaning that the down going western block (II) is not faulted by seismically visible faults. The block curves downward along the downthrown side of the central fault (Cartwright et al (1996).

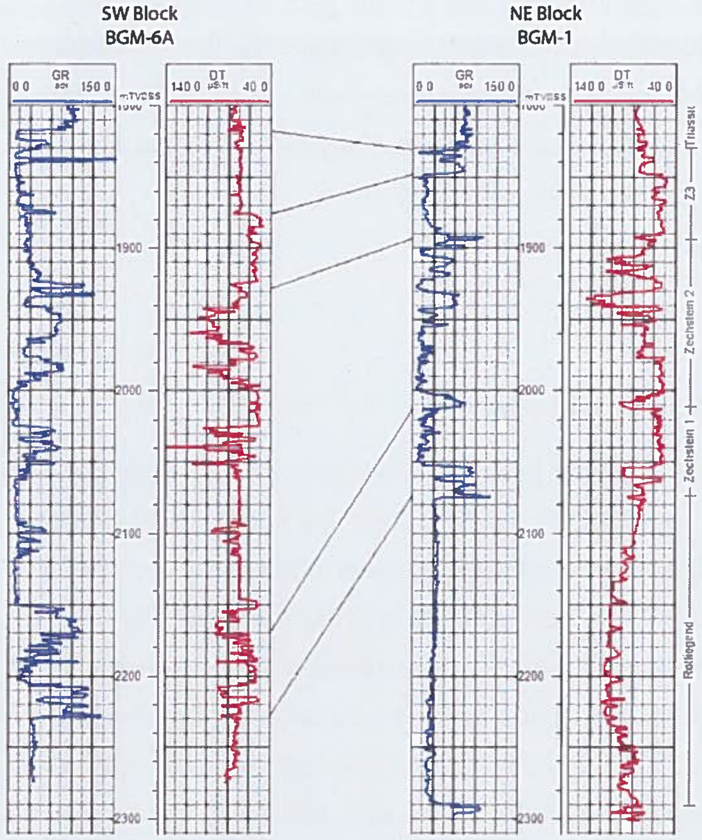


Fig. 3. Log correlation between BGM-1 and BGM-6A, illustrating the clean nature of the Rotliegend sandstone.

Given the strike orientation of the boundary faults and the central fault in the Bergermeer field relative to the maximum horizontal present day stress, the present day normal stress on the faults is not expected to be very high (Fig. 4). However, considerable erosion of younger formations indicates that palaeo depth has been greater than presently and normal stresses have been correspondingly higher. The resulting fault rock in the central fault is a cataclastic gouge with limited porosity and just enough permeability to act as a baffle that slows down the pressure communication between the blocks on either side of the fault. The gouge is not tight enough to form a complete seal.

The process of cataclasis has been studied extensively (A. Aydin, 1978) in the sandstone formation in Utah USA that has been used as an outcrop equivalent of the Rotliegend sandstone that forms the Bergermeer reservoir. The study of Aydin shows that normal faults in sandstone form a cataclastic gouge that increases in thickness up to a displacement of more than 10 m. Subsequently, the gouge stays more or less equal in thickness because the gouge itself starts to act as a gliding surface. The thickness of such a gouge depends on the roughness of the starting geometry of the fault. Fault gouge thicknesses of 10 to 20 cm have been reported from field cases in Utah and elsewhere. A cataclastic gouge becomes more or less sealing depending on the normal stress that was acting on the fault during deformation. However, in all cases a smooth fault rock is formed following some 10 m of displacement.

Based on the similarity between the Bergermeer Rotliegend sandstone, the field analogue in Utah and a similar fault seal study on a clean sandstone reservoir using seismic, cores, analogue models and a finite element study (Nieuwland and Walters, 1983), the following conclusions, relevant for the Bergermeer sandstone, may be drawn:

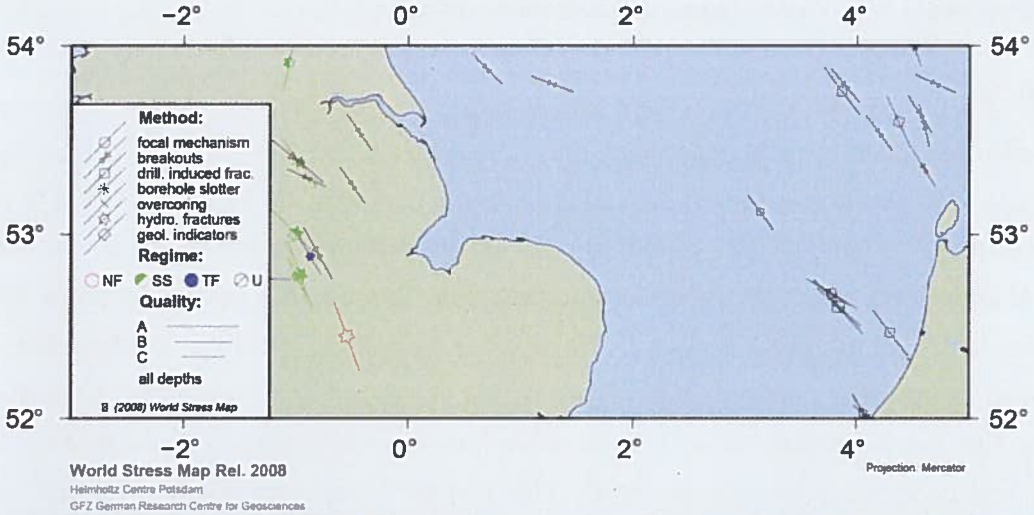
- The central fault has a cataclastic gouge as fault rock.
- The cataclastic gouge forms a smooth slip surface.
- The cataclastic gouge forms a partial seal (baffle).

Fault size, fault properties and earthquake magnitude.

The area to the north and northwest of the central fault shows no faults that are large enough to be seen on regular 3D seismic sections (Fig. 1), this indicates that the throw of individual small faults in potential deformation zones (sub-3D seismic) have a maximum throw that is less than about 25 m, the lower limit of detection of faults in cross sections (Fig. 5). The geometry of the normal faults that form a soft-linked relay ramp is a good indication of segmentation along the fault strike (Cartwright et al, 1996; Dawers et al., 1994; Needham et al, 1996; Soliva et al., 2005). Individual fault segments commonly form a deformation zone ahead of the active tip of the seismically visible fault. In line with published work on aspect ratios of normal faults, such small faults will have a maximum length of 200 to 300 m (most commonly L/T=10). This excludes a continuous fault extending from the detectable northern tip of the central fault further NNW than 300 m. The throw of the Bergermeer central fault is decreasing towards the north. Consequently the individual faults that may occur along a fault path further to the north are expected to have a smaller throw and a smaller associated length along strike.

The activity of the fault tip is in the Bergermeer field is in agreement with the location of the induced earthquakes of 1994 and 2001 at the tip of the central fault. Recent micro-seismic events, detected by the down-hole micro-seismic monitoring array, also occur in the vicinity of the tip of the fault.

The maximum size of an earthquake is determined by the size of the fault area that moves (Scholtz, 1990). For the Bergermeer central fault the maximum possible magnitude has been calculated as M=3.9. (Muntendam et al., 2008). The calculated magnitudes for seismic events induced by gas production and injection during a production-storage cycle, fall in the range M=2.4 to M=2.7. Following the same procedure for the much smaller sub-seismic faults that may occur along the trend to the north, potential earthquake magnitudes are expected to be very small, probably too small to be felt at surface and most likely only detectable as micro-seismic events (M<1.5).



(Fig. 4. World Stress Map, 2008. The maximum horizontal stress direction σ_{Hmax} has been derived from the world stress map and is applied to analyze the Bergermeer fault system (Fig. 1). M<1.5).

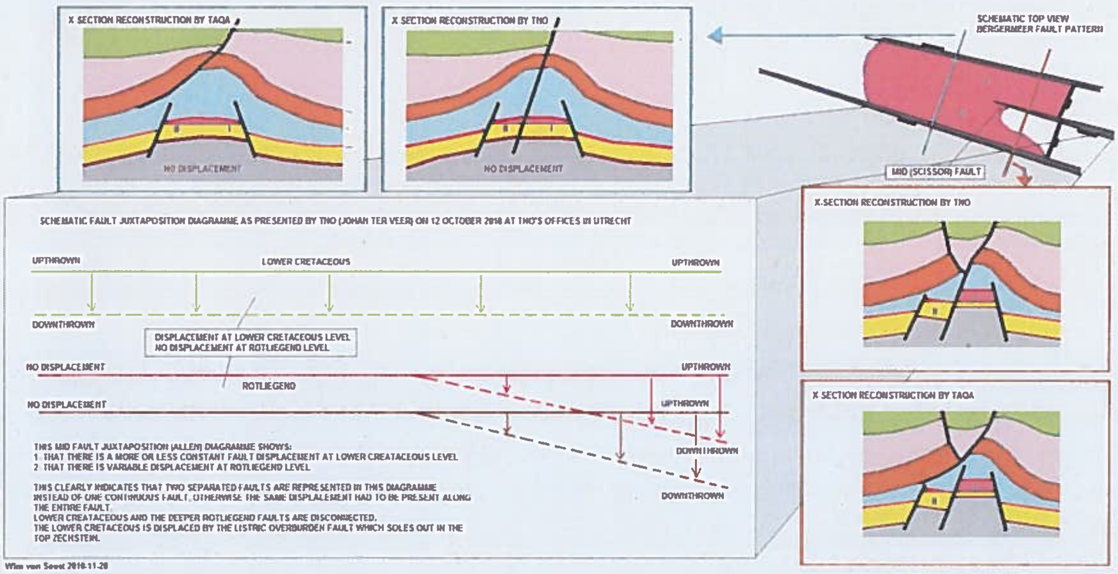


Fig. 5. Structural geometries in the Bergermeer field. The central fault has the geometry of a soft link relay ramp. In the zone to the north of the central fault the deformation may continue, but with a decreasing offset and accommodated by segmented individual small normal faults.

The faulting above the Zechstein evaporates is decoupled from the faulting in the Rotliegend sandstone of the reservoir. Two scenario's presented in figure 5, illustrate the decoupling. An interpretation with a through going normal fault cutting through the Rotliegend, the Zechstein and the Triassic overburden and an interpretation with a normal fault that cuts the

Rotliegend, but terminates upward in the upper halite layer of the Zechstein. Faulting in the overburden is in this scenario accommodated by a listric fault that soles out along the top of the salt. From the geometry of the overlying sediments it is clear that the structural geometry with the decoupling along the top halite the separate normal fault in the Rotliegend and the listric normal fault in the Triassic gives the best fitting solution.

Conclusions

The Bergermeer structure is a horst block that is defined by two NW-SE striking boundary faults and is at its southern end split by a central normal fault (Fig. 1). The central fault forms a relay ramp with a soft link at the northern tip, whereas at the southern end of the horst block it is terminated by a SW-NE striking normal fault. Towards the north the central fault decreases in throw to below standard 3D seismic resolution. Potential continuation of deformation, beyond the northern fault tip, can not be visualized by conventional 3D seismic methods. This means that the throw is below 25 m (the lower limit of the resolution of the 3D seismic) and decreasing towards the north. This has as a consequence that normal fault deformation that may continue to the north, will be in the form of segmented separate small faults. Since the magnitude of seismic events depends on the fault area that can be activated, any events that might occur along the deformation zone north of the central fault, will be of very small magnitude, probably of micro-seismic level (M<1.5).

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Comments on "Seismic Hazards of Underground Gas storage in the Bergermeer reservoir, a review", by 10.2.e *&* 10.2.e

In general this review gives a good overview of studies relevant to the Bergermeer gas storage project. However, I do have some comments that I will list below.

P2, 2nd paragraph:
At the time of the 2004 study, the seismicity of the Groningen field did show only one event of magnitude 3.0 (2003-11-10). Since that time more events M>3 did occur, with a maximum M 3,5 on 2006-08-08, which makes the hazard more in line with Bergermeer/Roswinkel.

By the way, one should take into consideration that in these hazard studies it is assumed that earthquakes can happen everywhere within the reservoir, so no preferred fault-reactivation is taken into account.

P3, 2nd and 3rd paragraph:
I explained to the authors that the probability of occurrence of the largest magnitude events cannot be given, due to the error in the number of events per year. So, an estimate of the return period of Mmax= 3.9 of 200-500 years is just as valid as 10.000 years.

In all discussions on Mmax, one should take into account that this value is not valid for Bergermeer only, but is derived for all induced activity in the northern part of the Netherlands. This means that if an event of magnitude M=Mmax would happen, it could also be e.g. in the Groningen field. In case of figure 5 in Eck et al., 2006, this figure was derived only for the Roswinkel field, based on a limited dataset. This implies a less reliable result.

The second remark on the Mmax issue, is that the calculated hazard is valid for the period of gas exploitation. However, after production stops, there is no guarantee that the seismicity will stop. This was also mentioned explicitly in the MIT report. In case of gas-storage we assume that a similar hazard is still applicable, since the estimated available fault-surface is sufficient to enable a Mmax size earthquake. Therefore, gas storage does not introduce a new type of hazard.

The issue of fault length has been treated at length in earlier publications, including the Logan 1997 report. Both statistics and physics should give similar results.

P4
The determination of Mmax and its modeling is explicitly discussed in several KNMI publications. From the Monte Carlo modeling we took as definition for Mmax a value the mean plus one standard deviation, covering 84% of the total distribution, as explained on p3.

P6
The Reamer/Hinzen relation is valid for the Roer Valley Graben region, not for the northern part of the Netherlands. The KNMI magnitudes have been calibrated for the northern part of the Netherlands.

The number of < 1% probability can only be derived from extrapolating either figure 3 or figure 5 from the Eck et al. 2006 publication.

A first intensity-magnitude relation for the northern part of the Netherlands was derived by de Crook et al, 1998 (KNMI TR-205). This relation is based on intensity data for the period 1986-1997 and shows a large scatter. This relation predicts for a M=3.5 event a maximum intensity of 5.4 and for a M=3.9 event a maximum intensity of 6.1, with an error of almost 1 intensity. So, estimating Intensities from magnitudes has a high uncertainty.

P8
The mentioned SBR limits are derived for natural events, that are characterized by a longer duration compared to the induced events. A study on the applicability of the SBR limit was made by TNO-bouw (Staalduinen et al., 1998; TNO report).

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Geachte 10.2.e. [redacted]

Door de Tweede Kamer (mw. Witteveen) is naar aanleiding van de aardbevingen bij Alkmaar een vraag gesteld over de mate van kwetsbaarheid van buizen en leidingen in de ondiepe ondergrond bij aardbevingen. In dit verband is het KNMI (Afdeling Seismologie) om advies gevraagd door het ministerie van EZ (10.2.e. [redacted]).

Tijdens de aardbevingen bij Alkmaar is de elektrische spanning op het net weggevallen in delen van de stad. Dit lijkt mij een relevant feit in het licht van de gestelde vragen. Kunt u opheldering geven van de oorzaak van de bewuste stroomstoringen? In verband met de afwikkeling richting Tweede Kamer wil ik u verzoeken om een antwoord op korte termijn.

Hoogachtend,

10.2.e. [redacted]

Hoofd Seismologie

NUON

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Behandeld door
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Uw kenmerk	*Ons kenmerk*	*Doorkiesnummer*
2001/3889	Inf/dir/az01.057	10.2.e.

Onderwerp	*Datum*
Aardschokken regio Alkmaar	12 oktober 2001

Geachte heer 10.2.e.

In uw brief van 2 oktober jl. vraagt u om informatie over de oorzaak van de stroomstoringen in delen van Alkmaar tijdens de aardbevingen in deze stad.

Tijdens de beving is een 50 kV transformator uitgevallen op de zogenaamde Buchholzbeveiliging. Deze beveiliging werkt met een membraam die reageert op de olie of gasstroming door de beveiliging. Deze beveiligingen staan kritisch en dit hoort ook zo. Zij zijn niet bedoeld om tegen aardschokken bestand te zijn.
Het membraam heeft bewogen op de trillingen van de aardschokken, waardoor de beveiliging van betreffende transformator er twee maal uit is gegaan.

Ik hoop u hiermee voldoende geïnformeerd te hebben.

Met vriendelijke groet,
10.2.e.

Directeur Infra West

Cc :
10.2.e.

K.N.M.I. | Week: 42 | Afd. term.: 8w
Reg. No.: 2001/4123 18 OKT. 2001
Klass. No. 550.340
Doss.: 94-497 | Beantw.:
Ter ... aan:
Disp. 10.2.e.
10.2.e. 19/10 | Dep.

alkmaria victrix
gemeente ALKMAAR

DIENST STADSONTWIKKELING EN BEHEER

Aan KNMI
afd. Seismologisch onderzoek
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3730 AE DE BILT

Uw kenmerk	Ons kenmerk	Toestelnummer
	MIL/6107	10.2.e.
Uw brief d.d	Behandeld door	Bijlagen
	10.2.e.	

Onderwerp
Aardschokken Alkmaar/
Bergen aan Zee 2001.

Datum
25.03.2002

Geachte mevrouw/mijnheer,

Na de aardschokken van 9 en 10 september 2001 nabij Alkmaar en 10 oktober 2001 nabij Bergen aan Zee heeft uw afdeling Seismologie een rapport uitgebracht na onderzoek en analyse van deze aardschokken. Uw rapport is vervolgens besproken in de bijeenkomst van de Technische Commissie Bodem Bewegingen van 4 december 2001 te Amersfoort.

Uw rapport en het verslag van de bespreking in de TCBB hebben wij overeenkomstig regionale afspraken toegestuurd aan burgemeester en wethouders van de gemeenten in Noord-Kennemerland.

Uit de bevolking en op bestuurlijk niveau hebben ons vragen bereikt en is ongerustheid uitgesproken over het effect van de aardschokken op de kernreactor van ECN te Petten. Met name is ongerustheid ontstaan door berichten over het scheurtje in het reactorvat en het stilleggen van de reactor door milieuminister Pronk. Is hier wellicht een relatie te leggen met de aardschokken?

Uit de ons beschikbare informatie is het onmogelijk om te reageren op deze bezorgdheid.
Wij verzoeken u dan ook om ons hierbij te adviseren c.q. om uw standpunt hierover kenbaar te maken.

Deze vraag zullen wij eveneens voorleggen aan de Technische Commissie Bodembeweging.

Hoogachtend,
het college van burgemeester en wethouders van Alkmaar,
namens deze,
hoofd afdeling Bouwen a.i,

10.2.e.

10.2.e.

K.N.M.I. | Week: 13 | Afd. term.:
Reg. No.: 2002/1350 27 MAART 2002
Klass. No.: 530.348/S.G.
Doss. No.: 940497 10.2.e.
Ter behandeling aan: Result Alkmaar
Disp.
S.Po
10.2.e.
Dep.

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Ministerie van Economische Zaken

Aan

KNMI
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Postbus 201
3730 AE DE BILT

Datum

- 0 4 APR. 2002 -

Bijlage(n)

Het bijgaande wordt u toegezonden:

te uwer informatie

Opmerkingen

Van

10.2.e.

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Verzoeke bij beantwoording van deze brief ons kenmerk te vermelden

02.00.ALG - 03/2001

COPIE

Ministerie van Economische Zaken

K.N.M.I. Week: 14
Reg. No.: 2002/1083 5 APR. 2002
Klass. No.: 550.348. 10.2.e.
Dossier No.: 10.2.e. 940497
Ter behandeling aan: Afd. Ned. Alg.
Disp. 10.2.e.
10.2.e. 14 Dep.

Aan
10.2.e.

Datum	Uw kenmerk	Ons kenmerk	Bijlage(n)
- 04 APR. 2002 -		ME/EP/MA/ 02017708	div.

Onderwerp
Aardbevingen in de omgeving van Alkmaar

Op 12 maart 2002 heeft u ons schriftelijk benaderd met vragen en opmerkingen over de aardbevingen bij Alkmaar op 9 en 10 september - en op 10 oktober 2001. Aangenomen kan worden dat deze bevingen zijn veroorzaakt door de winning van gas uit het Bergermeerveld van BP.

In de eerste plaats stelt u dat er nog dagelijks voelbare schokjes voorkomen.
Het KNMI is verantwoordelijk voor de registratie van aardbevingen. In de omgeving van Alkmaar staat een seismometernetwerk wat zelfs in staat is om ook zeer kleine trillingen uit de ondergrond op te vangen die niet worden "gevoeld" door bewoners ter plaatse. Sinds de drie hierboven genoemde bevingen is er geen seismische activiteit meer geregistreerd in de omgeving van Alkmaar en Bergen. Als u nog trillingen voelt dan kunnen deze niet geassocieerd worden met de drie hierboven genoemde bevingen in september en oktober.
Een overzicht van de geregistreerde aardbevingen in het jaar 2001 zend ik bijgaand toe. Tevens zend ik u het rapport toe van het KNMI over de aardbevingen van september en oktober 2001. Deze rapporten zijn openbaar toegankelijk, bijvoorbeeld via de web pagina van het KNMI: www.knmi.nl

Direct nadat de aardbevingen hebben plaatsgevonden is er intensief contact geweest tussen de gemeente Alkmaar, BP en het Ministerie van Economische Zaken. Op de voorlichting en informatievoorziening aan burgers kom ik nog terug.

Vervolgens stelt u dat er een soort "geheimzinnigheid" bestaat rond het toelaatbare aan gaswinning en opslag van gas in het concessiegebied rond Alkmaar. U refereert daarbij aan een krantenartikel van de heer Van der Sluis.

Ministerie van Economische Zaken

Het KNMI heeft in 1997 een uitgebreid onderzoek gedaan naar de seismische risico's in Noord Nederland. De bevindingen zijn neergelegd in een openbaar rapport wat ook naar de Tweede Kamer is gestuurd. Daarnaast is in opdracht van EZ in 1998 een uitgebreid onderzoek uitgevoerd door TNO bouw naar de relatie tussen schade aan gebouwen en lichte, ondiepe aardbevingen in Nederland. De conclusies zijn samen met de bevindingen van het KNMI aan de Tweede Kamer gerapporteerd. Een afschrift van die brief zend ik bijgaand mee. De recente aardbevingen bij Alkmaar zijn geen aanleiding om de conclusies van beide rapporten te herzien.

In die brief is sprake van een breed samengestelde commissie. Die commissie is er inmiddels: de Technische Commissie Bodembeweging (Tcbb).

Verder heeft u nog een artikel bijgevoegd waarin wordt ingegaan op de import van Russisch gas. De essentie van dat artikel is juist: naast het exporteren van gas wordt door Nederland (Gasunie) op bescheiden schaal gas geïmporteerd.
Het beleid van EZ inzake energie wordt regelmatig vastgelegd in Energierapporten. Bijgaand zend ik u het meest recente exemplaar van februari 2002.

Ten slotte merk ik op dat in het artikel van de heer Van der Sluis ook sprake is van risico's voor de kernreactor van ECN in Petten. Inmiddels heeft de Gemeente Alkmaar over dit onderwerp de Tcbb benaderd voor advies. Zodra dit advies gereed is zal ik ook u een kopie daarvan sturen.

Ik heb goede nota genomen van uw ongerustheid en vraag om meer helderheid rond gaswinning en aardbevingen in de omgeving van Alkmaar. De Tcbb heeft zich bereid verklaard om een informatieavond te beleggen in Noord Holland. Dit zal vermoedelijk op 11 juni 2002 in de gemeente Alkmaar plaatsvinden in een nog nader te bepalen locatie. Zodra dit definitief is vastgesteld ontvangt u een uitnodiging. Op deze avond zal uitgebreid ingegaan worden op de seismische risico's rond de gaswinning in Alkmaar.

De Minister van Economische Zaken,
namens deze:

10.2.e. [redacted]

10.2.e. [redacted] 10.2.e. [redacted]

directeur Energieproductie

02.00 ALG - 03/2001

P+A

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Datum
28 augustus 2002
Ons kenmerk
2002/2982
Uw kenmerk
MIL/6107
Contactpersoon
10.2.e.
Telefoonnummer
10.2.e.
Bijlage(n)

Onderwerp
Aardschokken Alkmaar/Bergen aan Zee 2001

– 2002/930

Geachte mevrouw 10.2.e.

In uw brief met kenmerk MIL/6107 vraagt u naar de effecten van de aardbevingen bij Alkmaar en Bergen aan Zee op het ECN te Petten.

Voorzover mij bekend, is het stilleggen van de reactor een beslissing geweest van minister Pronk die los van de aardbevingen bij Alkmaar genomen is. Het KNMI is in dit kader niet door het ministerie van VROM benaderd.

Zoals beschreven staat in het KNMI rapport "Seismische analyse van de aardbevingen bij Alkmaar op 9 en 10 september en Bergen aan Zee op 10 oktober 2001" had de krachtigste beving een magnitude van 3,5 op de schaal van Richter en een intensiteit in het epicentrale gebied van VI+. Wanneer de afstand in aanmerking wordt genomen tussen het epicentrum en het reactor centrum van 15 kilometer dan kan geconcludeerd worden dat de intensiteit van de trillingen op de intensiteitenschaal ter plaatse van Petten ongeveer I was. Dit betekend volgens de Europese Macroseismische Schaal (EMS) dat de aardbevingen op die plaats waarschijnlijk niet door mensen gevoeld is, geen effecten heeft veroorzaakt en dat er geen schade kan zijn ontstaan.

Het ligt in de bedoeling voor Alkmaar en omgeving tot een schatting te komen van het seismische risico, om verdere onrust over het ECN in dit opzicht weg te nemen en om de bovenstaande conclusie te verifiëren is het wenselijk ook het ECN te Petten in deze risicostudie op te nemen.

Hoogachtend,

10.2.e.

Hoofd Afdeling Seismologie

Ministerie van Economische Zaken

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Ons kenmerk
ET/EM / 9135720

Uw kenmerk

Informatiekopie aan
10.2.e. (EM), 10.2.e. (SodM)

Bijlage(n)
1

minute

Datum 31 juli 2009

Betreft Project description: Technological review of TNO's Bergermeer seismicity study

10.2.e.
MT DGET/EM

Verzendwijze: Per post

Brieftekst op de volgende pagina

Ontvangen BBR	Ontvangen Postkamer	Datum verzending	Paraaf Postkamer

Ministry of Economic Affairs

> P.O. Box 20101 2500 EC Den Haag The Netherlands

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10.2.e.
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10.2.e.

Our ref.
ET/EM / 9135720

Your ref.

Cc

Encl.

Date

Re Project description: Technological review of TNO's Bergermeer seismicity study

Dear mr. Toksöz,

Recently you have had email contact with Ms 10.2.e. regarding a potential assignment to technically review the Bergermeer field seismic study.

Enclosed you find the Project Description and we invite you to write a proposal that contains the following items:

- Résumés of reviewer(s)
- Working plan
- Schedule
- Overview of the planning costs (including and excluding VAT):
  - Overview of planned hours and tariffs for piecework;
  - Travelling expenses for a trip to the Netherlands to give a presentation to the local community

We expect to receive the proposal on August **21st** 2009. The final assignment can be expected **DATE**. Appended you can also find the Terms of Reference (Arvodi).

For any further correspondence you can contact Ms 10.2.e.
10.2.e.

We are looking forward to your quick reply.
Yours sincerely,

10.2.e.
Member of the EM-management team

Directorate General for Energy and Telecom
Energy Market Directorate

Our ref.
ET/EM / 9135720

Project description

Technical Review of TNO's Bergermeer Seismicity Study

Introduction

In the near future TAQA Energy B.V. wants to utilize the depleted Bergermeer gas field as an Underground Gas Storage facility. The Netherlands Organisation for Applied Scientific Research (TNO) has performed a study regarding the seismic risk of the injection/production activities and is called the *Bergermeer Seismicity Study.* Assumptions made in the report have raised questions and concern among the local community. They fear that the gas storage activity will cause severe earthquakes and damage to their homes. Therefore, the Minister of Economic Affairs has been asked to have the report of TNO reviewed by an independent expert. This Project Description contains the scope of work for this technical study.

Deliverables

The Ministry of Economic Affairs expects :
1. A report containing:
    a. a critical technical review of the assumptions, conclusions and recommendations of the *Bergermeer Seismicity Study*, TNO report 2008-U-R1071/B, 6 November 2008.
    b. answers to the questions raised by the "Gasalarm2 foundation" and the Soil Movement Technical Committee (see appendices)

The report as mentioned should be submitted in both hard copy (20 copies) and in electronic form. The final report will be preceded by a draft report.

Optional:
2. An oral presentation in the municipality of Bergen (The Netherlands) for representatives of the local community.

Timing
The report is to be completed and delivered by September 21st, 2009.

<u>Remarks:</u>
1. Some of the questions raised in the appendices will need an explanation from the governmental experts who are involved in the Bergermeer project. The

Ministry of Economic Affairs is willing to organize an information meeting between the reviewer and these experts.

2. TAQA Energy B.V. supports the study and is willing to supply any information needed.

Reports supplied:

- Logan, J.M.; Higgs, N.G.; Rudnicki, J.W.; Seismic risk assessment of a possible gas storage project in the Bergermeer field, Bergen concession, 1997
- Van Eck, Torild; Goutbeek, Femke; Haak, Hein; Dost, Bernard; Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands ; KNMI scientific report, 2004
  http://www.knmi.nl/~goutbeek/Submitted-seismic-hazard.pdf
- Van Eijs, R.M.H.E.; Mulders, F.M.M.; Nepvue, M.; Kenter, C.J.; Scheffers, B.C.; 2006; Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands. Engineering Geology, 84, 99-111.

Reports or papers that need to be purchased can be reimbursed.

Directorate General for Energy and Telecom
Energy Market Directorate

Our ref.
ET/EM / 9135720

Appendix 1: Questions of the Gasalarm2 foundation

1. Is the assumption of TNO justified that the changes of the thickness of the reservoir develop gradually during injection and production?
   (i.e. that the change of the thickness [compaction and decompaction] follows the pressure change in a gradual way and that the reservoir is in an equilibrium condition every time).

2. TNO uses elasto-plastic geomechanical models to calculate potential slip on a faultplane. A critical geometry of reservoir and fault structure is chosen, which is sensitive for reactivation of the fault. Plastic slip is calculated on the fault, during depletion and injection, each time in an elasto-plastic equilibrium condition.

   Question: Is the above mentioned approach of TNO correct to calculate the maximum potential slip that can occur, especially during the injection phase? (Clarification: Gasalarm2 assumes that in reality asperities may be present on the fault, preventing movement along the fault during the depletion phase.

3. (With reference to the calculations in chapter 7 in the TNO report)
   Gasalarm2 assumes, that in the injection phase tremors with magnitudes of 3.4 up to 3.8 might occur. This hypothesis is based on the assumption that asperities are present along the fault plane, causing slip not to occur along the whole fault during the depletion phase.
   Remark State Supervision of Mines: during re-pressurization of the reservoir, decompaction of the reservoir-rock will take place and therefore in an uplift at the surface. The potential relative shear displacement (slip) on the fault will decrease.

   Question: What is the opinion of the expert(s) about the suggested magnitudes?

4. Figure 3,2 of the Seismicity Report shows a 3D view of the Bergermeer gas field (based on a model of Horizon 2006). From this view Gasalarm2 concludes, that the main (internal) fault may be longer than anticipated. According to Gasalarm2 the length of the fault is probably 4.1 to 5.9 kilometres and not 2.5 kilometres. Consequently, Gasalarm2 assumes, that the probable size of the reactivated part of the fault plane may be much

larger than is stated in table 2.2 of the TNO report (page 18) and therefore the potential magnitude of earth tremors may be much higher (M=4.1).

Question: What is the relation between the length of the fault plane, the probable activated part of the fault plane during the events and the maximum magnitude of a seismic event? How important is the estimation of the total length of the central fault?

5. Maximum magnitude issues.
   - TNO conclusion 7: "During injection, the largest slip ***observed in the geomechanical models*** corresponds to seismic magnitudes ranging between 2.4 and 2.7."
   - TNO page 85: "For the range of seismic magnitudes ***expected*** during the injection stage (2.4 to 2.7)..."
   - TNO conclusion 8. The maximum possible seismic magnitude is 3.9. Larger magnitude earthquakes are improbable due to the limited dimensions of the faults.
   - Gasalarm2: Occurrence of earth tremors with magnitudes larger than 4 are possible during the gas storage project Bergermeer

   Question: what is the opinion of the expert(s) about the different views of TNO and Gasalarm2, taking into account the arguments about the size of the probable activated part of the fault plane and the possibility that in the depletion phase, slip on the fault plane may be prevented by one or more asperities.

6. Gasalarm2 assumes that the stabilisation of the fault structures at reservoir level due to the pressure-increase (during injection) will be negligible. The assumption is based on table 7-1 of TNO's Seismicity report.
   TNO assumes that the re-pressurization of the reservoir will lead to a more stable fault structure (see chapter 6.3 of the TNO Seismicity Report)

   Question: what is the opinion of the expert(s) about these different views?

7. Gasalarm2 observes that for the operating phase of the Bergermeer Gas Storage reservoir only the first production/injection cycle is modelled by TNO. According to Gasalarm2 this is erroneous. Gasalarm2 expects, that the continuing cycle of alternating production and injection will cause erosion of the fault planes. To the opinion of Gasalarm2 it is also an omission that the seismic risk of the recovery of the working gas at the end of the storage

period is not taken into account.
TNO has made a recommendation (page 87, number 3) to extend the current report with an analysis of subsequent injection/production cycles to investigate the temperature distribution and the rock response (e.g. fatigue effects).

Question: what is the opinion of the expert(s) about the missing geomechanical analysis of the subsequent injection/production cycles? Is this analysis essential to draw conclusions about the seismic risk of the injection/production activity? Or can this analysis be characterized as a "fine tuning" of the model?

8. Gasalarm2 believes, that TNO has made the wrong basic assumptions in their model, because they don't assume inhomogeneous properties of the reservoir rock and non-elastic (irreversible) deformation behaviour.

   Question: what is the opinion of the expert(s) on this subject?

9. According to Gasalarm2 the temperature effects are not addressed in a satisfactory way in the TNO- report

   Question: what is the opinion of the expert(s) on this subject? Has TNO made the wrong assumptions or did they investigate these effects in an insufficient way ? (e.g. the distance to the faults, the heating by compression, long term effects; a large surface area of the reservoir is influenced by temperature effects, etc.)

10. Gasalarm2 fears that injection of production water in the well BGM-4 will cause a weakening of the rock salt caprock, resulting in a sudden stress-release. They suggest that the production water can pollute the groundwater due to an upward or a sideward migration.

    Question: what is the opinion of the expert(s) on this subject?

11. Additional question about the focal mechanism
    At the end of chapter 6 (page 81) of the TNO report concludes:
    "All plastic fault displacements observed during depletion and injection are normal faulting movements. This means a discrepancy exists between the interpretation of focal mechanisms reported by the KNMI (reverse faulting mechanism) and the displacement mechanisms from the geomechanical

analysis (normal faulting mechanism). It is noted that in an extensional tectonic setting such as the setting for the Bergermeer Field, predominantly normal fault movements are expected."
This remark was based on the figures 6 and 7 of a report from the seismological department of the KNMI with an interpretation of the focal mechanism of the Bergermeer events. The report (in Dutch) can be found at: http://www.knmi.nl/bibliotheek/knmipubTR/TR239.pdf

Question: what is the opinion of the expert(s) about the focal mechanism of the Bergermeer earthquakes (see figures 6 and 7 of above mentioned report).

Translation of captions:

Fig. 6: Schematic representation of the central fault in the Bergermeerfield. The epicentres of the earthquakes are indicated with an asterisk. The fault formed in an extensional setting, currently the focal mechanism is a reverse fault.

Fig. 7: Overview of the epicentres of the earthquakes near Alkmaar and Bergen aan Zee. The location of the gasfields are indicated in grey and the faults in black.

Appendix 2: Questions of the Soil Movement Technical Committee

The following questions were asked by the Tcbb (Technische commissie bodembeweging; english: Soil Movement Technical Committee):

1. What is the opinion of the evaluator on the risk estimates and are they compatible with the physics (ref. TNO report and KNMI risk reports)?

2. The fault dissecting the Bergermeer field is (partly) sealing: what pressure difference between the hanging- and foot-wall may cause earthquakes?

3. The Tcbb considers the possibility of seismic monitoring at reservoir level, since only larger events (M>3) have been recorded with the current monitoring system. Is this a justified approach or are there alternatives?

4. How is excessive movement to be prevented? Can this be done by changing the rate or volume (maximum pressure difference) of production?

Stichting Gasalarm2
10.2.e. [redacted]

Haarlem,
2 oktober 2009

Mijne heren,

Naar aanleiding van het recente contact, dat ik heb gehad met u als bestuur van de Stichting Gasalarm2 stuur ik u deze brief.

Ik heb u opmerkzaam gemaakt op het onderzoek, dat GeoConsult heeft uitgevoerd met gemeten hoge bodemdalingsnelheden ter plaatse van de Hondsbossche en Pettemer Zeeweringen.
Een artikel, dat dit onderzoek beschrijft, is geaccepteerd door het tijdschrift Geotechniek, na inhoudelijke beoordelingen door wetenschappelijk hoofdmedewerkers van de TUDelft (Geodesie) en de Vrije Universiteit, Amsterdam (Geologie). Met name de mogelijkheid van het optreden van verplaatsingen langs breuken als oorzaak voor bodemdaling wordt door de geologische beoordelaar ondersteund. Het artikel zal aan het einde van dit jaar in het tijdschrift Geotechniek gepubliceerd worden. De belangrijkste aspecten uit de publicatie zijn weergegeven in Bijlage 1.

Naar aanleiding van de signalering van de hoge bodemdalingsnelheden door mij werd in 2005 een workshop georganiseerd door RWS teneinde de problematiek door een aantal deskundigen te laten belichten. De bijdragen van de workshop en een verslag ervan werden gebundeld en gerapporteerd in 2008 (RWS/Deltares/TUDelft, 2008).
Men heeft het helaas niet aangedurfd om het artikel van GeoConsult in de bundel op te nemen. De algemene conclusie in de rapportage luidt, dat er sprake is van door de mens veroorzaakte bodemdaling, waarbij aardgasonttrekking en verhoging van de Hondsbossche en Pettemer Zeewering als mogelijke activiteitenen genoemd worden. Voor de presentaties in de workshop werd geen intensief onderzoek uitgevoerd, met uitzondering van het InSAR onderzoek door Geodesie van de TUDelft (Hanssen et al., 2008). Deze komen als enigen, evenals GeoConsult tot de conclusie, dat er een kanteling van de dijk van noord naar zuid optreed, die oorzaken in de diepere ondergrond moet hebben.

Een van de belangrijkste conclusies van het onderzoek van GeoConsult is, dat de hoge bodemdalingsnelheden ter plaatse van de Hondsbossche Zeewering van ca. 50 cm/eeuw, gerelateerd zijn aan neo-tektonische bewegingen langs breuken die doorlopen van vrijwel het maaiveld tot in\door zoutlagen, die de gasvelden in de regio afdekken, en tot in de zandsteen van de reservoirs zelf (Fig. 1).

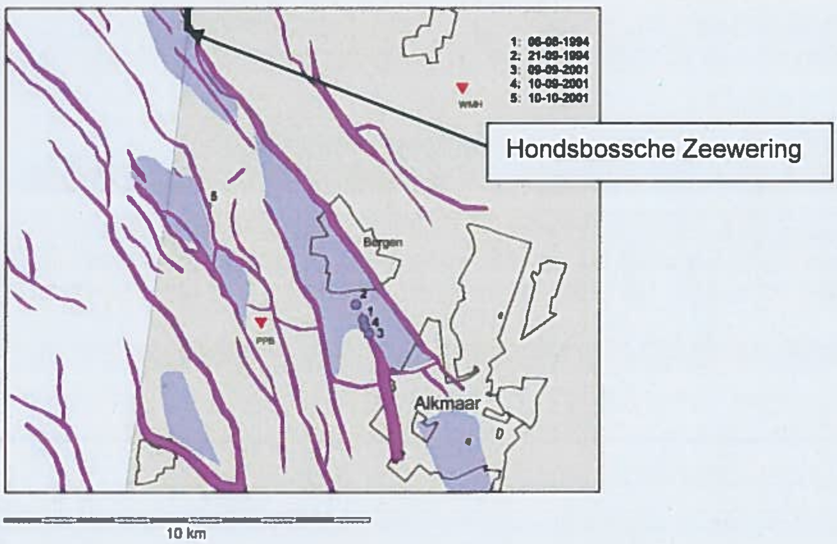

Fig. 1 Breuken aan bovenzijde gasreservoirs (KNMI, 2001)

Tevens kon in het onderzoek een verband worden gelegd tussen het optreden van de aardbevingen in het Bergermeer- en Bergenveld, in september resp. oktober 2001, en het optreden van plotselinge verplaatsingen ter plaatse van de Hondsbossche Zeewering van ca. 5 tot 10 mm. De breuk waarlangs de verplaatsingen ter plaatse van de Zeewering optreden is naar alle waarschijnlijkheid dezelfde die het Bergermeerveld aan de Noordoostzijde begrensd, hoewel dit niet in detail onderzocht is (Fig. 1). De aardbevingen in het Bergermeerveld treden op langs een breuk in het midden van het veld, en die door de onderzoekers van KNMI (2001) aangemerkt wordt als een actieve breuk. Een verkennende inventarisatie leert, dat daar tijdens de aardbevingen verplaatsingen aan het oppervlak van ca. 20 mm opgetreden zijn.

Over de eventuele toekomstige opslag van aardgas in het Bergermeerveld heb ik van u de informatie ontvangen in uw brief d.d. 16 augustus 2009, waarin ondermeer de Bergermeer Seismicity Study (TNO report 2008-U-R1071/B) en uw kritiek daarop. Ook heb ik inzage gehad in de aanvraag door EZ van het Second Opinion Onderzoek, dat aan het Massachusetts Institute of Technology uitgevoerd zal worden (ET/EM/9135720).

Uit deze informatie en de resultaten van het onderzoek van GeoConsult kan worden geconcludeerd, dat de geplande gasopslag een risico kan vormen voor de stabiliteit en intregiteit van de Hondsbossche Zeewering.

De volgende omstandigheden zijn bekend uit het onderzoek van GeoConsult:

- Ter plaatse van de Hondsbossche Zeewering en de Pettemer Zeewering vinden zakkingen plaats langs breuken met extreem hoge snelheden
- Tijdens de aardbevingen in het Bergermeerveld van 2001vinden er zakkingen plaats bij de Hondsbossche Zeewering die ongeveer de helft zijn van de zakkingen boven de epicentra (afstand ca. 10 km)
- De breuk waarlangs de grootste verplaatsingen optreden bij de Hondsbossche Zeewering is naar alle waarschijnlijkheid dezelfde als die welke het Bergermeerveld aan de Noordoostzijde begrenst.

Er zijn de volgende risico's te onderscheiden bij het optreden van aardbevingen in het Bergermeerveld ten gevolge van de geplande opslag van gas, waarbij men een aantal vragen kan stellen:

1. <u>Risico's van grote differentiële verplaatsingen die de integriteit en stabiliteit van de Hondsbossche Zeewering in gevaar kunnen brengen</u>
    - Kunnen er aardbevingen optreden in de breuk die het Bergermeerveld aan de noordoostzijde begrenst en met welke magnitude en grootte van verplaatsingen?
    - Wat voor orde van grootte van verplaatsingen kunnen we verwachten indien aardbevingen met een magnitude $M = 3.9$ optreden?
    - Wat is er bekend over de grootte van verplaatsingen langs breuken tijdens aardbevingen, waarlangs al gedurende honderden jaren bewegingen plaatsvinden met relatief hoge snelheden, en waarbij de residuaire wrijvingswaarden al bereikt zullen zijn?

2. <u>Risico's van het optreden van zettingsvloeiingen in zanden onder de dijk tengevolge van versnellingen door aardbevingen in combinatie met verplaatsingen langs een breuk</u>
    - In RWS/Deltares/TUDelft, 2008; Hst. 5.5.6 wordt gewaarschuwd voor de kans op verweking van zettingsvloeiinggevoelige lagen;
      Zijn deze lagen aanwezig onder de Hondsbossche Zeewering en zodanig gesitueerd, dat optredende waterspanningen niet direct kunnen verminderen en instabiliteit kan optreden?
    - Zijn er steile taluds aanwezig (door zeestroming) waardoor oevervallen op kunnen treden?

Om deze risico's van de geplande opslag uit te beoordelen zullen beïnvloedende processen moeten

worden geanalyseerd en de openstaande vragen adequaat moeten worden beantwoord.
Uw suggestie om de vragen ondermeer voor te leggen aan de deskundigen van het MIT ondersteun ik ten zeerste.

Ik ben gaarne bereid over deze problematiek verder contact met u te hebben.

Met vriendelijke groet,

10.2.e.

dr ir 10.2.e.
GeoConsult B.V.
10.2.e.
10.2.e. HAARLEM

Bijlage 1

Resumé van publicatie in het tijdschrift Geotechniek:

Bodemdaling Hondsbossche en Pettemer Zeewering is gevolg van geologische processen in diepe ondergrond

Samenvatting

November 2004 werden door 10.2.e. van GeoConsult bodemdalingsnelheden ter plaatse van de Hondsbossche Zeewering van meer dan 40 cm/eeuw in de media vermeld. In relatie met de in de toekomst verwachte zeespiegelstijging en klimaatverandering is de hierdoor veroorzaakte verlaging van de hoogte van de zeewering zorgwekkend. In dit artikel wordt juistheid van de hypothese aangetoond, dat de optredende bodemdaling een natuurlijke oorzaak heeft en verband houdt met tektonische en mogelijk andere geologische processen in de diepe ondergrond. Het belangrijkste bewijs voor een neo-tektonische oorzaak is het periodische karakter van het dalingsverloop van de aangemeten peilmerken van het NAP. Deze duidt op een kleef-slip beweging langs breuken. Dergelijke grote verticale neo-tektonische bewegingssnelheden zijn nooit elders in de wereld op deze wijze geregistreerd en beschreven.
De juistheid van de hypothese wordt verder ondersteund door waarnemingen aan geofysische 2D-seismische opnamen afkomstig uit de olieindustrie, door laboratorium onderzoek van bewegingen langs breuken, door historisch geologisch onderzoek en door recent satellietradarinterferometrie onderzoek (remote sensing uit de ruimte).
Uitgebreider onderzoek naar de oorzak(en) van de bodemdaling ter plaatse van de Hondsbossche en Pettemer Zeewering is van belang om voorspellingen over langere termijn te kunnen doen en tevens om inzicht te krijgen in vergelijkbare geologische processen die op andere locaties langs de Nederlandse kust hoge bodemdalingsnelheden veroorzaken.

Vraagstelling

Uiteindelijk zal antwoord gevonden moeten worden op de volgende vraagstelling:

A. Vindt er locaal en/of regionaal bodemdaling plaats, en wat is de bodemdalingsnelheid en wat is de oorzaak ervan?
B. Indien er bodemdaling optreedt, is er dan een voorspelling te doen over het verloop van de bodemdaling en de bodemdalingsnelheden in de toekomst?
C. Indien er bodemdaling optreedt, is er dan kans op differentiële bodemdaling?
D. Zijn er op grond van de waarnemingen uitspraken te doen over het optreden van bodemdaling langs de overige delen van de Nederlandse kust?

In het artikel wordt slechts een deel van deze vraagstelling belicht en met name waar het onderdeel A betreft. Voor vraagstellingen B, C en D is uitgebreider onderzoek vereist in het Noord-Hollandse gebied en langs overige delen van de Nederlandse kust.

Hypothese

Uitgaande van bovenbeschreven vraagstelling wordt in het artikel de juistheid van de volgende hypothese beargumenteerd:

De gemeten bodemdaling ter plaatse van de Hondsbossche Zeewering wordt veroorzaakt door grootschalige geologische processen in de diepe ondergrond, waarbij neo-tektoniek het belangrijkste proces vormt.

Analyse van bodemdaling met verschillende methodieken

Er is een in het volgende beschreven combinatie van methodieken toegepast om de oorzaak van de bodemdaling ter plaatse de Hondsbossche Zeewering te onderzoeken.

- *Tijd-verplaatsing diagrammen*

  Hierbij wordt het karakter van de beweging per peilmerk geanalyseerd aan de hand van de gemeten NAP-hoogtes per epoch

- *Historisch dalinggedrag*

  Hoogteliggingen van de Hondsbossche Zeewering op verschillende momenten in het verleden, bekend uit archieven, worden met elkaar vergeleken

- *Satellietradarinterferometrie*

  Achtereenvolgende radarbeelden uit satellieten worden met elkaar vergeleken, waarmee bodemdalingsnelheden met een formele precisie van 0,1 tot 0,2 mm/jaar waargenomen kunnen worden. Deze methodiek heeft globaal dezelfde nauwkeurigheid als waterpassen, echter de acquisitiedichtheid (in ruimte en tijd) op harde oppervlakken is vele malen groter ten opzichte van een peilmerkennet, dat vereist is voor het waterpassen.

- *Interpretatie van 2D-seismische opnamen*

  Interpretatie van 2D-seismische refractiebeelden tot meer dan ca. 3000 m diepte, een geofysische techniek veel gebruikt voor de opsporing van olie, gas en mineralen, levert informatie over de opbouw van de ondergrond en het voorkomen van structurele discontinuïteiten, zoals breuken en breukzones. Tevens kan hieruit eventueel in het geologische verleden opgetreden bodemdaling uit de geometrie en positie van lagen afgeleid worden.

Analyse van tijd-verplaatsing diagrammen (TVD'en)

Bij gesteentematerialen, waarin bijvoorbeeld breuken of discontinuïteiten aanwezig zijn, zal bij opgelegde tektonische spanningen niet-lineariteit evenzeer als in grond het geval zijn, maar hier zullen de breuken invloed hebben op de snelheid van deformatie die optreed langs de breuken en kan al dan niet een periodiciteit van de effecten optreden, die een serie van achtereenvolgende snelheidstoenamen en afnamen te zien geeft. Dit kleef – slip (Eng.: stick – slip) gedrag is aangetoond in zandkist proeven op zand (Nieuwland et al., 1999; Nieuwland et al., 2000)) (Fig. 1.1) en wordt ook beschreven bij onderzoek naar het optreden van aardbevingen in Californië (Anderson et al., 2003).

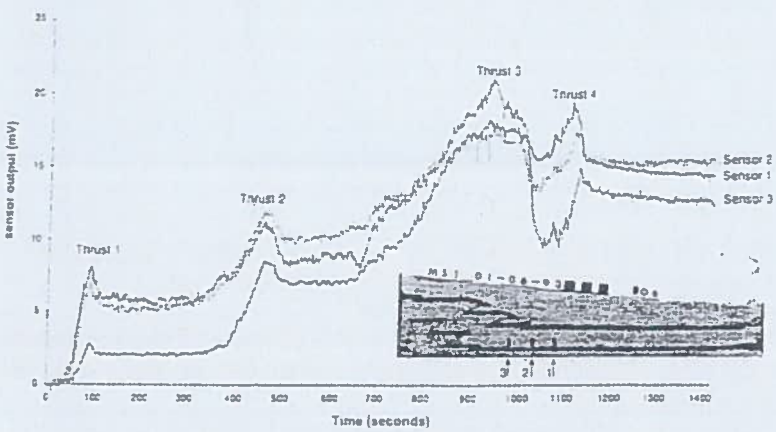

Fig. 1.1 Tijd-verplaatsings diagrammen uit zandkistproeven (Nieuwland et al., 1999)

Of er bij de TVD die de maximumdalingsnelheid ter plaatse van de Hondsbossche Zeewering (Fig. 1.2) sprake is van een multipele zettingcurve, ten gevolge van achtereenvolgende dijkophogingen van de Hondsbossche Zeewering, dan wel dat tektonische en andere geologische processen in de ondergrond werkzaam zijn die dat beeld leveren is onderzocht. In het volgende wordt beargumenteerd, dat het hier gaat om natuurlijke processen, die in het gehele gebied van Bergen tot Petten en mogelijk tot in wijdere omgeving optreden.

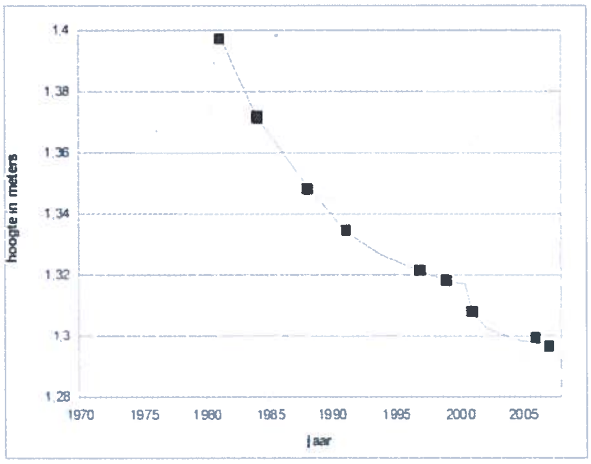

Fig. 1.2 TVD van Peilmerk 14C125 t.p.v. de Hondsbossche Zeewering

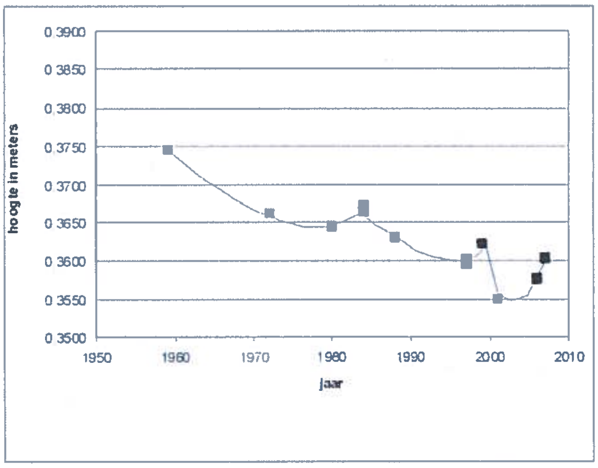

Fig 1.3 TVD van Peilmerk 14C025 ten oosten van de Hondsbossche Zeewering

- Er worden op verschillende locaties in het gebied, en niet ter plaatse van ophogingen door dijklichamen, peilmerken aangetroffen die vanaf 1950 meerdere periodes van dalingsnelheidstoename en -afname te zien geven (Fig. 1.3).
- De toename van de steilheid van de curve na 2001 wordt door het gehele gebied aangetroffen. Bij de andere peilmerken die meerdere periodes te zien geven, wordt de toename in steilheid op verschillende tijdstippen waargenomen
- De periodiciteit van de TVD'en is te zien over het gehele traject van Petten tot Bergen-aan-Zee, en met name waar de grond niet belast is door de dijkophoging
- De periodiciteit is ter plaatse van het Groetveld gesuperponeerd op de dalingslijn die het resultaat is van de snelheid van bodemdaling door aardgasonttrekking

Geconcludeerd kan worden, dat de periodiciteit van de beweging niet gerelateerd is aan de ophoging van de Hondsbossche Zeewering en tevens geen relatie heeft met de gasonttrekking in het Groetveld. Het fenomeen heeft een grote ruimtelijke verbreiding en is in tijd niet gerelateerd aan de menselijke invloeden maar vindt ook in een periode van 20 jaar daarvoor plaats (start gaswinning rond 1970, start ophoging Hondsbossche Zeewering naar Deltahoogte 1977).
Omdat de periodiciteit, zowel in het gebied rond Petten, als in het poldergebied, als in het duingebied tussen Camperduin optreedt, is de invloed van eventuele door de mens veroorzaakte waterstandveranderingen uiterst onwaarschijnlijk. Overigens is deze invloed in zandige aquifers zeer gering (in elastische bereik).

Opmerkelijk is, dat de meting die direct na de aardbevingen van 2001 is uitgevoerd door het hele gebied een aanzienlijke neerwaartse verplaatsing aangeeft, waarmee nieuwe periode begint (Fig 1.2 en 1.3). Deze geeft in veel gevallen een grotere dalingsnelheid aan, dan in alle waargenomen voorgaande periodes. Een relatie van de bewegingen met het voorkomen van de aardbevingen wordt daarmee zeer waarschijnlijk.

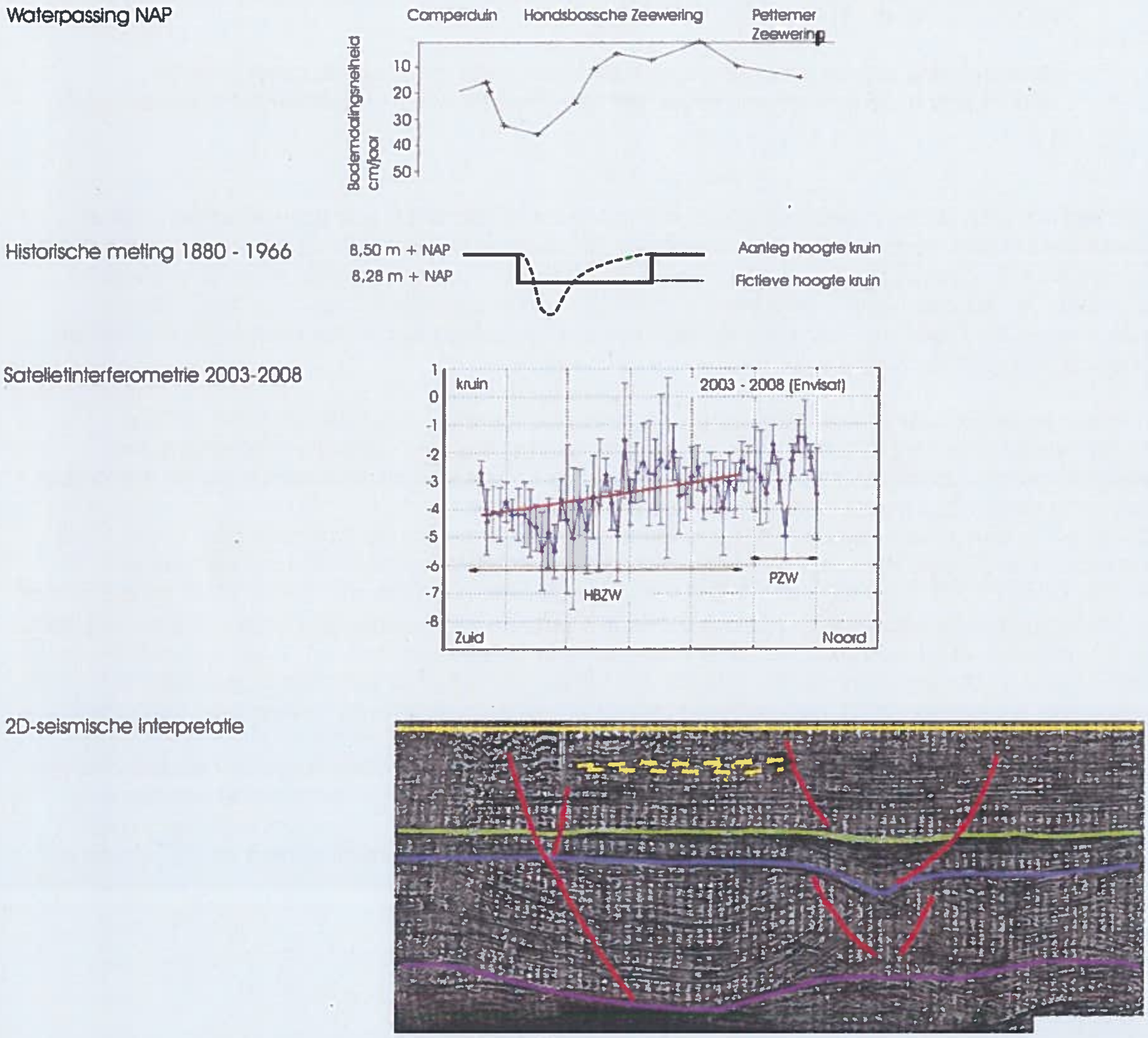

Fig. 1.4

Conclusies en discussie

1. De juistheid van de hypothese, dat de gemeten bodemdaling ter plaatse van de Hondsbossche Zeewering wordt veroorzaakt door geologische processen in de diepe ondergrond is in het voorgaande aangetoond. Met name het periodische karakter van de TVD'en, de overeenkomst voor wat betreft locatie en geometrie tussen de diverse metingen van de in het verleden opgetreden bodemdaling, waarbij bodemdaling langs breuken optreedt, vormen de kern van het bewijs (Fig. 1.4).
De voorlopige indicatie voor de oorzaak van de bodemdaling is, dat plastische deformatie van de Zechstein steenzoutlagen (zouttektoniek) het belangrijkste aandrijvende mechanisme vormen. Zouttektoniek hoeft echter niet noodzakelijkerwijs op zichzelf te staan, en kan verband houden met regionale neo-tektonische processen. Dit is temeer waarschijnlijk, omdat gedurende het Kwartair hoge bodemdalingsnelheden in dit gebied en in grote delen van het Noordzee Bekken zijn geconstateerd (Kooi et al., 1989). Opmerkelijk is, dat in dit gebied gedurende het Kwartair het dikste pakket aan zanden van ca. 500 m werden afgezet bij vorming van de gehele Nederlandse delta. Hiervoor is zeker een belangrijk gedeelte aan tektonische daling noodzakelijk.

2. De vergelijking van de hoogten uit 1875 en die uit 1966 lijken aan te geven, dat de bodemdaling al gedurende een eeuw met een snelheid van minimaal 50 cm/eeuw optreedt.

Hiermee is deel A uit de vraagstelling beantwoordt. Voor wat betreft B kan gesteld worden, dat er aangenomen moet worden, dat de waargenomen processen honderden en zelfs duizenden jaren door kunnen werken. Daarbij kunnen er wel steeds temporele en locatie verschillen in de bewegingen optreden. Om hierover verderstrekkende uitspraken te doen zal uitgebreider onderzoek moeten plaatsvinden. Dit mede met het mogelijk optreden van vergelijkbare fenomenen in andere gebieden langs de Nederlandse kust.

In relatie tot deel C van de vraagstelling is er belangrijke informatie beschikbaar in de TVD'en.
De periodiciteit van de TVD'en vertoont veel overeenkomst met een cyclische beweging die is waargenomen in "zandkist" proeven, waarbij onder een constante deformatiespanning de tektonische beweging langs breuken gesimuleerd wordt (Fig. 1.1).
Opvallend is de steilheid van de curve, en daarmee de toename van de dalingsnelheid, gerelateerd lijkt te zijn aan de aardbevingen, die begin 2001 hebben plaatsgevonden (3,5 op de schaal van Richter)(KNMI, 2001)(Fig. 1.2 en 1.3). Dit is de grootste snelheidstoename, die door het gehele gebied op het zelfde tijdstip waargenomen wordt. Andere waargenomen snelheidtoenamen variëren in plaats en tijd. In KNMI, 2001 wordt een verband gelegd tussen de aardbevingen en de aardgasonttrekking in het Bergen- en Bergermeerveld. Ter plaatse van het Bergermeerveld bedraagt de gemeten sprong in een aantal peilmerken ca. 20 mm in de omgeving van het epicentrum van de bevingen, ter plaatse van de Hondsbossche Zeewering is dit ca. 5 à 10 mm
Er zal in Noord-Holland nader onderzocht kunnen worden of er een relatie is tussen het optreden van aardbevingen en van het optreden van verplaatsingen langs andere aan het gasveld gerelateerde breuken, die niet de epicentra bevatten. Vervolgens kan dan worden onderzocht of er geen risico bestaat voor differentiële bodemdaling uit deel C die de integriteit en stabiliteit van de dijk in gevaar kan brengen.

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Seismic Hazards of Underground Gas Storage in the Bergermeer reservoir, a review

[redacted] 10.2.e , [redacted] 10.2.e , December 2, 2009

Preamble. The review has been written because at this point in time, early December 2009, more than one month after the publication of the second-opinion report[3] by the MIT, no clear overview has been presented yet of what, based on all now available knowledge, and the MIT findings in particular, the best scientific estimate is of the seismic risk associated to operating an underground gas storage in the Bergermeer reservoir. Yet, such an overview is the only sensible starting point for a discussion at decision making level, with all important stakeholders, about whether or not these seismic risks are acceptable. The authors invite all parties involved to indicate whether they agree with the review given, or consider parts of the review presented below incorrect, and- if so- on what arguments, and what the best presentation of the facts would in their view be.

Overview of studies

Logan

In 1997, at the request of Amoco (at that time owner of the field), John Logan (Univ. of Oregon) did a study of the seismic risk of the Bergermeer field. The reason to carry out the study was that a plan was under investigation to in future use the field for underground gas storage, while shortly before, in 1994, two earthquakes had occurred. Study team members were N. Higgs (Amoco) and J. Rudnicki (N-Western Univ.). The report includes a fairly detailed description of key parameters of the field, in particular measured reservoir rock parameters from a large number of bore holes in the Bergen concession (Bergermeer and other fields). The data show a rather wide variation in e.g. Young modulus, reservoir rock porosity, mineral composition etc. The data show that the Young modulus of the reservoir rock increases with decreasing porosity[4].

To estimate the largest expected size of earthquakes in the Bergermeer field the study utilizes a rule-of thumb formula (based on slip approximated as 1×10^{-4} of fault height (38 mm was used), fault area (approximated by vertical height x length) and elastic parameters of the reservoir rock). The estimate: M=3.8 is the order of magnitude of the largest earthquake to be expected. (When the Logan report was written M=3.2 was the largest event in the Bergermeer field. A detailed study of the reservoir fault geometry was not available at the time (fault zone used: see Annex 2)).

The Logan report explicitly underlines the approximate nature of the estimates: "We reiterate that the estimates discussed are based on relations developed for earthquakes from regions other than the Netherlands and for earthquakes larger than those anticipated in the Bergen concession. Although comparison with the measurements for the 1994 Bergermeer event gives credence to our predictions for future events, the predictions remain estimates and it would be unwise to adhere to them too rigidly". *Conclusions, p. 126*)

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[1] Assoc. Prof. UNESCO-IHE, Delft (retired)
[2] Shell Research , Amsterdam (retired)
[3] Second opinion on the TNO geomechanical study underpinning the BSG project proposal (commissioned by the Min. of EA.).
[4] No reservoir rock samples are available of the fault zones. Since samples from Bergermeer wells 1,2,5,8A (TNO 2008, p23) show that the porosity of the reservoir rock at the bottom and top of the reservoir is very low –next to 0- it appears logical to assume the same for the (reservoir bounding) fault plane areas and for the internal part of the central fault –which is sealing gas flow from one part of the field to the other.

Seismic analysis 2001 earthquakes in the Bergermeer reservoir (KNMI 2001)
Based on detailed measurements, the KNMI made a study of the two 2001 earthquakes in the Bergermeer M=3.5 and 3.2) (and one of 2.7 on the NE bounding fault of the neighboring Bergen-aan- Zee reservoir). (Overview of findings: see Annex1).

The study shows that the two Bergermeer quakes are independent, and that both occurred along the central fault in the reservoir, at the southern end of the fault. The first one was preceded by 0.16 seconds by a smaller one (M=1.8), most likely triggering the entire event.
Since the two quakes were only one day apart and the hypocenters very near to each other, it appears quite possible the second quake concerned an as-yet (during the first event) not-slipped part of the same fault area (barrier, asperity model; Scholz (1990)).
The earthquake was determined from the seismograms as being a "reverse faulting" event.

The macro seismic intensity was assessed by the KNMI as EMS scale VI+ at the epicenter, with the EMS-IV iso-intensity circle at approximately 6 km from the epicenter. An estimate of the EMS-V contour line can be derived from comparison with the 1997 quake in Roswinkel ((approx. same depth) where more measuring equipment was at the site –including accelerometers- and more detailed iso-intensity circles were reported (annex 3)). The EMS-IV contour was in that case also at 5.5-6 km and the intensity at the epicenter VI. The estimated EMS-V contour of the Bergermeer 2001 quake thus was at approximately 2-3 km, i.e. in the city of Bergen the intensity was mostly between V- (just below V) and V+.
The PGV and PGA of the Bergermeer 2001 quake are not available from measurements. Again based on comparison with Roswinkel 1997 (as presented in the KNMI 2004 study) the likely value of PGV (the most relevant measure in view of damage to buildings) in the city of Bergen, at 2 to 3 km from the epicenter, was from 10 to 20 mm/sec. (PGV of approx. 30-40 mm/sec at the epicenter).

Seismic hazard study 2004 (KNMI, TNO/KNMI summary study; paper van Eck ea. 2006)
During 2003, a number of studies were carried out by the KNMI and TNO to assess the hazard of damage to buildings caused by earthquakes induced by natural gas production in the Netherlands (KNMI being responsible for seismic hazard analysis and TNO for the analysis of local sub-soil response and risk of damage to buildings).

The key findings are summarized in the annex in a number of maps, of all gas fields in the Netherlands showing their seismic risk level and the estimated T(10) and T(100) ground velocity from earthquakes (Annexes 4.1 and 4.2). The maps clearly show that the Bergermeer field, together with the Roswinkel field in Drente, stands out as the field with by far the largest hazard. The map also shows that in the Bergermeer case, the hazard is in fact highest at the northern end of the reservoir (i.e. in the city of Bergen), due to the particular sub-soil conditions.

For the city of Bergen the predicted ground-velocity (PGV) that can be expected once per 100 years (T(100)) is 60-70 mm/sec (annex 4.1). The T(10) PGV is 20-30 mm/sec (ref. 4).

For the *city of Bergen* this implies that (under the conditions prevailing during depletion of the field):

- There was a probability of 10% per year at an earthquake leading to a PGV of 20-30 mm/sec.
- There was a probability of 1% per year at an earthquake leading to a PGV of 60-70 mm/sec.

The probabilities given above well reflect the 4 events that took place (M=3.0, 3.3, 3.2, 3.5) during the around 30 years of gas production from the field (the first quake –reactivating the existing fault(s)- taking place when the pressure in the field had dropped to approximately 1/4 of the initial value).

Apart from the "concluding" hazard estimates summarized above the KNMI study reports the outcome of an analysis of the frequency/magnitude relationship for the ensemble of all induced earthquakes in the Netherlands in the 1986-2003 period. Using a model that postulates the existence of a "maximum" earthquake for the "family" of shallow induced earthquakes an applying a Monte-Carlo simulation, it was found that for this data-set there is a 50% probability that the M_{max}=< 3.7, a 84% probability that it is =< 3.9, and a 95% probability that it is =<4.1.(Or, equivalently: there is a probability of 50% that M_{max} >3.7, of 16% it is >3.9 and of 5% it is > 4.1.
Note: in a discussion on Nov. 20, 10.2.e (KNMI) communicated that a very recent re-calculation with all data up to 2009 gives the same result i.e. the earthquake data 2004-2009 exactly fit the pattern of the preceding period.

While the T(100) values for PGV given above are prediction on basis of an extrapolation very little beyond the domain of observed induced earthquakes in the Netherlands and likely to be fairly reliable (and the T(10) estimates based on values well within the domain of the observations), prediction of the probability of larger induced earthquakes is more speculative (the outcome being quite dependent on the model selected for the extrapolation). Worded differently: the confidence interval of such predictions is large. In the KNMI 2004 study no values for the probability of occurrence of larger earthquakes (e.g. M=3.9 or 4.0) have been given. Based on the data-set and the seismicity models derived by KNMI for both N-Netherlands in total and for Roswinkel/Bergermeer a reasonable estimate for the return period of an M=3.9 quake in the Bergermeer is [200, 500][5] years (i.e. the probability of a quake M=3.9 is around 3 times lower than that of an M=3.7 quake). For a safety study, in situations with this type of uncertainty, best practice is to take the upper bounds of the confidence limits as the ruling risk estimate (i.e. in this case: once in 200 years for M=3.9).

Although not explicitly mentioned in the KNMI 2004 study there is one important caveat to the estimate of maximum earthquakes in the N-Netherlands *at a specific location.* Irrespective of the overall statistical probability estimate, it is very unlikely that the maximum earthquake at any given site will exceed a value determined by the actual physical conditions at that site. More in particular: the geometry, size, and characteristics of fault areas at a location that can give rise to an induced earthquake. In fact all induced earthquakes in the Netherlands with M>3.0 occurred either in Bergermeer, or Roswinkel, or near Westeremden in the Groningen field; nowhere at locations where fault dimensions don't match quakes of a considerable size did those happen (note: no comprehensive overview of all major fault areas in gas fields in the Netherlands has been published, so whether other as yet not reactivated "high risk" locations exist, e.g. within the Groningen field, has not been assessed in the open literature).

For this reason it is likely that actual physical conditions of a given location are the determinant of the likely maximum of a quake at that site[6] rather than the prediction from the overall frequency/ magnitude relationship for the North of the Netherlands. This corresponds to the way in which the KNMI has carried out the hazard study, where the relative probability of a quake occurring was taken from the overall relationship, but the probability of a particular size (magnitude) represented by a scaling factor (for the approximate (observed) repetition time for the largest known quakes at that location).

[5] I.e. the likely return period lies lies in an interval between 200 years and 500 years.

[6] It cannot be excluded that operational practices of gas production in a certain field, or -even more- in case of UGS (see later section on ΔT and $\Delta P/\Delta t$) also influence frequency and even magnitude of quakes.

TNO study 2008

The TNO study starts with re-iterating the Logan M_{max} estimate, using the same rule of thumb. For the calculation of the slipping area TNO adjusts the Logan calculation by taking the actual (inclined) fault area rather than vertical fault height. This increases the Logan estimate by 0.1 magnitude point to 3.9.

The report gives no estimate of error margins of the input data for the calculation, nor of the relationship used to derive M_L from the estimated M_0 (Hanks and Kanamori)[7]. For the Young modulus the same value was taken as in the Logan report (the upper bound of the range of values measured in the Bergermeer wells 1 and 2). For the slip-area the fault-plane area of the Northern part of the central fault was taken (up to where the difference in height between the two (mutually sealed) compartments of the field disappears) (the area excludes the fault continuation just above the reservoir (see annex 2 drawing and comment in MIT report). For slip (δ) 10^{-4} x fault plane height was taken (4.5 cm).

In particularly the uncertainty in slip estimate is considerable (note that in the geomechanical model presented by TNO chap.6 typical slips calculated for the depletion period are 10-15 cm). Assuming a plus or minus 20% variation in one of the three above mentioned input parameters changes the estimated M by approx. 0.1, while the scatter in the Hanks/Kanamori relationship is typically 0.5 (*MIT, p.11*).

All in all, stating that the likely maximum earthquake to be expected in the Bergermeer reservoir is of the order M_L= [3.7, 4.1] *(lies between 3.7 and 4.1)* better reflects the available knowledge than the 3.9 presented as "worst event possible" in the TNO study (i.e. present a confidence interval rather than a point estimate).

The TNO study then proceeds with an estimate of macro (average) reservoir parameters (such as the compaction coefficient) from subsidence data. The main finding, the compaction coefficient being between 0.3 and 1.1 10^{-5} bar^{-1} ("credible" *MIT, p. 10*), -confidence limits being shown here (the only part in the TNO study where this is done)- shows a large uncertainty: a factor 4 between the lower and upper bound of the interval.

The next step in the study is an investigation of the thermo-mechanical response of the reservoir to injection of gas[8] that is considerably colder than the reservoir (in particular at the start of cushion gas injection). The finding is that locally the temperature change of the reservoir rock is considerable (up to 10 ^{0}C at 100m from the well and to 4 ^{0}C at 200 m from the well)[9], which –given the very considerable maximum slip displacement created by a temperature gradient (roughly a δ=1 cm per 1^o temperature gradient; TNO p.21)- leads to the conclusion that a safety margin of at least 150 m between wells and fault zones and close monitoring during operation are needed for safety reasons (taking into account accuracy of fault location: 200 m) ("sound recommendations". *MIT p.10*)[10,11].

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[7] And equating M_L to M_W derived from Hanks and Kanamori.

[8] In its recommendations, TNO adds that in case of water injection (apparently also provisionally intended) the temperature effects are much larger –due to the high heat-capacity of water- and that it will require a detailed study to find out whether water injection would be safe.

[9] The study doesn't address the combined effect of the eventually envisaged 26 injection wells, although the dimensions of the field are not really large compared to the recommended safety margin (block width between longitudinal faults around 1,000 m –reducing to the North-, field length around 6 km).

[10] Note: this appears to imply that some of the existing boreholes cannot be used safely for gas injection (this has not been reflected in the project proposal, which appears to assume that all 6 existing boreholes can be used).

[11] The TNO study mentions a caveat: " ...that unrecognized sub-seismic faults are present ...; ... effect of potential thermal cracking on permeability and preferential flow has not been investigated." A simplified reservoir image (TNO p.23, taken from Horizon (2006)) also shows the existence of faults in the field perpendicular to the main longitudinal (NW/SE) faults.

The core element of the TNO study is the geomechanical model analysis of the reservoir ("In the geomechanical analysis the impact of gas storage on seismic hazard in the Bergermeer gas field is investigated", *TNO, p.50*).

The main conclusion presented from this analysis is that as a result of the use of the reservoir for underground gas storage the risk of earthquakes of a significant size reduces strongly, and that no events with a magnitude higher than M=2.4-2.7 are to be expected (Table 7.3, *TNO p. 84*; "fault movements during injection are much smaller than during depletion and are limited to a maximum of 0.7 cm", *TNO p.81*).

In its report, MIT rejects the validity of the TNO geomechanical analysis for predicting the behavior of the reservoir. A number of reasons is given for this, an important one being that the model is unable to predict the earthquakes that occurred during the depletion period correctly (-even at all) (*MIT, p.11, 12, 13*). With the exception of the sections re-iterating the Logan estimates, the thermal effects study and the subsidence analysis, the MIT report invalidates the TNO study as a source of information about the seismic hazard of underground gas storage in the Bergermeer field that can be relied on for decision making.

MIT second Opinion

The nature of the MIT report is different from that of the reports reviewed above, in that it is a second opinion on the TNO 2008 study -not a stand-alone study of the seismic risks of the Bergermeer reservoir- and because, as the authors underline themselves, the time available for their study/report was quite limited.

The key findings of the MIT (already mentioned in the review of the TNO 2008 study above) are:

- The geomechanical model proposed by TNO for estimating the size of likely earthquakes in the reservoir (TNO ch.6, 7) does not provide valid predictions (*MIT p. 16 conclusion 4; p.11,12,13*). The conclusion of the TNO study that during the operation of the UGS the largest seismic event would be of M=2.4-2.7 is rejected (p.5, point 7).
- The probability of earthquakes will during a period of underground gas storage (the proposed BGS project) be similar to what it was during the later part of the depletion period ("maturity phase of the field", i.e. after the first stage of depletion has reactivated faults) (*MIT p.14 para.4; p16. conclusion 5; p.4, points 4 and 5; p. 20, 21, answers to questions 1 and 2 of Gasalarm2*).
- The best available estimate of the seismic hazard presented by the Bergermeer reservoir is the one given in the KNMI/TNO 2004 study (publication in English: paper van Eck et al. 2006) (*MIT p.17, conclusion 7*).
- The estimate of the likely maximum earthquake given by Logan and re-calculated in TNO(2008) (M_{max}=3.9) is credible, and consistent with the KNMI(2004) probabilistic seismic hazard analysis (*MIT p.5, point 8*).
- One observation by MIT (although somewhat hidden in the report on p. 25, answers to questions of the Tccb) has to be added in this shortlist: "the probability of triggering earthquakes depends on both the stress level and the rate at which stress changes". The implication is that during injection/production the probability of triggering earthquakes increases ($\Delta P/\Delta t$ being around 20x higher than during initial depletion of the field)[12].

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[12] It is significant to note that in a reverse sense the MIT observation is confirmed by the seismic history of the Roswinkel field (the field in the Netherlands with the most detailed measuring equipment in place, including measuring equipment at hypocenter depth capable of detecting mini-events (slips of areas of only a few m2)). In Roswinkel, where a high level of seismic activity was observed throughout the second part of the depletion history, after depletion (i.e. with $\Delta P/\Delta t$=0) the seismic activity came to a full stop (including mini-events).

The summary attached to the MIT report doesn't seem to fully reflect the key technical conclusions of the MIT concerning the TNO study, in that "c'est le ton qui fait la musique". The summary starts with stating agreement with TNO on the "most important conclusion", formulated to be M_{max}=3.9. In actual fact, in the TNO study the M_{max} calculation is in chapter 2 "Background", and the key conclusion that was brought forward from the TNO study to the EIA submitted in support of the project request was that during BGS operation the maximum event would be M=2.4-2.7, i.e. that the project would in fact strongly reduce the seismic risk (stabilize the field). This conclusion of the TNO study was explicitly rejected by MIT (point 1 in the shortlist above).

The MIT report also contains comment on the probability of occurrence of earthquakes and estimation of the magnitude of such quakes. In a general sense it emphasizes the uncertainty margins of such estimates. On p. 8, Table 1, M_L estimates are shown from two different statistical relationships between M_0 and M_L, exhibiting a 0.2-0.3 difference between the two M_L estimates for Bergermeer (using Reamer/Hinzen(2004) gives the higher estimates compared to Kanamori/Hanks). On p. 14 it is stated that uncertainty for a given magnitude M_L is +/- 0.1 anyhow[13].

Specifically, the report also comments on the probability of an earthquake of magnitude 3.9, basing itself on the KNMI 2004 study (the van Eck et al.(2006) paper). However, the statement in the MIT report, referring to van Eck (2006), that the probability of an M=3.9 is extremely low (*MIT p. 17*) cannot be directly retraced in a quantitative manner in the KNMI study/paper (see review KNMI 2004 above).

Along the same line, the MIT report, again referring to KNMI 2004/vanEck(2006), the MIT report mentions a probability of <1% over the life of the project that an event M=3.9 would occur (*MIT p. 23, answer to question 7 of Gasalarm2*). In the reference quoted, the only place where a 1% percentage probability is given is in the T(100) graphs and maps (for PGA and PGV, without explicitly mentioning the corresponding M_L; see review KNMI 2004 above). This means 1% *per year* over the life of the project, i.e., taking a project duration of 50 years (large scale use of gas in the NW Europe region being foreseen until at least 2070-80), a probability of approximately 50% in the entire project period[14].

The MIT report also contains a brief comment on the intensity at surface level of an earthquake with magnitude 3.9, stating that this would an intensity[15] VI+ ("between VI and VII, but closer to VI"). This is inconsistent with the KNMI observations of the 2001 event, which was M=3.5 (detailed calculation: M=3.45), and had EMS VI+ intensity (see review KNMI 2001 above).

Given the VI+ intensity of the 2001 event, a $10^{(1.5 \times 0.45)}$= 4.7 times heavier (at the epicenter) quake must, in the local conditions given, be expected to generate around EMS VII intensity. This indeed is a high value for a quake of such a relatively low magnitude, and far more than could be expected for a tectonic earthquake of that magnitude. However, given the existing experience with induced shallow quakes in the Netherlands and in the Bergermeer in particular, this is what has to be reckoned with in a safety study.

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13 Apart from uncertainty in either M_0 (in case of a deterministic estimate) or in the magnitude/frequency relationship (in case of a probabilistic estimate).

14 It should be added that applying the attenuation relationships given in the KNMI study the estimated M corresponding to the T(100) PGV is just above 3.7, while the probability of a 3.9 event is roughly 3x lower according to the frequency/magnitude relationship.

15 No mention of the intensity scale meant is included, we assume the EMS scale is meant.

Experience from the 2001 M=3.5 earthquake

Apart from the knowledge about the earthquakes in the Bergermeer in 1994 and in 2001 documented in the studies reviewed above, there are also the "experts by experience" living on top of or close to the Bergermeer reservoir. When it comes to the actual damage created by the 2001 M=3.5 quake, these experts (/ their 2001 buildings) indeed are the most reliable source of information. It is regrettable that no attempt was made as part of the EIA to analyze this information in a comprehensive manner. This means that only case-study information is available. Yet, this case study information provides a quite consistent picture of the 2001 event and the damage it created.

The immediate impact on those indoors in their building at the moment of the event in Bergen city (i.e. 2-3 km N of the epicenter, roughly at the EMS V contour line) was generally described as one of immediate alert that a severe accident might have happened nearby (such as a vehicle accidentally driving into the wall of the building, or an airplane having crashed nearby).

Damage to buildings varied considerably, depending on construction strength and type. The worst damage reported consisted of through cracks in bearing masonry construction walls (both outside walls and interior walls), and internal walls tearing loose from external construction walls. Individual damage claims of up to EUR 5,000 were paid by BP for repairs. In most cases of minor damage (small cracks in walls and cement floors) no claims were submitted, and in many older houses small cracks were also not immediately or at all recognized as caused by the event, while cracks in masonry foundations (the standard foundation used in Bergen –the subsoil being sand- in houses built before 1950) went unnoticed anyhow.

In general, buildings dating from the 1970's and later (commonly with reinforced cast concrete foundations and/or construction walls) appear to have experienced no significant damage.

The damage experienced from the 2001 quake, which in the city of Bergen had an intensity of approximately EMS-V, appears to have been more severe than was to be expected on the basis of general literature. The TNO 2008 study mentions that expected damage from an EMS VI quake (i.e. a quake which is one order of magnitude on the EMS scale stronger than the one experienced in Bergen-city in 2001 (EMS-V)) is: "most buildings have damage of category 1 (no structural damage, hair-line cracks in a few walls), some buildings will have damage of category 2 (slight structural damage like cracks in walls and fall of fairly large pieces of plaster[16])" (*TNO 2008, p.19*). Had TNO investigated the actual damage experienced in Bergen in 2001 it would have noted the difference.

A possible explanation why the actual damage was quite high, given the relatively low intensity of the quake[17], lies in on the one hand the sub-soil conditions (the transition between the soft peat containing soils East of the dunes and the old sand deposits of the dunes on which Bergen is built (see annex 4.1), and on the other hand the dominant type of buildings in Bergen: most of the housing stock in and immediately surrounding the center consisting of free-standing houses built before 1950, typically with masonry foundations.

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[16] Note: plaster of the type that could fall off in larger pieces is a very uncommon type of internal wall finish in this region (so not to be expected on a significant scale in the case of Bergen); it is much more typical of construction habits in countries were tectonic earthquakes are common, such as Italy.

[17] The Bergen inhabitants were lucky in 2001 that the epicenter of the quake was at the southern end of the reservoir, 2-3 km away.

Best estimate of the seismic risk caused by UGS in the Bergermeer reservoir
Based on the review of available information given above, the best estimate of the seismic hazard caused by the operation of an UGS in the Bergermeer reservoir is given by the KNMI 2004 study, as summarized in annex 4.1. The T(100) predictions can be considered to be quite reliable.

For the city of Bergen the prediction implies that there is a 50% probability[18] of an earthquake generating a ground velocity >= 60-70 cm/sec. during the BGS project period.
This velocity is an estimated 3-5 times higher than that of the quake of 2001. The energy-content of a blow, which determines the damage, caused by a certain level of ground velocity can generally speaking be expected to increase with V^2 (the square of the velocity V; collision impact). The actual damage can be expected to increase proportionally with energy content of the quake *within a given construction strength regime* (semi-elastic behavior). However, when the strength of a blow exceeds the maximum strength limit of a certain construction, it will fail, and hence damage will suddenly increase to a much higher level at that point, as damage descriptions given in the EMS scale broadly confirm.

The probability of having a (number of) smaller event(s), of a size comparable to the 2001 event is much higher (slightly below the T(10) estimated in MKNI 2004): around 300% during the project period (i.e. on average one every 15 years).

Larger quakes are possible. An estimate of the probability of their occurrence is more uncertain. The best estimate for a safety study purpose is that the probability of an M=3.9 quake (approx. 2x heavier than the T(100) event above; approx. 3.7) is around 0.3x that of a 3.7 quake, i.e. 15-20% in the project period[19].
The ground velocity PGV_{max} of an M=3.9 quake will be approximately 90 mm/sec[20] (based on KNMI 2004 attenuation relations). Larger than M=3.9 quakes are also possible (with an again higher uncertainty in predicting their probability). Based on the difference in probability of an M_{max}> 3.9 and 4.1, respectively, in the KNMI 2004 Monte Carlo simulation, a 5% probability of a 4.1 event during the project period has to be reckoned with in a safety study (with an expected PGV of 130 mm/sec).

A final reference is important: to available knowledge about the damage to a building that can be expected from shock waves (/vibrations). In the Netherlands there is an SBR[21] limit for the ground-level speed of shock waves. For speeds exceeding this limit a building can be expected to start developing damage (increasingly with further increase of V). For common building types in the Netherlands the SBR-limit is 6 mm/sec, while for vulnerable buildings (old, or with construction weaknesses) it is 3 mm/sec. (see ref.4). The implication of this limit is that in existing built environments new activities likely to create shocks/vibrations in excess of this limit should not be undertaken, while new buildings near installations that risk to produce larger shocks/vibrations from time to time should meet construction strength requirements enabling them to withstand such shocks without being damaged.

[18] Note that this estimate is based on slow gas flow conditions, as they were during the initial ges production from the field. In the case of UGS the rate of pressure/stress change will be much higher (20x), and this will increase the probability that quakes occur. However, since there is no quantitative estimate available of the extent of this increase, we have omitted it here. This means that the estimate of 50% has to be considered the minimum-estimate (the real probability might be quite a bit higher).
[19] For safety study purposes the upper bound of the confidence limit being taken.
[20] Note that this is consistent with the energy-content being roughly proportional to the square of PGV (sqrt(2)*65=90).
[21] SBR: Building Reserch Foundation

The PGV experienced in the center of Bergen from the 2001 quake reached an estimated 10-20 mm/sec, i.e. well above the SBR limit. Reported damage from the 2001 quake is consistent with this, with the remark that apparently at a PGV exceeding the SBR limit for normal well constructed buildings by a factor 3 the damage was still quite modest. This can be explained from the short duration of the shock wave. Yet, given the steep increase in expected damage with increasing PGV, it is very likely that a PGV 3-5 times higher than in 2001 (the KNMI 2004 T(100) PGV prediction) will lead to severe damage to all vulnerable buildings and to a significant number of normal buildings, while a large majority of all other buildings will experience damage varying from light to substantial[22].

References

1. Logan J.M, Higgs N.G., Rudniki J.W.(1997). Seismic risk assessment of a possible gas storage project in the Bergermeer field.
2. Haak H.W, Dost B,Goutbeek F.H. (2001; KNMI TR-239). Seismische analyse van de aardbevingen bij Alkmaar, 2001.
3. Seismic hazard due to small shallow induced earthquakes. Van Eck T, Goutbeek F, Haak H and Dost B. (KNMI, WR-2004-01)
4. Seismisch hazard van geinduceerde aardbevingen (integatie van deelstudies), TNO/KNMI 2004 Wassing B, van Eck T, van Eijs, R. TNO-NITG 04-244B/KNMI Publ. 208.
5. Horizon bv. (2006) Geomechanics of the Bergermeer field (data; not publicly available)
6. TNO report 2008-U-R1071/B Bergermeer Seismicity Study
7. Hager, Toksoz, MIT (2009) Second Opinion on TNO report (ref.6).

[22] This damage expectation based on extrapolation of local 2001 experience is broadly consistent with damage descriptions given in the EMS scale for the applicable intensities.

Annexes

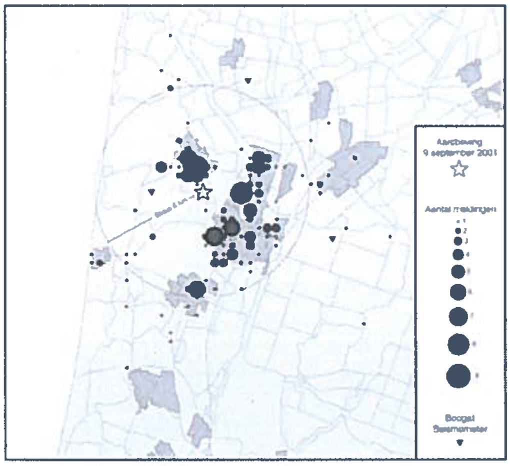
1. Key data Bergermeer 2001 quakes (source: KNMI 2001)

	9 september	10 september	10 oktober
Epicentrum (RD)	x: 109.374 y: 518.265	x: 109.274 y: 518.445	x: 105.011 y: 521.739
Diepte	2,0 km	2,0 km	2,5 km
Intensiteit I_o	VI+	IV-V	III+
Magnitude M_L	3,5	3,2	2,7
Moment M_o	$1{,}9\cdot 10^{14}$ Nm	$6{,}3\cdot 10^{13}$ Nm	$1{,}8\cdot 10^{13}$ Nm
Straal van breuk	680 m	470 m	460 m
Verschuiving	7,4 mm	5,0 mm	1,4 mm
Stress drop	2,8 bar = 0,28 MPa	2,9 bar	0,8 bar

The detailed calculation of Mw: (in the table above M_L is taken equal to Mw)

	9-9-2001	10-9-2001	10-10-2001
M_0	$1{,}9\cdot 10^{14}$ Nm	$0{,}63\cdot 10^{14}$ Nm	$0{,}18\cdot 10^{14}$ Nm
M_w	3,45	3,13	2,77

Damage claims received



Type of quake: reverse faulting (report text is Dutch)

Het haardmechanisme sluit precies aan bij de richting van de strekking van de breuk waarlangs de aardbevingen hebben plaatsgevonden (zie figuur 6 en 7). Het is dezelfde breuk en hetzelfde mechanisme als van de bevingen uit 1994. Het haardmechanisme, kan omschreven worden als een inzakking langs een overhellende breuk met een strekking van 130°, een hellingshoek van 66° en een duiking van 73°. De breuk midden in het gasveld heeft een overeenkomstige hellingshoek van ca. 70° en een strekking van 127° en loopt door tot aan de basis van het Tertiair. Uit figuur 6 wordt duidelijk dat de breuk ontstaan is in een proces van afschuiving (normal faulting). Het proces dat nu tijdens de drukdaling door gaswinning plaatsvindt is opschuiving (reverse faulting). Hierbij zakt het gesteente onder het overhangende deel in en vormt daarmee een bijdrage aan de compactie.

Macro seismic intensity: EMS VI+ at epicenter, R (I=IV): 6 km. (report text is Dutch).

Op grond van de meldingen van schade is een kaart samengesteld (zie figuur 8). De verdeling van de schade is vergeleken met de schade van de bevingen uit 1994. Omdat het tijdsverschil tussen de twee bevingen op 9 en 10 september zo klein is, kan er moeilijk een onderscheid gemaakt worden tussen schade van de eerste of de tweede beving. De trillingen van de eerste beving op 9 september waren tenminste een factor twee krachtiger dan de bevingen op 10 september. Toch was de beving van 10 september nog een factor 1,2 groter in amplitude dan de beving van 21 september 1994 (zie de seismogrammen in figuur 2). Uit de verspreiding en de aard van de gemelde schade wordt duidelijk dat in het epicentrum een intensiteit van VI is bereikt. Dit is in overeenstemming met de magnitude van de beving op 9 september. De straal R_4 waarbinnen de intensiteit IV of hoger is, wordt voor deze beving geschat op 6 km. Dit is ook de straal waar binnen de meeste meldingen van schade gelegen waren.

2. Fault zone Bergermeer reservoir with central fault as shown in Logan report (1997)

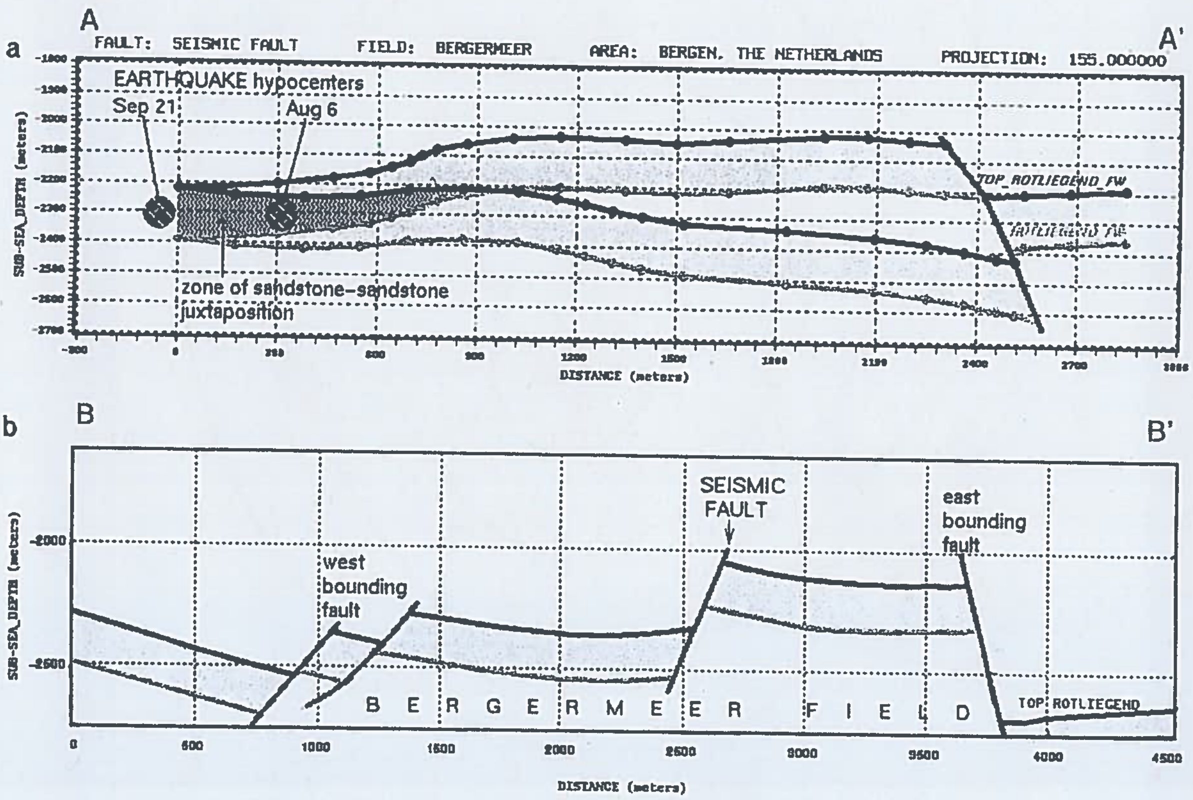
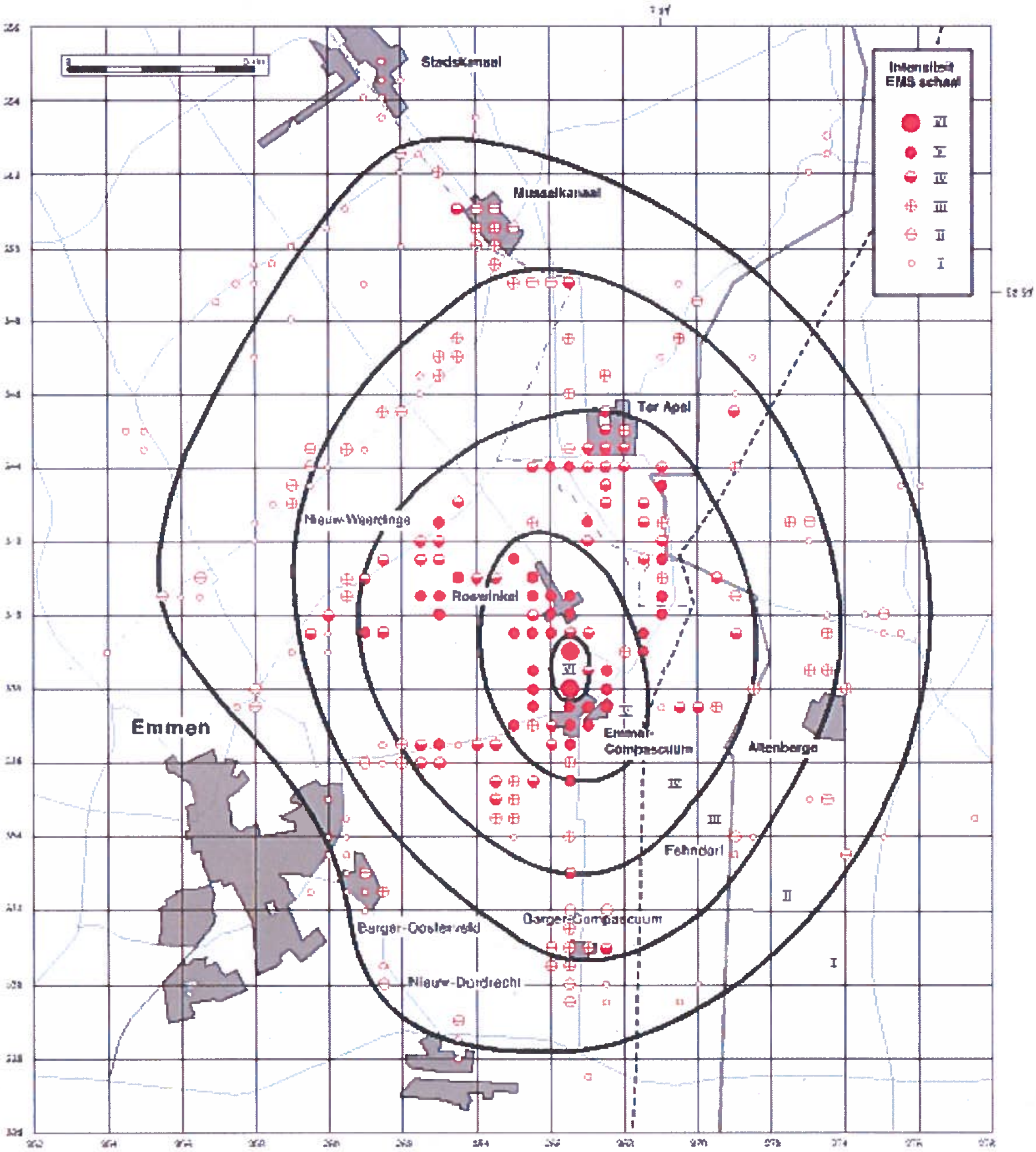


Figure D-2. a) NNW-SSE fault plane section A-A' along seismic fault, Bergermeer Field.
b) SW-NE cross section B-B' across Bergermeer Field, The Netherlands.

Note: The continuation of the central fault to the north (as apparent from the 2007 reservoir geometry study by Horizon bv., reported in the TNO 2008 study) was not considered –note the epicenter of the Sept 1994 quake (M=3.2) being just at the start of this northern continuation.

3. Macro seismic intensity (EMS scale) of quake Roswinkel M=3.4 (1997)

Note: a similar map for the 2001 quake in the Bergermeer is not available. However, since the attenuation relations to be used in both cases are the same (KNMI 2004), the different intensity zones of the Bergermeer event will be quite similar, in particular the distance between Intensity zones. The Bergermeer 2001 quake occurred at a dept similar to the Roswinkel 1997 one.

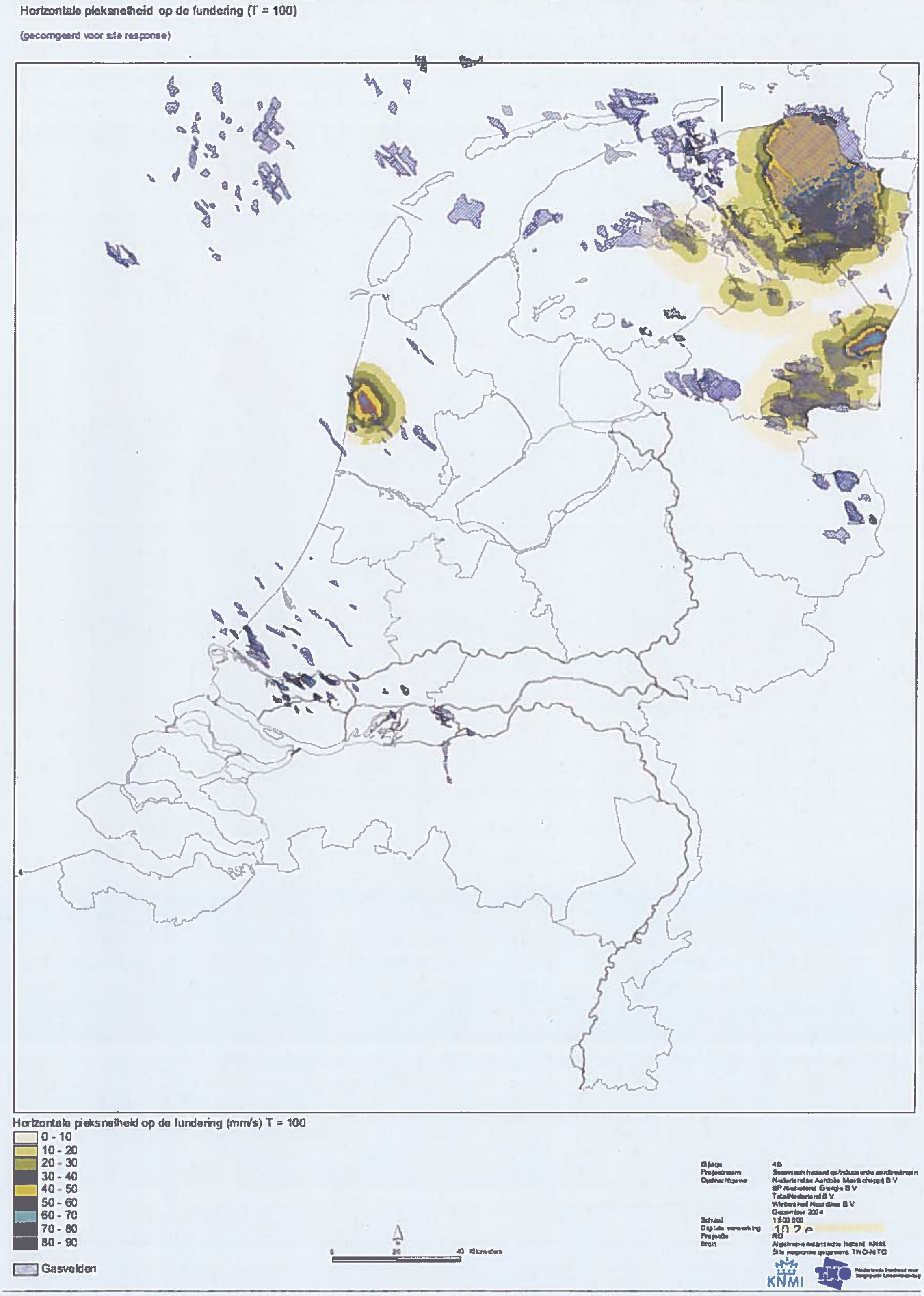


KNMI

10.2.e.

4.1 Seismic risk map for gas fields in the Netherlands (quakes induced by gas production)

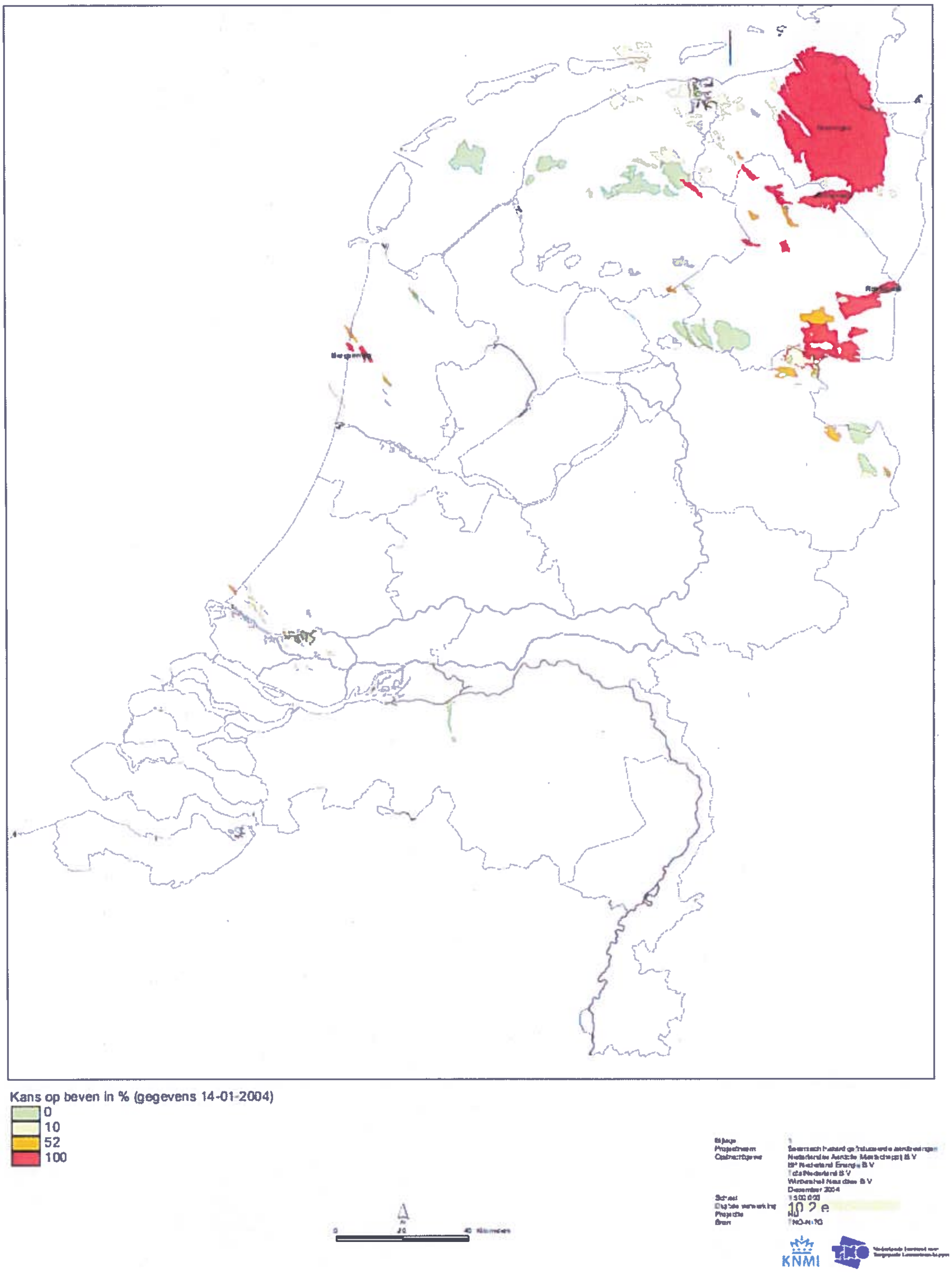
Note: as can be seen from the map, the highest velocities above the Bergermeer field are to be expected in the northern part, i.e. *in the city of Bergen*. This is due to the local specific shallow sub-soil conditions.



4.2 Overview of gas fields in the Netherlands and their seismic risk

As can be seen from the map, there is a significant number of small fields with zero or very low seismic risk (which can be used for underground gas storage).

Kans op beven (in procenten) op basis van verwachte totale drukval voor de verschillende voorkomens



Questions regarding the Technical review of Bergermeer seismicity study by profs. Hager and Toksöz

1) There has been considerable debate about the interpretation of the findings of the *Technical review*. Most of the issues of debate have been mentioned in the *Bro-reactie voorontwerp-rijksinpassingsplan Bergermeer Gasopslag* (pp. 29-30), submitted bij the municipalities of Alkmaar, Bergen, Heiloo and Schermer. We would like professors Hager and Toksöz to comment on the accuracy of the findings of the municipalities. Is their interpretation of the *Technical review* adequate?

2) In the *Gasopslag Bergermeer. Voorontwerp Rijksinpassingsplan* (RIP) the probability of a Ml = 3.9 earthquake is mentioned as "less than 1%" (p. 62). In the *Technical review* this probability is also defined as "less than 1% over the life of the project" (p. 23). The Gasalarm 2 foundation has argued repeatedly that the probability of a Ml = 3.9 or Ml = 3.7 earthquake is much higher, because a correct interpretation of the available sources leads them to conclude that the probability is 1% *every* year over the life of the project. If this is correct, the probability would not be "less than 1%", but almost 40% over the life of the project.

   A conclusion on this issue depends on the interpretation of the relevant sources; in the *Technical review* reference is made to the Van Eck (2006) study. The Gasalarm 2 foundation argues that a KNMI TNO-NITG report by Wassing, Van Eck and Van Eijs (december 2004) clearly shows that the estimate of a probability of "less than 1% over the life of the project" in the *Technical review* is not consistent with the conclusion in the report by Wassing et al..

   a) Although reference is made in the *Technical review* to the van Eck et al. (2006) study to substantiate the claim that the probability is less than 1%, we have not been able to find a passage in which this probability is mentioned. Are professors Hager and Toksöz able to specify their claim by giving a reference to the page number in the publication of Van Eck et al. (2006)?
   b) Are they able to elaborate on their interpreation of this source and on the way in which they conclude that the probability of an Ml = 3.9 earthquake is less than 1% over the life of the project?
   c) Can professors Hager and Toksöz give their opinion on the claim of the Gasalarm 2 foundation that the study of Wassing et al. clearly indicates that the probability is 1% *every* year over the life of the project?
   d) Do professors Hager and Toksöz agree that if indeed the probability of a Ml = 3.9 or 3.7 earthquake is 1% every year over the life of the project the probability of such an earthquake is almost 40%?

3) The intensity of an earthquake of Ml = 3.9 is described in the *RIP* (p. 60) as "very light" ("zeer licht"). On the European Macroseismic Scale (EMS) such an occurence (intensity VI+ according to the *Technical review* (p. 15)) is described as varying from "light", to "heavy" and even "very heavy" damage (depending on the kind of construction under consideration). How does the qualification of an Ml = 3.9 earthquake as "very light" cohere with the descriptions used in the EMS?

4) The intensity of the 2001 earthquake (Ml = 3.5) in Alkmaar was also VI+ on the EMS. A Ml = 3.9 earthquake would be considerably heavier (on a logarithmic scale, about 2.5 times heavier) but it's intensity would according to the *Technical review* also be VI+ on the EMS. How is it possible that an earthquake 2.5 times as heavy, has the same intensity (and thus would cause similar damage)?

10.2.e.

GroenLinks Bergen

Discussion of Second Opinion, "Bergermeer Seismicity Study"

Bradford H. Hager
Robert D. van der Hilst
M. Nafi Toksöz
MIT

Outline

- Context and scope of our review
- Summary of review of TNO report
- Responses to:
  - Gasalarm2 questions
  - Soil Movement Technical Committee questions
  - New questions from 10.2.e , GroenLinks Bergen

Context

- Is the risk of the Bergermeer Underground Storage Project acceptable?
  - Rewards?
  - Risks?
    - Financial
    - Political
    - Seismic
    - .....

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  - Rewards?
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Seismic Risk

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  - Seismic hazard (ground motion)
  - Vulnerability
  - Cost
  - Exposure

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Seismic Hazard

- Probability of exceeding a given ground motion within a given time period at a given site
  - Individual earthquake source properties
    - Fundamental
      - Hypocenter (latitude, longitude, depth)
      - Style (normal, reverse, strike-slip, mixed)
      - Source time function: **u**(x,y,z,t)
    - Averaged
      - Moment, M_0, M_W
      - Magnitude, m
    - Probability distribution: P(m, x, y, z, t)
    - Wave propagation effects
      - Between earthquake and near-site
      - Site effects

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Estimating the Probability Distribution: P(m, x, y, z, t)

- Statistical (empirical)
  - Log(n) vs. m
  - m_{Max}
  - Poorly constrained by data
    - Handful of events detected in Bergermeer
- Deterministic (geomechanical)
  - Fault area, slip, elastic shear modulus
- Subjective (expert opinion and intuition)
  - Formalized by USGS & California
    - Averaging of estimates using various approaches

TNO Report 2008-U-R1071/B

- Review of previous studies
- Reservoir modeling
  - Thermoelastic effect of injecting cold gas
- Geomechanical modeling, production & storage
  - Calculated predicted fault displacements
  - Realistic mechanical properties
  - Two-dimensional
- Seismic Hazard Analysis from geomechanics
  - Predicted m ~ 2.4 – 2.7 from geomechanical models
  - Upper bound m = 3.9 from fault area

Independent Review

- Tasks:
  - Review TNO study
  - Respond to questions of Gasalarm2
  - Respond to questions of Soil Movement Comm.
  - Participate in meeting to discuss review
- Personnel
  - M. Nafi Toksöz – expert on induced seismicity & seismic hazard evaluation in US, Turkey, Oman
  - Bradford H. Hager – geomechanics, earthquake geodesy, chair of USGS Parkfield Earthquake Experiment Evaluation
  - Robert D. van der Hilst – seismology, Director of Earth Resources Laboratory

Review of TNO conclusions

- The Report addresses, broadly, the issues related to the seismicity and seismic hazard at the Bergermeer field.
- The computations and numerical models are done with "state-of-the-art" computer codes.
- The results of the subsidence study and the reservoir simulations, for flow and for temperature, are clearly presented. We agree with their conclusions and recommendations.

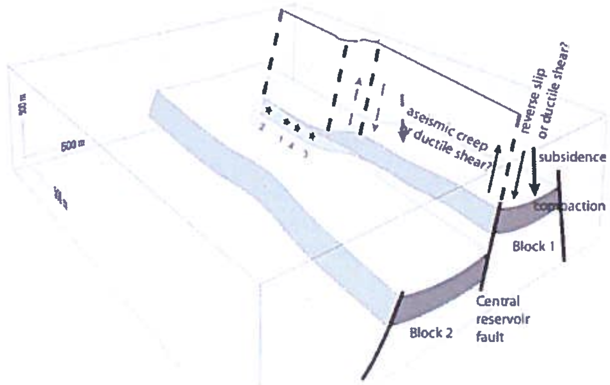
Review of TNO conclusions

- Geomechanical model provides insights into potential deformation and fault slip on the faults included in the mesh. However, the approach has some shortcomings for the prediction of location and magnitudes of potential earthquakes.
  - It does not predict the observed reverse faulting mechanisms.
  - It is a two-dimensional model dealing with a three-dimensional reservoir that varies substantially along strike of the model, particularly along the Central Reservoir "scissors" fault.

Geomechanical (continued)

- Fault structures or other means of accommodating anelastic deformation are not included in the regions immediately above the reservoir, where large stresses are generated by production and injection.
- It assumes two-dimensional planar fault surfaces without heterogeneities, asperities or stress concentration from slip variations in the third dimension.

Possible explanation of reverse faulting



Review of TNO conclusions

- Because of the limitations of the geomechanical modeling, we suggest relying more heavily on available earthquake data for estimating the maximum magnitudes of potential earthquakes. For the maximum magnitude, the reviewers agree with the value of M_L=3.9 cited in the report.
  - Probabilistic seismic hazard estimate for induced earthquakes in the Netherlands has been done for gas fields in the Netherlands (van Eck et al., 2004, 2006). This includes the Bergermeer field, albeit with few data. The results are consistent with those of the TNO report in that the probability of any event of M_L=3.9 or greater is extremely low.

Review of TNO conclusions

- A detailed analysis and modeling of seismic records from close-in stations of the 2001 Bergermeer earthquakes would provide more detailed information about their source mechanisms. We do not expect further analysis to change the conclusion that these are reverse faulting events. However, more accurate determination of the depth, amount of fault slip, and dimensions of the faults that slipped could be obtained. We recommend that this be done.

Answers to Gasalarm2

- Is the [geomechanical] TNO approach a complete and reliable way to explore maximum potential slip during the project phase?
- *The two-dimensional models might underestimate the stress that could accumulate on asperities if loading is transferred "out of the plane" along strike of a fault. It therefore seems plausible that larger magnitude events than those predicted by the TNO geomechanical analysis could occur. This conclusion agrees with both the TNO seismic hazard analysis and our inference from seismicity models that a maximum expected earthquake of magnitude 3.9 might occur.*

Answers to Gasalarm2

- TNO used static elastic moduli to calculate moment release. Should they have used the dynamic moduli, which would increase M_0?
- *We agree with the TNO report that the static shear modulus is the appropriate modulus to use to calculate the stress state on faults caused by quasi-static loading. It is this stress, associated with slow loading, that is released during an earthquake. Increasing the magnitude of a potential earthquake by using the dynamic modulus is not appropriate.*

Answers to Gasalarm2

- What is the relation between the length of the fault plane, the probable activated part of the fault plane during the events and the maximum magnitude of a seismic event? How important is the estimation of the total length of the central fault?
- *The magnitude of a seismic event is proportional to the area of the part of the fault that ruptures during an event, not the total length of the fault. Thus it is the estimate of that part of the Central Reservoir fault that would break, not the total length of the fault, that is important. We agree with the TNO report that the part of the Central Reservoir fault that cuts through the rocksalt of the Zechstein formation is unlikely to slip in a seismic event. Therefore the length of 2.5 km is appropriate*

Answers to Gasalarm2

- Gasalarm2 assumes that the stabilisation of the fault structures at reservoir level due to pressure increase during injection will be of minor importance as compared to potential previously created unreleased tensions. TNO assumes that the re-pressurization of the reservoir will lead to a more stable fault structure. What is the opinion of the experts about these views?
- *While repressurization will generally tend to reduce the stresses caused by production, the amount of repressurization planned is substantially less than the amount of depressurization, so stresses on some faults might not be completely reversed. There is often a time delay between when a fault is stressed and when it eventually ruptures in an earthquake. Thus, earthquakes at Bergermeer might well occur even if repressurization did not proceed.*
- *NEW: The earthquakes that have already occurred may have reduced the stresses to near zero. Repressurization might increase the stresses on such faults.*

Answers to Gasalarm2

- Gasalarm2 observes that for the operating phase of the BGS only the first production/injection cycle has been modelled by TNO. In particular, the recovery phase of the cushion gas has not been covered. Apart from risks resulting from phenomena such as erosion of the fault plane and fatigue, (see TNO recommendation page 87, #3), the seismic risks associated with final cushion gas recovery should not be ignored. What is the opinion of the expert(s) about the missing analysis?
- *In our view, including the final recovery of the cushion gas would not change the conclusions in an important way. The recovery phase is expected to be similar to the second half of the initial production phase.*

Answers to Gasalarm2

- According to Gasalarm2 the temperature effects are not fully addressed in TNO (2008). In particular did Gasalarm2 expect an estimation of the effect of potential preferential flow as a result of the presence of cracks, minor faults and flow channels generated in the past gas production phase and a judgement on the necessity of a corresponding *additional* safety margin for the distance between well and fault.
- *The volume of rock affected by the temperature changes associated with the initial storage is small compared to the source dimensions of damaging earthquakes. Also, since the permeability of reservoir rock is high, flow along fractures may not be critical. Preferential flow paths are likely to be oriented parallel to faults along the tectonic fabric. In our opinion, the thermal models are sufficiently conservative.*

Answers to Gasalarm2

- There is a probability ≥15% that the central part of Bergen will during the project life-time be hit by an earthquake with a 10 times stronger impact than the one experienced in 2001, and that this will cause severe financial damage. The m=3.5, intensity VI+, 2001 event caused significant damage near epicenter. (Approx. 4x stronger event (3.9 vs. 3.5), approx. 2x stronger felt in Bergen due to epicenter extending immediately within the build-up area). Does the TNO study present convincing evidence to reject this hypothesis?
- *The occurrence of a M_L = 3.9 earthquake is possible, but unlikely, with a probability much less than 15%. First, the probability that a M_L = 3.9 event would occur in the Bergermeer field is less than 1% over the life of the project (van Eck et al., 2006). Second, the region covered by the built up area of Bergen covers only a small fraction of the area affected by production of the Bergermeer reservoir. Third, slip on the scissors fault dies out towards Bergen and the geometry of the reservoir appears to be simpler there.*

Answers to Gasalarm2

- Given the uncertainty margins in reservoir rock parameters, precise fault dimensions, reservoir rock homogeneity, uncertainty about the precise mechanism underlying the 2001 earthquake and other uncertainties (e.g. concerning thermal effects during injection/production, effects of water injection), there is a probability ≥5% of an earthquake with an even 20x stronger impact (M = 4.1) than the 2001 event. Does the TNO study present convincing evidence to reject this hypothesis?
- *In our opinion, the probability of such a high impact event is substantially less than 5%. As stated above, the probability of a magnitude 3.9 event in the field is less than 1% and the probability of a magnitude 4.1 event is even lower.*

Answers to Gasalarm2

- What is the experts' opinion about the treatment/reporting of uncertainty/error margins and confidence intervals in the model calculations and scenario choice in the TNO study?
- *The TNO study addresses the effects of many of the uncertainties in material properties by running a substantial number of models. It does not discuss some other sources of uncertainty/error propagation that could influence interpretation. The uncertainties in the geomechanical models associated with fault geometry are not adequately addressed. In particular, the possible effects of three-dimensional structure are not investigated. This could affect whether or not smaller earthquakes occur during storage, but would not affect the conclusions about earthquakes with magnitudes greater than M_L = 3.9 being extremely unlikely.*

Answers to Soil Movement Comm.

- What is the opinion of the risk estimates and are they compatible with the physics (ref. TNO report and KNMI risk reports)?
- *The estimate in the TNO report that the maximum magnitude earthquake that could be expected is $M_L = 3.9$, is compatible with the physics.*

Answers to Soil Movement Comm.

- The fault dissecting the Bergermeer field is (partly) sealing: what pressure difference between the hanging- and foot-wall may cause earthquakes?
- *Determining a quantitative estimate of the pressure difference across this fault that could lead to earthquakes is beyond the scope of this review. However, the 1994 and 2001 earthquakes appear to have occurred on this fault, so pressure changes associated with seven years of production appear to have been sufficient to trigger earthquakes.*

Answers to Soil Movement Comm.

- The Tcbb considers the possibility of seismic monitoring at reservoir level, since only larger events (M>3) have been recorded with the current monitoring system. Is this a justified approach or are there alternatives?
- *This approach is justified by the importance of monitoring the behavior of the reservoir. In addition, we recommend more comprehensive geodetic monitoring including the use of GPS to measure horizontal motions, in addition to vertical motions.*

Answers to Soil Movement Comm.

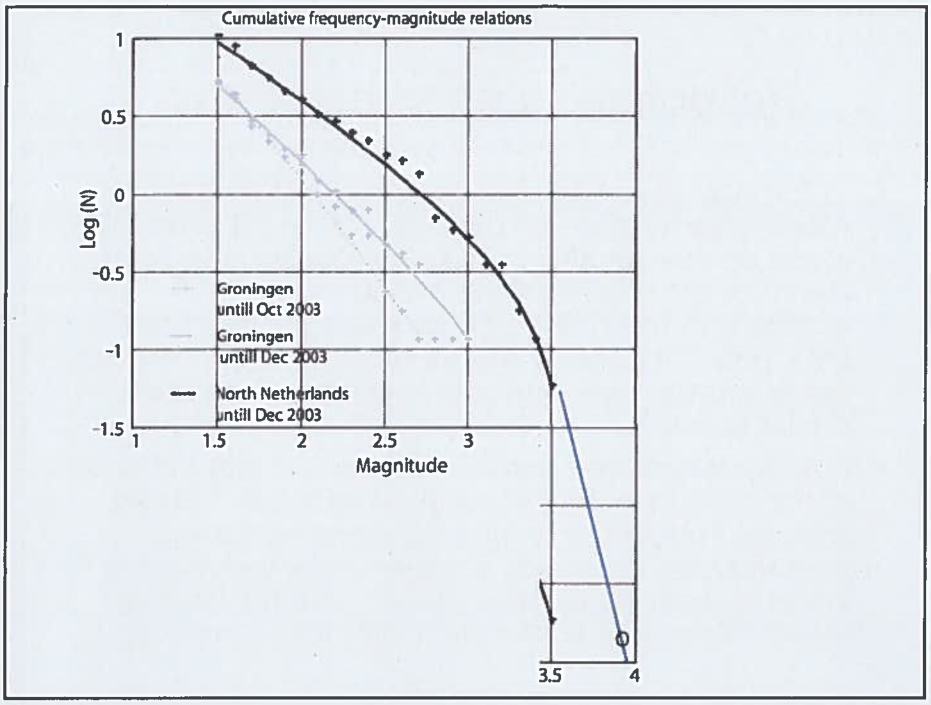
- How is excessive movement to be prevented? Can this be done by changing the rate or volume (maximum pressure difference) of production?
- *The probability of triggering earthquakes depends upon both the stress level and the rate at which the stress changes.*

Response to new questions

- 1) There has been considerable debate about the interpretation of the *Technical review* [see] *Bro-reactie voorontwerp-rijksinpassingsplan Bergermeer Gasopslag* (pp. 29-30), submitted by the municipalities of Alkmaar, Bergen, Heiloo and Schermer. [Please] comment on the accuracy of . . . . their interpretation of the *Technical review.*
- *A very general question – please ask again **later** if anything is not covered elsewhere in the discussion today.*

Response to new questions

- 2) Explain better how the estimate of 1% over the life of the project for m = 3.9 was obtained.
- *This has nothing to do with the T=100 PGV calculation of van Eck et al. (2004, 2006), but is from an extrapolation of Fig. 3 to m=3.9.*
  - *Assumptions:*
    - *Use log(n) vs m for northern Netherlands gas fields*
    - *Extrapolate from m=3.5 to m=3.9 => 0.02/yr*
    - *Assume Bergermeer < 20% of region => n < 0.004/yr*
    - *Assume 25 yr lifetime => n < 0.01/lifetime*



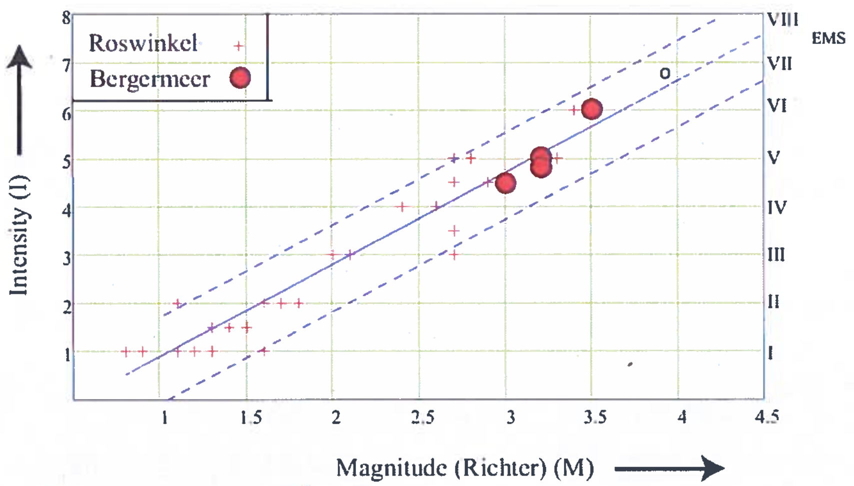
Response to new questions

- 3) The intensity of an earthquake of Ml = 3.9 is described in the *RIP* (p. 60) as "very light" ("zeer licht"). On the European Macroseismic Scale (EMS) such an occurence (intensity VI+ according to the *Technical review* (p. 15)) is described as varying from "light", to "heavy" and even "very heavy" damage (depending on the kind of construction under consideration). How does the qualification of an Ml = 3.9 earthquake as "very light" cohere with the descriptions used in the EMS?
- *We have nothing to add to the EMS descriptions and wish to avoid commenting on the nuances of interpretation of documents not in our native language.*

Response to new questions

- 4) The intensity of the 2001 earthquake (Ml = 3.5) in Alkmaar was also VI+ on the EMS. A Ml = 3.9 earthquake would be considerably heavier (on a logarithmic scale, about 2.5 times heavier) but it's intensity would according to the *Technical review* also be VI+ on the EMS. How is it possible that an earthquake 2.5 times as heavy, has the same intensity (and thus would cause similar damage)?
- *Data for Bergermeer and Roswinkel show that the slope of the intensity vs magnitude relation is 1.9. Thus an increase from m=3.5 to m=3.9 gives an increase in intensity from 6.1 to 6.9. Because of the quantization if intensity, both are described as VI+. But the intensity would be closer to VII than to VI (see following slide).*

Intensity vs magnitude, from KNMI



Note: Bergermeer is well calibrated
and the extrapolation is modest.

Figure courtesy of 10.2.e

Thank you

Main observations of the expert meeting with prof. Bradford H. Hager and prof. Robert D. van der Hilst (MIT) about the technical review of the Bergermeer Seismicity Study, The Hague, 14-01-2010

Present: 10.2.e (Soil movement technical committee, Tcbb), 10.2.e (KNMI). 10.2.e (Ministry of Economic Affairs) 10.2.e (State Supervision of Mines, SodM), 10.2.e (Bergen),10.2.e (Alkmaar), 10.2.e (Heiloo), 10.2.e (prov. Noord-Holland), 10.2.e (HHNK), 10.2.e (Gasalarm2), 10.2.e (Taqa Energy BV), 10.2.e (MRD),

General remarks:

Prof. M.Nafi Toksöz is not present for personal reasons.
Powerpoint slides of the presentation of MIT will become available for all participants.

Presentation of the findings of MIT.

After the welcome and opening words of the Chair, and the introduction of attendees, the formal part of the meeting started with a presentation by Prof Hager with a summary on the MIT review of the TNO report 2008-U-R1071/B as well as the MIT review of the TNO conclusions. (See PowerPoint slides.) Responses will then be given on the original questions of Gasalarm2, the Soil movement technical committee, and on a number of new questions.

Prof Hager explains the context and scope of the MIT review of the TNO report. The focus of the MIT review is on seismic hazard, i.e. the probability of exceeding a given ground motion within a given time period at a given site.
The probability distribution P (m,x,y.z,t) has been estimated using three approaches:

a. Statistical analysis of limited data (empirical)
b. Deterministic, geomechanical approach with fault area, slip and shear modulus
c. Expert opinion.

A possible explanation is presented for the mechanism of the observed reverse faulting (see 3-D figure). The re-activated fault in the Bergermeer field is called a "scissors-fault".Compaction takes place in the sandstone reservoir. As a result, aseismic shearing occurs where the sandstone is in contact with salt layers and as a result stress is transferred along the strike of the fault, concentrating in the pivot of the scissors where seismic events take place.

Summary of responses to earlier questions

Answers to the earlier questions of Gasalarm2 and the Soil movement committee are presented (see PowerPoint slides). In addition to these earlier answers on the effect of repressurization, a number of new elements are added by MIT. "The earthquakes that have already occurred may have reduced the stresses to near zero. Repressurization might increase the stresses on such faults."
In addition to the earlier response to the questions by the Tcbb about the rate of stress changes, Prof. Hager adds that it is important 'How fast you are injecting', in his opinion the cycling nature of the injection is not important.

Answers to new questions/discussion

The 1 % probability of an M_L=3.9 event during the lifetime of the project given in the MIT report in response to a question by Gasalarm2 has to be seen as an operational definition of 'a very small probability'. The estimation is based on an extrapolation of the log (N) vs magnitude plot for the Northern Netherlands, under a number of assumptions (e.g. neglecting uncertainties). This probability is much less than the value of 15% mentioned in the Gasalarm2 question. In response to a question of mr 10.2.e , prof. Hager answers that the lifetime of the project should be corrected from 25 to 50 years. The stated probability has to be modified to a chance less than 2 % over the life of the project.

There was a question about the statement in the review that a M_L=3.9 event would be related to an intensity VI+. Prof Hager: "We used the Modified Mercalli Intensity scale, but on the European Scale (EMS) the intensity of a magnitude 3.9 event would indeed be closer to VII than to VI. (see attached figure of Magnitude vs. Intensity, courtesy 10.2.e.). 10.2.e. notes that the EMS scale should only be used when no accurate data are available. For the Bergermeer field there are accurate data for calibration as the seismic events have been recorded.

In the 'Rijksinpassingsplan' (RIP) an M_L=3.9 event is described as 'very light'. Question: "Is that a scientific qualification?" Answer by prof. Hager: "The evaluation of the EMS scale is not the topic of the MIT review". 10.2.e. adds: "Natural events are usually deeper than induced events. The descriptions of the impact of earthquakes are related to natural events. The induced events in the Netherlands occur at a depth of only 2-3 km. The impact is different from that of natural seismicity and concentrated in a smaller area. "Very light" is the right qualification for a natural earthquake, but for an induced earthquake this qualification is not preferred.
10.2.e. asks a clarification on what 3.9 means for a natural earthquake.
10.2.e explains that a deeper source radiates over a larger area, spreading the energy and the effects of the earthquake. 10.2.e. concludes that an EMS Magnitude–Intensity relation is generally used for natural earthquakes and 10.2.e. summarises for the record that the qualification 'very light' is not appropriate for a M_L=3.9 induced, shallow earthquake.

10.2.e. asks about the likelihood that an M_L=3.5 earthquake occurs in the field. Prof Hager answers that some relief of stresses could be expected while injecting gas in the field. Most experts would think that the fault structure stabilizes as a result. He himself belongs to the 10% of the experts that are not convinced about this because the earthquakes that occurred during production might have relieved the stresses. In that scenario, injecting gas would increase the stress.

The question on the likelihood of an M_L=3.5 event is repeated. A period of once every 15 years is mentioned for the region, based on the available cumulative frequency-magnitude relationship. 10.2.e. answers that no information is available on the (distribution of the) small earthquakes in Bergermeer. The lack of statistical information on smaller quakes in the Bergermeer field is subsequently discussed in more detail.

10.2.e. states: "we are looking for a sense of security for our citizens."
10.2.e. addresses the important point of monitoring. He expects a continuation of the events, which have been seen in the past. Hager expects that what has been calculated, is the worst case. What may well happen is that at higher gas pressures the stresses due to production tend to reduce.

10.2.e. is of the opinion that not enough data are available for extrapolation and drawing conclusions. 10.2.e. underlines that monitoring is an important issue. 10.2.e. makes the remark that monitoring could be 'mustard after the meal.'

Continuation of discussion after short break.

Mr 10.2.e remarks that a lot is known about the Bergermeer gas field. The four events are confined to a small part of the central fault in the middle of the field. Geomechanical models give similar results with respect to the maximum magnitudes. At the moment the most conservative (careful, prudent) approach is followed.

10.2.e. makes the remark that the Groningen field is not as mature yet as the Bergermeer field. 10.2.e. replies, that also gas fields such as Eleveld are taken into account, which are as mature as the Bergermeer field. 10.2.e : different fields show a different behaviour, however when the events observed for different fields are added together, a consistent behaviour emerges.

Mr 10.2.e. makes some introductory remarks about the storage-plan and monitoring. State Supervision of Mines is an advisory body for the approval of storage plans. Conditions for approval may be related to the monitoring of seismicity and subsidence. The storage has to be operated in

accordance with the NEN norm for gas-storage 1918-2 1998. 10.2.e. points to the fact that Taqa has already obtained approval for a storage plan for a limited amount of gas, up to a reservoir pressure of 35 bar; Taqa is already injecting gas in the Bergermeer field. Taqa has asked approval for a second stage of injection with reservoir gas pressures up to a maximum of about 150 bar. This second phase (adaption of the storage plan) is studied. 10.2.e. expresses that most experts think, that due to the repressurization of the reservoir, the chance of seismicity may become lower. The importance of a good monitoring programme is underlined by the fact that there are some differences in opinion among experts about the behaviour of gas fields when they are repressurized. Questions asked are: What are the consequences of the observations of the monitoring? What should be accepted?
10.2.e. mentions that in the Dutch underground gas storage at Norg a fast repressurization did take place; however there is no significant level of seismicity. Only some minor events took place during depletion and injection. 10.2.e. noted that there was no seismicity before reinjection so that comparison with BGS is not appropriate. Mr 10.2.e. concludes again that the monitoring plays an important role.

Mr 10.2.e. presents a series of questions and concerns. He repeats the opinion that the geological/geomechnical model of TNO has too many limitations to predict the maximum possible magnitude. Prof Hager confirms that the best information to estimate the maximum magnitude of 3.9 comes from the geomechanical model like the fault area and maximum slip that can occur (not from statistics). Estimation of the probability is more difficult. The result is a very small probability, between 0,2 and 2% during the life of the project (much less than 15%). Prof. Hager estimates, as a worst case, that the probability for an M_L=3,9 event is roughly comparable with that for the second stage of the production phase. Prof Hager: the max. magnitude could be described by M_L=3.5 and the 3.9 can be seen as the upper bound at the 95% confidence interval (95 % limit at 2σ, σ = standard deviation). The 3.5 has to be seen as a calibration point. There is a rule of thumb to add 0.4 to the actually measured maximum magnitude.

Mr. 10.2.e. mentions that the 3.9 from the KNMI is a 1σ estimate. Prof Hager shows no disagreement with that figure based on a statistical analysis of KNMI (Monte Carlo method). Uncertainties are calibrated in the field with the events from 1994 and 2001. Estimates are made of the stress drop.

Mr 10.2.e. notes that differences in slip estimations are substantial. 10.2.e points to the fact that the difference in slip estimations might be explained by e.g. aseismic creep.

Mr 10.2.e. asks for examples of the influence of the rate of pressure change on seismicity. Prof Hager confirms to have many examples and also information on the theoretical background.
Prof Hager explains the following: earthquakes/seismic events may occur when stresses reach a certain threshold stress level. Stressing (injecting/producing) at higher rate will speed up this process. When we double the rate, the number of quakes may double in time. However only if a certain threshold stress value is exceeded.

Mr 10.2.e. presents two graph's with cumulative frequency-magnitude relationships, updated with recent data. Prof Hager is asked to give his opinion about the extrapolations. In the second (grey) graph an optimistic (A) and pessimistic (B) extrapolation is given.
Prof Hager makes the remark that combining inhomogeneous datasets from different fields could be a problem. There are many ways to do such a statistical analysis. He mentions that in the grey graph the curve intersecting magnitude 3.7 at N_{cu}= 0 means that an M_L=3.7 event should already have occurred at least once (10^0 =1). Such 3.7 event has not happened. The remark is made that, as this is based on the assumption of a Poisson distribution, the probability for the time period considered would be p=(1-1/e) = about 60 %. 10.2.e makes the remark that the probability of a magnitude 3.5 event is better defined than the probability of a 3.9 event. There are no observational data for a 3.9 event.
The proposed hypothesis of a more than 15 % chance of an earthquake, with 10 times stronger impact than 2001 (the question of Gasalarm2) can be rejected at a certain confidence interval.

In answer to a question about the use of Magnitude numbers of 2.4 and 2.7 in the MER-report, Prof. Hager refers to the text in the MIT study, where that question has already been answered. He does agree with the upper bound M_L=3.9 as described in the TNO report.

Mr 10.2.e. asks prof. Hager about living in the area close to an Underground Gas Storage. Prof Hager answers that, to illustrate his assessment, he would invest in a company that buys houses in the region and sells them after 5 years, when he expects that the concerns about seismic risk will have been greatly reduced. He would not protest if a UGS were to be built in his own neighbourhood. He acknowledges that possibly his neighbours, who are not experts in seismic hazard assessment, would do that.

Mr 10.2.e. asks about the need to move the gas storage to an area that is less sensitive for earthquakes or to design the installation for an M_L=3,9 event. Prof Hager answers: when in an alternative reservoir all properties are equal, yes, it is better to avoid the risk. In response to the second question he replies that an engineer would overdesign the installation to be safe for an M_L=3,9 event.

Prof Hager is asked for the upper limit of a seismic event that he has seen for an existing storage project. Prof Hager answers that he is advising on a gas production project with a predicted maximum event of M_L=4.5.

Main conclusions, summarized by Dr. 10.2.e. at the end of the meeting.
- Dr. 10.2.e. concludes that this has been a well-behaved meeting and he compliments all on this.

- An upper bound of maximum magnitude M_L=3,9 was derived with different methods. E.g. methods based on physics and the dimensions of the fault (generally preferred) and methods based on statistical arguments (which generally lead to more discussion). Because of the consistent outcome using the different methods, the M_L=3,9 is a credible number as a maximum value for the Bergermeer field.

- Statistical methods are inherently uncertain in predictive power but the probability of an M_L=3,9 event is still seen as very small by MIT.

- A period of 50 years should be taken into account for the project life, instead of 25 years.

- The effect of the cycling and the temperature effects do not seem to be important. The temperature effects are insignificant when the injection takes place at a certain distance from the fault (about 150 m). No impact is expected from fatigue. The rate of stressing has a certain effect and references to research on this topic will be provided by prof. Hager.

- Careful monitoring of the reservoir should be carried out and is recommended by MIT. Monitoring is part of the storage plan. Earthquakes and surface deformation are measured according to an approved measuring plan. The NEN norm 1918-2 1998 has to be followed.

- A Magnitude 3,9 event would result in an intensity close to VII on the EMS scale. (this is a correction of the original statement in the MIT review: MMI VI+ becomes EMS VII). The relation between magnitude and Intensity is a noisy one. The meaning of the relation is different for (deep) natural earthquakes and (rather shallow) induced earthquakes. In general a shallow event results in a relatively larger impact in a smaller area around the epicentre. However, special soil conditions may give large effects in other area's as well.

- TNO has used a 2-Dimensional geomechanical model. MIT concluded that a three dimensional model would be more appropriate. [Mr 10.2.e. repeats that the geomechanical model by itself is not enough to estimate the maximum magnitude.]

- There are two schools of thought on how the seismic risk is changing when a gas-reservoir is repressurized. School A: Injection is lowering the risk, because gradually inflating the reservoir will reduce the production-induced stresses in the reservoir-rock.

School B: The injection does not change the risk because the pressure increase during repressurization is substantial. (e.g. compared with the pressure drop between the events of 1994 and 2001). Prof Hager (in the position of the invited expert) states that he is a member of the second school of thinking, favoured by some 10% of the experts. Although he has reasonable doubts, he is not saying that the first school of thinking is wrong. He confirms that the rate of change in stress field will affect the frequency of events.

Final remarks

The mediator mr. 10.2.e. thanks prof. Hager and prof. van der Hilst for presenting the MIT review and answering so many questions. He thanks also all the participants who contributed to the constructive discussion in a balanced way. He mentions that a summary of the MIT-review is available in the Dutch language. The participants will get a copy of this summary.

Stichting Gasalarm2

Summary of key points discussed at expert meeting BGS 14-01-2010

This summary has been prepared as annex to the minutes of the meeting prepared and circulated by the Ministry of Economic Affairs, because these minutes in our view present an unbalanced account of what was discussed, contain unnecessary fragmented and selected discussion quotes, and fail to communicate the key points in a transparent manner. Although the summary below is based on the summary given by the chairman 10.2.e. *) at the end of the meeting, the order in which the points are covered is ours, based on the logical sequence of the issues dealt with. We realize that the picture emerging from this summary differs from the one conveyed in the Ministry of EA minutes, even though the basic facts are the same. We have formulated the summary from a public-interest hazard analysis point of view rather than from a "no reason to worry too much" point of view. We are convinced that that a good-governance geared decision making process deserves the crude exposition of the facts and issues given below –stripped of meeting "noise".*

1. The key conclusion of the TNO study presented in support of the BGS project authorization request (MER) by Taqa, derived from the TNO geomechanical model, i.e. *that the Bergermeer field will stabilize as a result of using it for underground gas storage and that no larger quakes than of M=2.4-2.7 are to be expected*, is invalid. The model used by TNO doesn't present a valid description of the field that could produce credible predictions of the risk of earthquakes, neither for the past production phase nor under UGS conditions[1].
2. For assessment of the seismic hazard of the Bergermeer field under UGS conditions, an M_{max} of M_L=3.9 has to be reckoned with. The M_{max} estimates derived by rules of thumb from field/fault dimensions and characteristics (TNO report Ch. 2) and those from statistical analysis of induced earthquakes observed in N-NL (KNMI studies, 2004) are both credible, and are mutually consistent (MIT, chair, others).
3. The macro-seismic intensity of an M_L=3.9 quake in the Bergermeer field will be of around EMS VII strength. In its presentation at the start of the meeting MIT corrected the estimate given in their report[2].
4. The only EMS VII earthquake recorded in the Netherlands was Roermond 1992. However, in this case the size of the EMS VII area was much larger than would be the case in Bergermeer[3]. Yet, unfortunately, in the Bergermeer case due to the soil conditions of the upper 50 m, the highest horizontal velocities are to be expected above the central and northern part of the field at the onset of the young dune sediments on which Bergen is built, and hence almost the entire build-up area of Bergen is likely to be included in the VII area[4].
5. The description given by the Min. of EA in the RIP text presented in preparation of BGS project authorization of an M_L=3.9 event as "very light" is wrong. A correct description is "substantially damaging" [5].
6. The basic probability that during the BGS project period a quake of M_L=3.9 will occur was estimated by MIT at =< 2% (in 50 years), based on the observed N-Netherlands

[1] The reasons for this are described in the MIT second opinion report.

[2] The reason for the correction being that the estimate in the report had not been based on the observed magnitude/intensity relationship for induced quakes in the Netherlands and the observed intensity of the Bergermeer 2001 quake in particular.

[3] The Roermond quake being a tectonic one of M_W=5.4 at 19 km depth.

[4] TNO-NITG/KNMI 2004; MIT affirmed not having included shallow subsoil conditions in its second-opinion analysis.

[5] A full description is given in the EMS scale.

frequency/magnitude relationship[6]. *Gasalarm2* presented a re-calculation (same method) based on observed quakes up to 2009 (rather than 2003, MIT) and a calibration of the N-NL/Bergermeer ratio to the observed M>=3.2 quake frequency in Bergermeer. This results in an estimated 10% probability (instead of 2%). The *KNMI* position with respect to this probability estimate is: it can be a 1 in 200 years probability, it can also be a 1 in 10,000 years probability, we just don't know, the uncertainty margins are too large. The issue being too complex for quick conclusions, it was agreed that this discussion will be continued and concluded between MIT and Gasalarm2 after the meeting.

7. The Bergermeer hazard analysis presented by KNMI in 2004, showing an estimated T(100) probability (=1/100 years) of a peak ground velocity of 60-70 mm/sec is credible and the best available estimate.
8. MIT reaffirmed that the rate-of-stress-change is a key variable influencing the probability (frequency) of earthquake occurrence[7]. Higher rates of change result in higher probability. The cyclic pattern of pressure change (for UGS operation) appears to be of no influence.
9. SodM representatives (State supervision of mining) expressed that in their opinion most experts[8] assume that re-pressurization of a depleted, during production seismic active, gas field will result in stabilization and strongly reduce the size of possible quakes. MIT reaffirmed that in this case they are of a different opinion, i.e. that there are good reasons to expect continued quakes[9] up to the M_{max} mentioned above.
10. Asked for his opinion[10] prof. Hager (MIT) stated that, presented with the choice between an UGS proposal in a reservoir with a seismic risk comparable to Bergermeer and one in a low-risk reservoir, it would be obvious to take the low-risk one.

[6] As explained in their presentation (graph and calculus)., assuming a 20% share of Bergermeer in expected M=3.9 quakes in N-NL (and: the observed data reflecting average pressure change conditions prevailing during gas production).
[7] Clear from both theoretical and empirical seismic research; MIT will communicate further references after the meeting.
[8] Mentioning 90%.
[9] Adding to expect quakes in the M=3.5 range (3.3-3.7) rather than a much less likely event of Mmax strength.
[10] By the chairman of the federation of neighbourhood committees ("wijkverenigingen") of Bergen.

Professor Hager's Comments on Gasalarm2's revised meeting minutes

Gasalarm2 has presented a version of the meeting minutes differing in emphasis from that given by the Ministry of Economic Affairs (MEA). The original minutes by the chairman ([10.2.e]) were in chronological order. Gasalarm2 has rearranged them in an order that they see as more logical, with a differing picture emerging.

The MEA sent me a link to the Gasalarm2 report and asked me for my comments. Below are my reactions to the points in the Gasalarm2 report, arranged in the order in which the points arise:

In the introductory paragraph, the statement is made: "*We have formulated the summary from a public-interest hazard analysis point of view....*" As I tried to make clear in my introductory slides, there are inherently conflicting public interests on both sides of the argument. While it is true that it is in the public interest to avoid inducing earthquakes, it is also in the public interest to provide a secure and economic source of energy. It is the responsibility of the government to make decisions on such conflicts of public interest. It is the responsibility of citizens to make sure that the government is well informed in making these decisions. But neither side of the argument should give the impression that all of the interests of the public are only on their side.

Bullet 1: I disagree that the key conclusion of the TNO report is that no larger quakes than M = 2.4 – 2.7 are to be expected. In my view, the key conclusion is that any earthquakes that might be induced by gas storage would not be much larger than those that already occurred during production, with M = 3.9 a reasonable upper bound.

Bullet 2: I see no disagreement on this key point.

Bullet 3: The statement that the intensity of a M=3.9 in the Bergermeer field would be about EMS VII is correct, as far as it goes. But it is a major omission of the Gasalarm2 version of the minutes that the fairly extensive discussion at the meeting about relative differences in intensity is not mentioned. Intensities for a M=3.9 would be about 0.8 EMS units greater than that for the M=3.5 that has already been experienced and can be used as a calibration.

Bullet 4: Again, the fact that there is already a "calibration" for the intensities at Bergen experienced for a M=3.5 event in Bergermeer makes the existing record at Bergen a much better reference than the 1992 Roermond event. The M=3.5 Bergermeer event also provides in situ calibration for any hypothesized effects of the shallow structure. I do not have the relevant reports at hand, but my memory is that not all of Bergen experienced EMS VI in that event. Only those places that experienced EMS VI+ for the M=3.5 event would be expected to experience EMS VII for a M=3.9 event.

Bullet 5: As I stated at the meeting, I am not qualified to comment on the details of the RIP report, which was in Dutch. Again, I point out that the intensity of a hypothetical M=3.9 event would be expected to be less than one EMS unit larger than that experienced already for the M=3.5 event.

Bullet 6: If there is an even distribution of repeat times from 200 yrs to 10,000 yrs, the best estimate (centroid) is 5,100 yrs. This translates into a best estimate of a 1% chance during the 50 yr lifetime of the project. I agree that there is considerable uncertainty in the estimate of this expected repeat time, given the uncertainties in applying the methodology to an inhomogeneous data set.

Bullet 7: This point was not discussed in the MIT report and was not addressed in any detail at the meeting.

Bullet 8: While I agree that stressing rate has an important effect, I disagree with the statement that the cyclic pattern of pressure change appears to have no influence. It certainly does because the stress change is a tensor, not a scalar. Changing the sign of the stressing reduces the stress until the stress changes sign, with its magnitude then increasing.

Bullet 9: This point is essentially correct, but I would have written the phrase "good reasons to expect continued quakes," along the lines "continued quakes are not unexpected."

Bullet 10: This statement is taken out of context. There is an important and obvious qualifier that I believe I used: "All other things being equal." I end my remarks as I began them – there are other important considerations beyond seismic hazard that factor into the decision that the government must make.

Seismicity Study 2nd phase (post MIT report)

Meeting notes progress meeting 01 Date 2010-07-07
Venue Den Haag, Prinsenhof , 13th floor , Mauve

Participants:

10.2.e. [redacted]	TNO
10.2.e. [redacted]	TNO
10.2.e. [redacted]	TNO
10.2.e. [redacted]	KNMI abasent (holiday)
10.2.e. [redacted]	KNMI
10.2.e. [redacted]	UNIV. HAMBURG
10.2.e. [redacted]	TAQA
10.2.e. [redacted]	TAQA

1-A powerpoint presentation on the geomechanical modelling progress was presented by 10.2.e. [redacted] (TNO). Minor changes in fault plane geometry of the Mid Field fault (upward extension of faultplane into the Zechstein overburden by 10.2.e. [redacted] will be incorporated in the model. A minor modification was made to the severity of the Top Rotliegend dip change on the southwestern side of the Mid Field fault.
The Rotliegend reservoir will now be subdivided with more detail into 3 distinct property zones. The same applies for the Zechstein caprock overburden which was now subdivided in Carbonate, Anhydrite and Halite layers. 10 injection cycles will now be modeled in order to assess the near borehole temperature effect.
Consequently the resulting eclipse reservoir simulation model will be upgraded, which implies that an upgrade of the production history matching is required.
10.2.e. [redacted] (TNO's res. Eng) will investigate possible effects of these adjustments in close cooperation with TAQA's reservoir engineer 10.2.e. [redacted] and report on this in the following progress meeting.
The cycling effect with regard to pressure differences is part of a separate geomechanical modeling study (probably by GMI). The geometry and parameter input of this study also needs to be aligned with this study and will be a topic during next progress meeting.
Todays presentation slides will be distributed.

2 - 10.2.e. [redacted] (Univ. Hamburg) presented preliminary results on their study to the focal mechanism. Although preliminary, it looks like KNMI reverse mechanism is will be confirmed, furthermore preliminary shakemaps for the Alkmaar region were shown.

3 - Microseismicity test positioning calculations by KNMI are in progress.
Microseismicity test positioning calculations by Univ. Hamburg. Results micro-seismicity test positioning-calculations

4 - Microseismicity data collection issues by KNMI will be discussed and arranged right after finalization of the geophone recording string tender (Baker, Schlumberger & ESG).

Next meeting late August / early September (in view of Holidays)

From: 10.2.e.
To: 10.2.e. (KNMI)
Cc: 10.2.e.
Subject: Re: Alkmaar Event
Date: vrijdag 5 november 2010 19:57:45
Attachments: alkmaar.pdf

Dear 10.2.e. ,

Here is a version of our report with some updated figures reflecting our new solution. I didn't manage to update the text yet because I am still unhappy with our inversion and modelling results. I will send it to you now anyway, as you may be waiting for the new polarity plots.

Best regards,
10.2.e.

On 11/05/2010 09:04 AM, 10.2.e. (KNMI) wrote:
> Dear 10.2.e.
>
> Thanks for the update. I did not yet find our first motions, but I will
> further try to recover them today or early next week. I am looking
> forward to your updated report.
>
> I will, also look if we do have the raw macroseismic data in a computer
> readable form.
> We did keep the original records, but I am not sure if the digital
> version is still there.
> I will also come back to you with this information.
>
> Best regards
> 10.2.e.
>
>
>
> -----Oorspronkelijk bericht-----
> Van: 10.2.e.
> Verzonden: Wednesday, November 03, 2010 3:35 PM
> Aan: 10.2.e. (KNMI); 10.2.e.
> Onderwerp: Alkmaar Event
>
> Dear 10.2.e.
> in your last mail you asked for more results concerning the Alkmaar
> event.
> We have now, after a pause waiting for data from UK and time of absent /
>
> traveling
> continued and think we are nearly finished.
> We recieved the UK stations, had some problems with calibration (still
> not absolutely solved),
> but find a mote consistent and stable solution as before.
> We also tried to use classical P polarities to verify and compare, since
>
> the event is really
> difficult to analyse (and 'strange' because of its possible small
> fore-runner)
>
> Concerning the mechanism, we find a different solution than yours in

> Haak et al., and I would like to send
> you our results first for discussion - may be we have overlooked
> something.
>
> THe polarities we pick are not consistent with the polarities predicted
> by the Haak et al solution.
> If we consider a 'composite polaritiy solution' to include the nearest
> borehole stations
> (assuming both events have similar mechanisms), we retrieve more a
> strike slip than a dip slip solution.
>
> Our moment tensor solution is difficult because of the high frequencies
> we have to use.
> Since we have a good azimuthal average now, we used all P and SH phases
> from all stations
> and inverted only amplitude spectra, in order to have no problems with
> phase delays.
> The best solution is relatively stable and is similar to our first
> motion solution:
>
> Scalar Moment: M0 = 2.11391e+14 (Mw = 3.5 +-0.1)
>
> Fault plane 1: strike = 60, dip = 70, slip-rake = -140
> Fault plane 2: strike = 314, dip = 53, slip-rake = -25
>
> error estimates:
>
> Strike = 314 (confidence interval 68%) = [289, 349]
> Dip = 53 (confidence interval 68%) = [48, 68]
> Slip-Rake = -25 (confidence interval 68%) = [-50, -20]
> Moment = 2.11e+14 (confidence interval 68%) = [1.61e+14, 2.75e+14
>]
>
>
> Do you still have your first motions as a plot or file, so that we may
> compare these at least?
> Do you have estimates of confidence intervals for your focal solution of
>
> Haak et al?
>
> Can we send you the updated report (shouldbe ready tomorrow, 10.2.e.
> will send it)?
>
> --------
>
> If you have macroseismic data (e.g. a table with coordinate) we may plot
>
> this together
> with the rough estimates of the shake amplitudes (velocities)
>
> Best regards
>
> 10.2.e
>
>

Source parameter study of the 9/10 September 2001 earthquakes at Alkmaar

10.2.e. and 10.2.e. , Geophysik, Universität Hamburg

December 9, 2010

Contents

1 Preface and purpose of the study

The source mechanism and the seismological study of the Bergermeer 2001 earthquakes plays a key role for the overall interpretion of the seismicity at Bergermeer. In order to obtain an independent viewpoint and estimate of source parameters, Taqa Energy asked us to re-analyse the seismological data by using a full waveform approach. One Postdoc of us, 10.2.e. , was payed for a period of one month to re-examine the waveform data and try to estimate source parameters and the seismic moment and depth of the largest of the events, the 9 Septemner 2001 earthquake. We finally needed a much longer period than 1 month, since the data were extremely difficult and a standard analysis was not successful.
We want to state that our research and the post doc was independent and not influenced by any party or group involved in the questions of the planned facilities at Alkmaar.

2 Seismological data and previous studies

On the 9 and 10 September 2001 two weak shallow earthquakes occurred beneath Alkmaar and Bergen, The Netherlands. The earthquakes have been felt by local population [e.g. Haak et al., 2001]. According to Haak et al. [2001] the local earthquake magnitude of the 9 and 10 September 2001 events were $M_L \approx 3.5$ and 3.2, respectively. The relative distance between both events was only few hundred meters and both events had the same radiation pattern (source mechanism). The source parameters from Haak et al. (2001) are summarised in Table 1.
The earthquakes epicenter had been derived by a Geiger-type location method (*hypo71* and/or *hypoinverse*) using P and S wave arrivals from more than 60 stations in a distance between 3 and 1000 km (see Fig. 1). The used 1D velocity depth model was an averaged model for gas fields based on the information received from NAM. The depth is commonly more difficult to constrain, since the closest broadband station that recorded the main shock on 9 September 2001 was about 70 km away (DBN) and did not pose depth constraints. The aftershock on 10 September was recorded at three borehole stations (vertical arrays $0 - 200\,m$ depth, short period) in 3 - 8 km epicentral distance. Haak et al., 2001 estimate the depth of the 10 September 2001 earthquake at $\approx 2\,km$, and conclude from a relative location and macroseismic observations that the 9 September event occurred in a similar depth. The shallow depth of the events is in accord with the pattern of felt intensities and the small perceptibility radius.

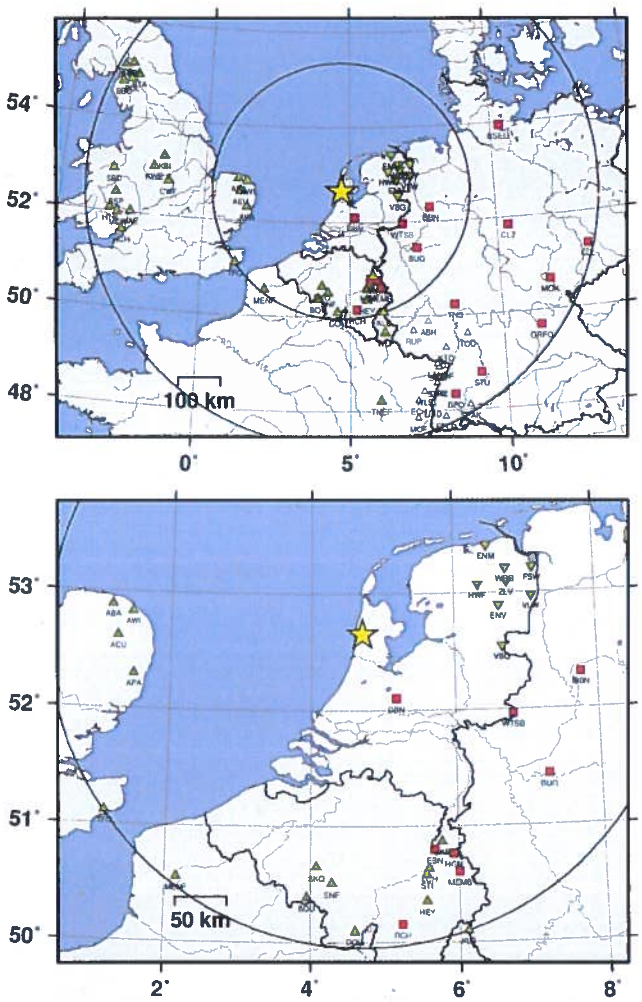


Figure 1: Epicenter (yellow star) of the 9 September 2001 earthquake (yellow star) and stations for which data are available (broadband declared by red squares, short period surface stations by green triangles and vertical borehole arrays by green inverse triangles). Stations for which arrival times are reported, but data are not available to us, are declared by open symbols. The 300 km and 600 km distance circle is indicated.

Table 1: Source parameters estimated by Haak et al. (2001). The seismic moment M_0 has here been transformed to moment magnitude M_W by using the Kanamori (1977) relation, i.e. $M_W = \frac{2}{3}\log_{10} M_0 - 10.7$, where M_0 is given in $dyne \cdot cm$.

	9 September	10 September
origin time (UTC)	$\approx$ 6:58 12s	$\approx$ 4:30 14s
lat/lon	52.651° / 4.713°	52.653° / 4.712°
depth	$2.0 \pm 0.2\,km$	$2.0 \pm 0.2\,km$
Epicentral Intensity I_0	VI+	IV-V
magnitude M_L	3.5	3.2
moment magnitude M_W	3.49	3.17
strike/dip/rake	130° / 66° / 73°	-

Since the 2001 events had similar first motion waveforms than two earlier earthquakes from the same location, a relative hypocenter location method (master event method) could be used to estimate accurate relative locations of the four events with relative errors in the range of $\pm 50\,m$. Two earlier events from August and September 1994 were included in the relative location. As a result, all four events occured at a similar depth and epicenters align on a NW-SE dipping plane striking at $\approx 158°$. The strike of the tip section of the central sissoir fault in the Bergermer gas field is very similar, and therefore the set of four earthquakes from 1994 and 2001 have been interpreted as the result of an incremental rupturing of the central sissoir fault in its tip region.
The seismic moments (Table 1) were estimated from the spectral plateau of the P pulse at several stations assuming a Brune source model.
The maximal intensity I_0 had been derived from macroseismic data. The macroseismic study was based on about 3500 reactions from a macroseismic inquiry in the local newspaper and mapped intensities. The intensity map also constraint the depth estimate of KNMI (10.2.e. pers. commun.).

3 Data processing

Seismograms of the 9 and 10 September 2001 earthquakes have been kindly provided by 10.2.e. , KNMI, The Netherlands (see Fig. 1). Most stations are surface stations, although some few locations in The Netherlands have been equipped by borehole vertical three component arrays. For instance, the closest stations PHP, WMH and OTL consists of 4-5 three component arrays in 200 m deep boreholes (placed at 50 m, 100 m, 150 m and 200 m). While the borehole arrays are mostly short period sensors, some of the other surface stations were broadband seismometers. We plotted and evaluated all data in order to select those that are suited for further waveform analysis. The digital data from The Netherlands have been restituted to ground displacement by means of pole zero files and amplification factors as provided in the report by [Dost and Haak, 2002] The pole zero files of German stations have been collected from the Central Seismological Observatory at the BGR, Hannover, Germany. 10.2.e. , pers. commun.). The parameters used are given in the appendices to this report. We have waveform data from several Belgian stations and information about the transfer function for 4 of these. We further downloaded data from two stations in France (THEF, MENF). We received waveforms from short period stations in UK and information on sensor characteristics. Data from France and UK were restituted to ground displacement. However, visual inspection of the UK stations indicated that the provided sensitivity factor is possibly a factor of π too large, and therefore we interpreted absolute amplitudes of UK stations with some caution.

The main goal of our study is to provide an independent estimate of the seismic moment as a function of hypocenter depth, and to prove the consistency of the depth and source mechanism of the 2001 events by means of a waveform analysis.
We compiled an average crustal and upper mantle velocity model Fig. 2 which is based based on information by Taqa Energy and different velocity studies or applications in the Northern European basin [e.g. Bayer et al., 2002, Hoffmann et al., 1996, Lindner et al., 2004, Dahm et al., 2007]. A Green function database has been generated with frequencies up to 5 Hz (Nyquist frequency, sampling rate is 10, Hz).
Fig. 3 shows true amplitudes of ground motion at regional distances, filtered at low and high frequencies. It becomes obvious from Fig. 3 that the earthquake did not radiate sufficient energy at frequencies below 1 Hz. The lack of regional distance surface waves was unexpected to us. For instance, the M_W 4.4, M_L 4.5 Rotenburg 2004 at 5.5 km depth and the M_W

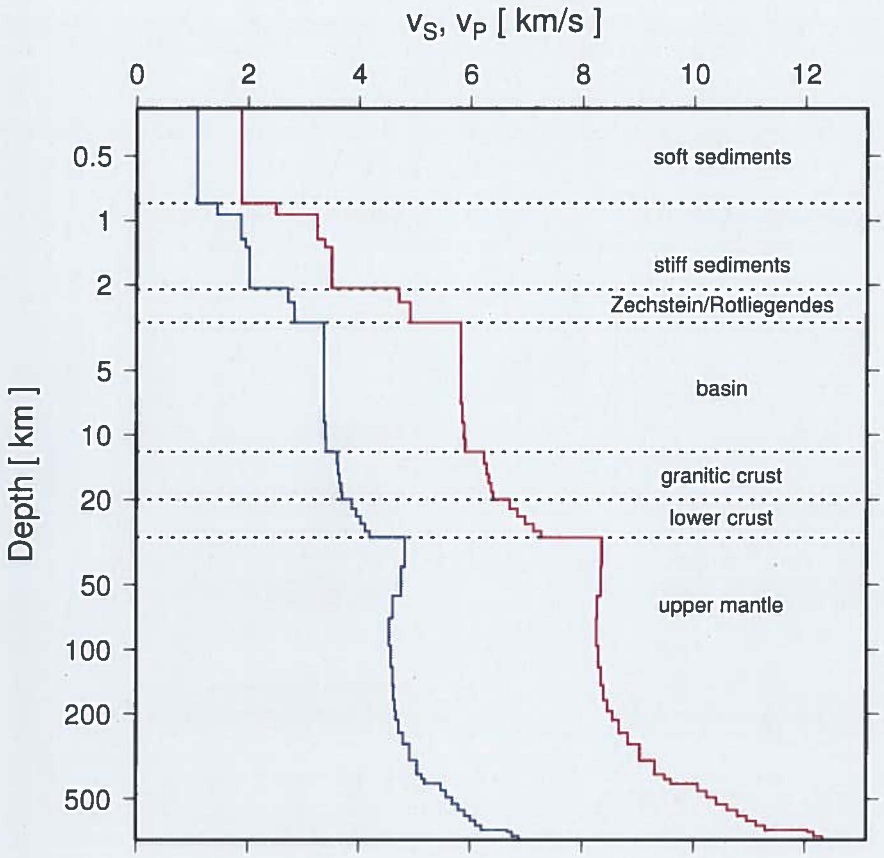
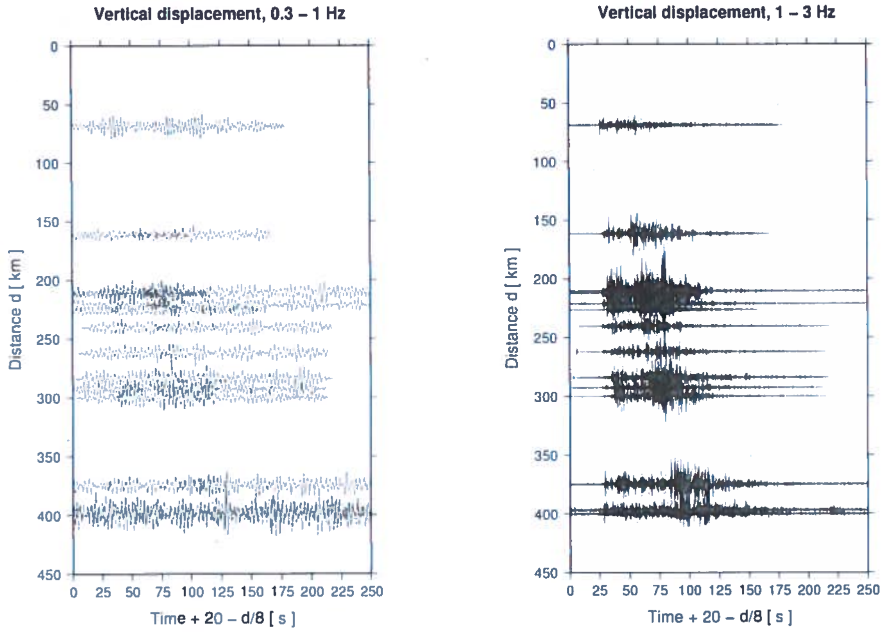
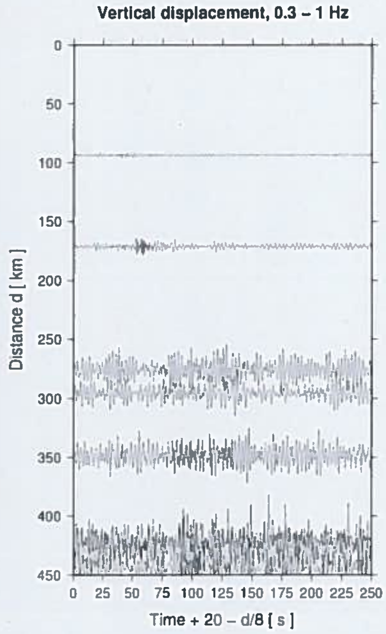


Figure 2: Average 1D velocity model used for the inversion and modelling study. P wave velocity is represented as continuous and S wave velocity as dashed line. Bulk densities were $2500\,kg/m^2$ in the uppermost soft sediments and taken from PREM reference model in the crust. The upper crustal velocities have been interpolated from the local interval velocities determined from vertical seismic profiling experiments (data and information provided by Taqa Energy).

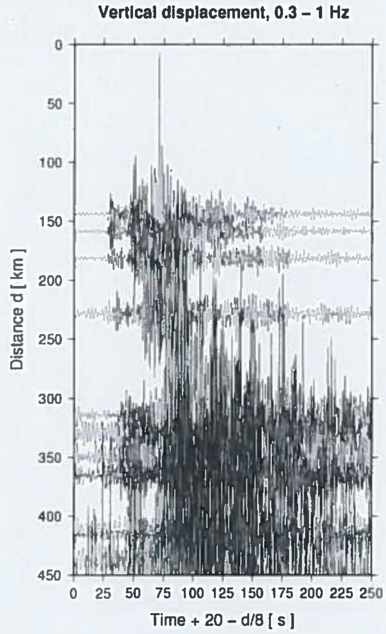


(a) $0.3 - 1\ Hz$ (b) $1 - 3\ Hz$

Figure 3: Recordsection (vertical component) of observed ground motion seismograms between 0 and 450 km distance in a low frequency (a) and high frequency range (b). True relative amplitudes are plotted, amplified by distance squared. The high frequency section is amplified by a factor 4 compared to the low frequency section.



(a) Basel, 2006-12-08, M_W 3, 4.7 km



(b) Saarbrücken, 2008-02-23, M_W 3.8, 1.6 km

Figure 4: Ground motion sections filtered between $0.3 - 1\,Hz$ for two induced shallow earthquakes in Basel 2006 and Saarbrücken 2008, respectively. The true amplitudes are scaled similar to Fig. 3a

3.8, M_L 4.0 Saarbrücken 2008 earthquake at $1.6\,km$ depth radiated strong surface waves below $1\,Hz$ and could be used for a moment tensor analysis [e.g. Cesca et al., 2010, M_L estimate from LGRB Freiburg and Fig. 4]. Weaker earthquakes, as for instance the M_W 3, M_L 3.4 Basel 2006 induced earthquake at $4.7\,km$ depth [e.g. Bäring et al., 2008, Deichmann and Giardini, 2009], showed a similar lack of surface waves below $1\,Hz$ and is considered similar to the Bergermeer event. We associate this phenomena to a strong attenuation of waves between 0.3 and 1 Hz, for instance by Q values of about 50 in the uppermost 4 km (intrinsic damping) or by scattering from strong lateral heterogeneities in the uppermost $4\,km$. However, a surface wave inversion, as originally planned, could not be tried for Bergermeer earthquakes.

4 Inversion results

4.1 Absolute location from arrival times

Haak et al. [2001] provided a list of first arrival times for P and S waves at seismic stations. Theses phase arrivals were used for absolute location. We re-located the 9 and 10 September earthquakes using the velocity model of Figure 2 and a location program that considers additional S-P differential times and apparent velocities. The program *HYPOSAT* gives estimates of error ellipses.
The hypocenter was indicated within the uppermost 3 km, but is not well constrained in a free inversion. The RMS error was 1.36 s and the azimuthal gap $108°$. Errors are about $\pm 2\,km$. The epicenter location is within its confidence intervals consistent with Haak et al. [2001].
P and S phases of the 10 September event were recorded at three close by borehole arrays between 3 and 8 km epicentral distances, i.e. at PPB, WMH and OTL. Additionally, we retrieved vertical slownesses from array waveforms and estimated horizontal apparent velocities. The absolute location of the 10 September was performed using the 7 closest stations in The Netherlands. Due to the S-P times and apparent velocities at the vertical arrays the hypocenter depth is better constrained at $2.2 \pm 1.2\,km$. The epicenter of the 10 September event was retrieved at $4.710 \pm 0.013°$ (LON) and $52.663 \pm 0.011°$ (LAT).

Summary of 4.1:

1. The epicentral location of Haak et al. [2001] can be confirmed within confidence intervals from own traveltime location.

2. Only the hypocenter depth of the 10 September 2001 event is constrained by phase arrival time data, if arrival-times and traveltime differences (and apparent velocities) measured at three close-by borehole vertical arrays are included. A depth of $\approx 2\,km$ is found.

4.2 Moment tensor inversion from amplitude spectra and evaluation of waveforms

Surface waves propagate slower and are associated with longer wavelengths than body waves. Their geometrical spreading (attenuation) is smaller than for body waves. Therefore, surface waves are better suited for a regional distance moment tensor inversion, especially if the velocity model is not very well known or varies in the uppermost kilometers at different stations. Our original plan was to apply a surface wave moment tensor inversion to the strongest Bergermeer event.

Fig. 3 shows that short period body wave amplitudes were strong between 1 and 3 Hz. Intermediate period surface waves at frequencies between 0.3 and 1 Hz are nearly not excited at a sufficient signal-noise-ratio (SNR) and cannot be used. The lack of intermediate period surface waves was unexpected to us. Other shallow events with $M_W \approx 3.8$ excited stronger surface waves between 0.1 - 1 Hz and could successfully be used for a regional surface wave inversion [Cesca et al., 2010].

As an alternative approach we had to invert the first arriving P and Pn phases including their coda depth phases between 200 and 1000 km distances. (vertical component displacement seismograms from stations HGN, HEY, KLB, TNS, CLZ, BSEG, CWF, MOX, MCH, STU, BFO, and GRFO). To extract the arrival phases and to compare synthetics and observations, here, we use two overlapping cosine-tapered windows of 10 seconds length, with their temporal positions offset to manually picked arrival times (offsets were (0,+1,+2,+3) s and (+2,+3,+4,+5) s, respectively). Amplitude spectra of the extracted phases were compared in the frequency band between 0.8 and 3.0 Hz, using an L1-Norm Strike, dip, rake were tested over the whole model space, moment and depth were confined to a small range between 1200-2000 m and M_w 3.5-3.9, respectively. Fig. 5 shows the misfit as a function of dip and strike of the fault plane. The diagram indicates a possible trade off strike, dip and rake. Additionally, the rake angle is ambigious for $\pm 180°$ if only amplitude spectra are inverted.

Two types of additional data have been considered to resolve the rake ambiguity and to evaluate the trade-off. **The first approach** compares theoretical waveforms with filtered seismograms of the 10 September aftershock observed at the closeby borehole arrays PHP, OTL and WHM in 3 to 8 kilometer distances (Fig. 6). The absolute and relative amplitudes of pulses are overall better fitted with our waveform solution than with the first motion polarity solution of Haak et al. [2001]. The waveform solution explains better the polarity o the first energetic pulse at station OTL. The polarity at station WHM seems reversed. However, modelling indicates that slight

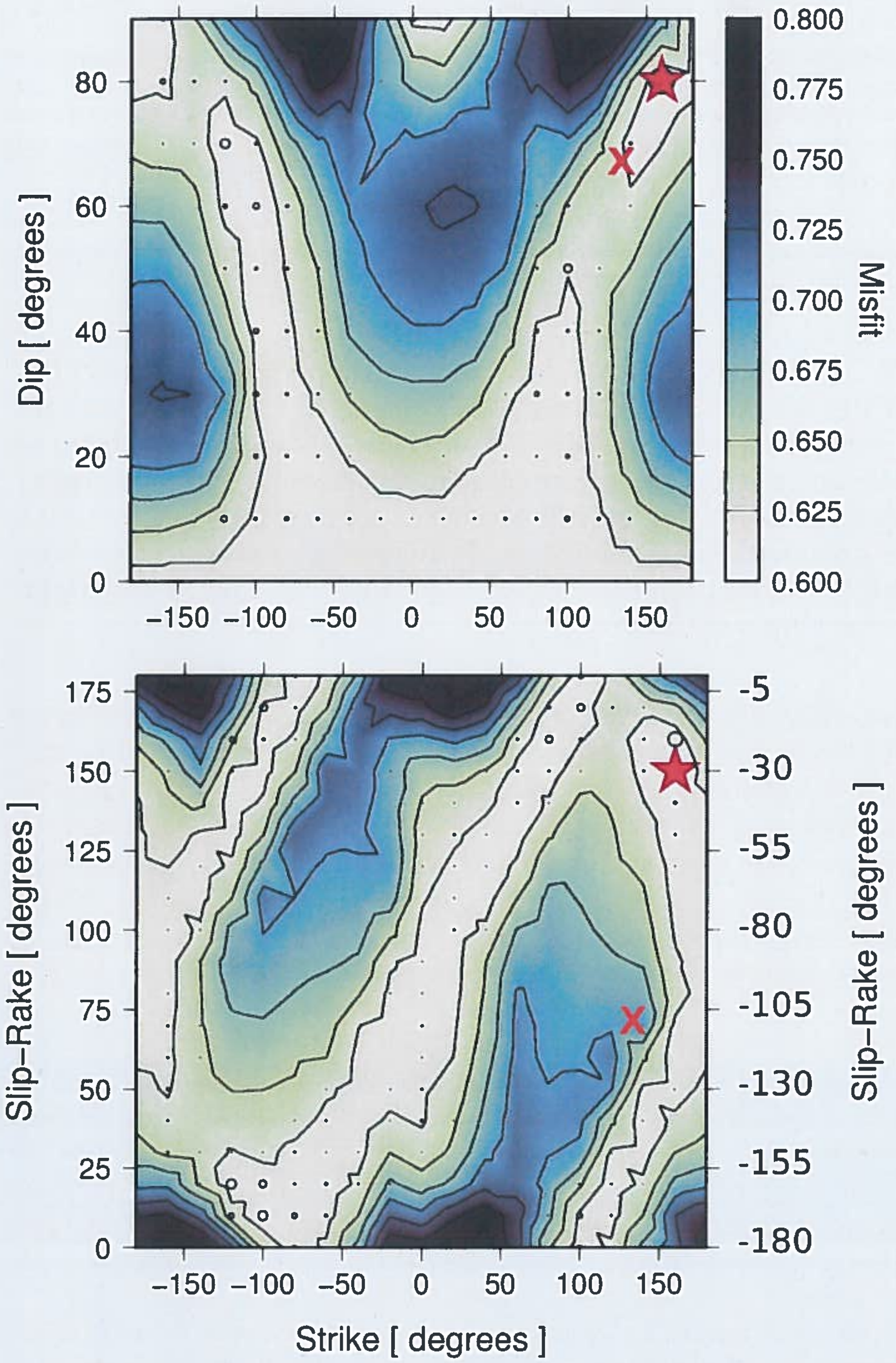


Figure 5: Amplitude spectra misfit is plotted as a function of fault plane angles strike-dip (top) and strike-rake (bottom). The solution of Haak et al. [2001] is indicated as red cross, the minimum misfit solution as red triangle. All combination of strike-dip-rake along the white valley are of similar likelihood and cannot be resolved. Slip rake is ambiguous (±180°) since amplitude spectra cannot resolve the polarity of the solution.

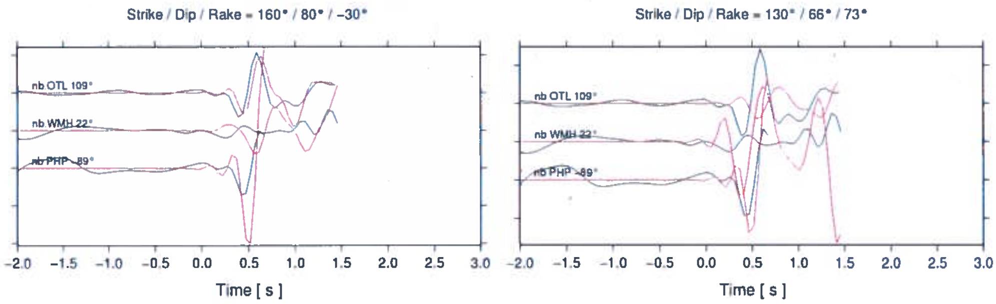


Figure 6: Modelling of first onset for vertical component at stations PHP, OTL, WMH for the 2001-09-10 04:30:15 aftershock. Synthetic traces are shown in red, data traces in black. The data traces have been restituted to displacement until recording were clipped. All traces have been filtered to the frequency range 1.5 to 3 Hz and a source depth of 2 km and $M_w = 3.4$ has been assumed. For the modelling, the following parameters have been used: **left (waveform solution):** strike = 160°, dip = 80°, rake = −30°. **right:** strike = 130°, dip = 66°, rake = 73°.

variation of the rake of our solution can flip the polarity at WHM without a signifcant change for the other stations, indicating that WHM is situated close to a nodal line of the radiation pattern. The same finding was used by Haak et al. [2001] to constrain their focal solution. Although the comparison in Fig. 6 is useful, it is hampered by the possibility that the 10 September event may have ruptured (slightly) different compared to the 9 September main shock.

The second approach compares waveforms at regional distances by forward modelling waveforms of Pn and pPn phases for strike, dip, rake combinations along the misfit valley in Fig. 5. Nine candidate models are plotted in Appendix E for visual inspection. We find two solution reproducing best the observed waveforms and polarities of strongest pulses, one for strike 160°, dip 80° and rake −30° (Fig. 7 left) and the other for strike −160°, dip 80° and rake −90° (Appendix E, Fig. 13). In contrary, the first motion solution of Haak et al. [2001] obtained for the 10 September 2001 event does not very well explain the relative amplitudes of the 9 September event at all stations in regional distances (Fig. 7 right).

The waveform inversion using true ground displacement and Green functions is used to estimate the seismic moment M_0, or alternatively the moment magnitude M_W. Both parameters have been questioned and discussed in previous reports. M_0 and M_W are one of the more robust pa-

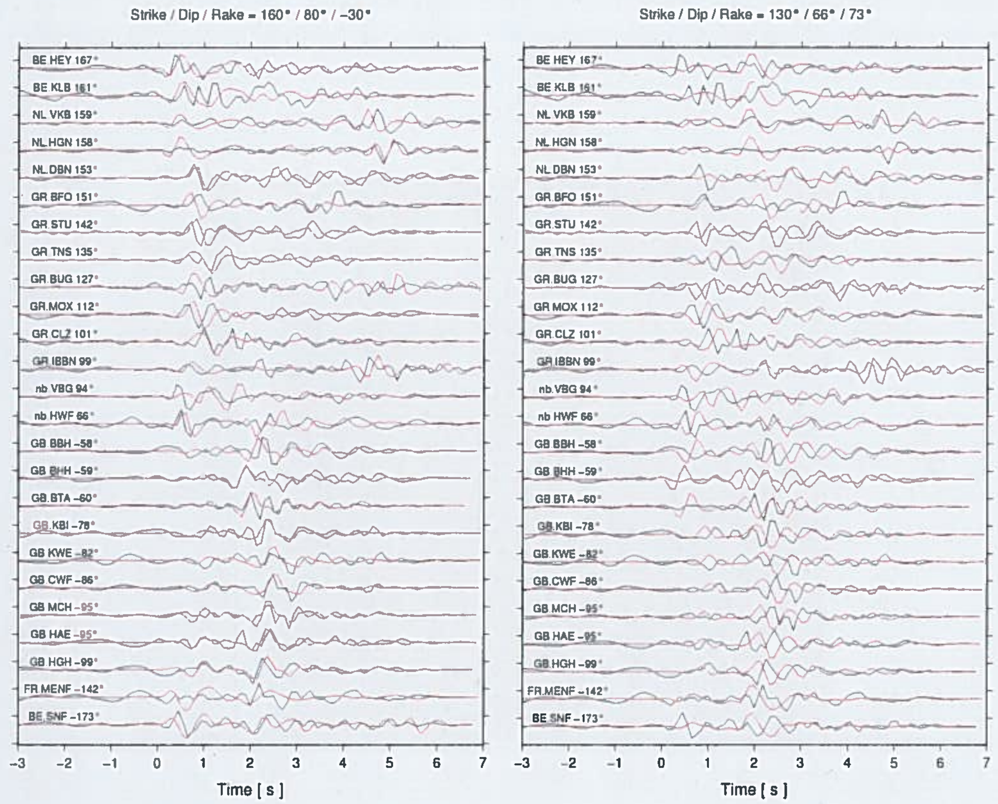


Figure 7: Comparison of theoretical waveforms at different stations in regional distances, using strike 160°, dip 80° and rake −30° (left) and the solution of Haak et al. [2001] (right). Measured data are plotted in black, theoretical ones in red. Traces have been filtered between 0.8 and 3 Hz, and are scaled to the maximum at each station in order to evaluate the relative amplitudes between first and secondary phases.

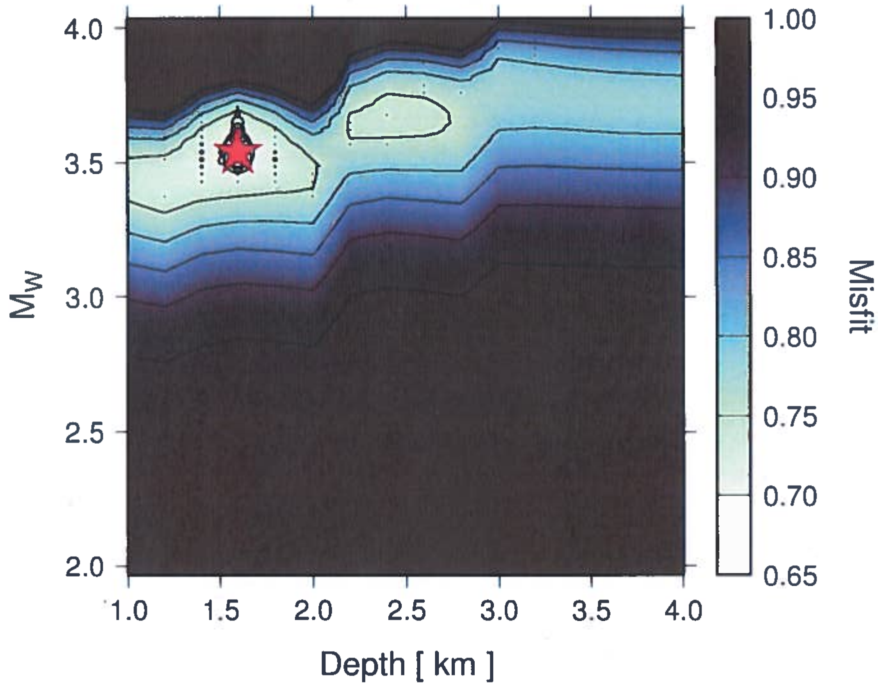


Figure 8: Grid search results (misfit, i.e. least squares sum, is indicated by coloured contours) for the depth-moment parameter subspace. Other source parameter of [taken from Haak et al., 2001] had been fixed.

rameters of an amplitude spectra moment tensor inversion. Fig. 8 shows the grid search result in the moment-depth space. The figure indicates a trend that higher moments are retrieved for deeper hypocenters, and smaller ones for the very shallow earthquakes. The moment magnitude at 2 km depth is $M_W \approx 3.5$ The largest moment magnitudes would be about $M_W \approx 3.6$ at a depth $> 2.5\,km$.

Summary of 4.2:

1. The seismic moment magnitude of the 9 September 2001 earthquake is estimated at $M_W = 3.45 \pm 0.2$, if the earthquake occurred at depth of $\approx 2\,km$. Our seismic moment is similar to the one derived in Haak et al. [2001].

2. **9. September event**: The waveform amplitude spectra inversion of P and S phases leads to bundle of equally likely solutions with different combinations of strike, dip and rake. The inspection of waveform patterns at stations in regional distances indicates that two solutions are more likely, (1) strike $\approx 160°$, dip $\approx 80°$ and slip rake at $\approx -30°$ and (2) strike $\approx -160°$, dip $\approx 80°$ and slip rake at $\approx -90°$ Solution (1) can be interpreted as rupture on the central sissoir fault of the field, but it involves a relatively strong strike slip motion during rupture. Solution (2) is a pure dip slip normal faulting, but cannot be interpreted as rupture on the central sissoir fault.

3. **10. September event**: The waveforms at borehole stations close the earthquake can be explained by the first motion solution by Haak et al. [2001]. However, a second type of source mechanism appears to also fit well the relative amplitudes and waveforms at three components of closest stations, although this analysis is hampered by the problem of clipped traces.

4.3 Regional distance depth-phase modelling

The hypocenter depth plays an important role for the geomechanical modelling. It is one of the most uncertain source parameter, especially since unclipped epicentral stations were missing. We tried to contribute to the depth problem by analysing high-frequency depth-phases at regional distances. The approach is difficult and non-standard, since only few stations show a sufficient SNR at regional distances and because of its dependence on assumptions about the source mechanism. Fig. 9 compares observed with synthetic waveforms calculated for different hypocenter depths. Four stations HAE (GB), CWF (GB), HWF (NL), and SNF (BE) are shown. Depth-phases in Fig. 9 are recognised as secondary phases with move-out over depth. The secondary phases are also visible in observed data and have comparable waveforms and amplitudes as the predicted ones. The occurrence time and waveforms fits best if the earthquake is simulated for a depth between 1.5 and $2.0\,km$, which confirms the depth estimate by Haak et al. [2001].

Summary of 4.3:

1. The modelling of regional distance high-frequency depth-phases indicates that the 9 September 2001 earthquake occurred between 1.5 and 2 km depth.

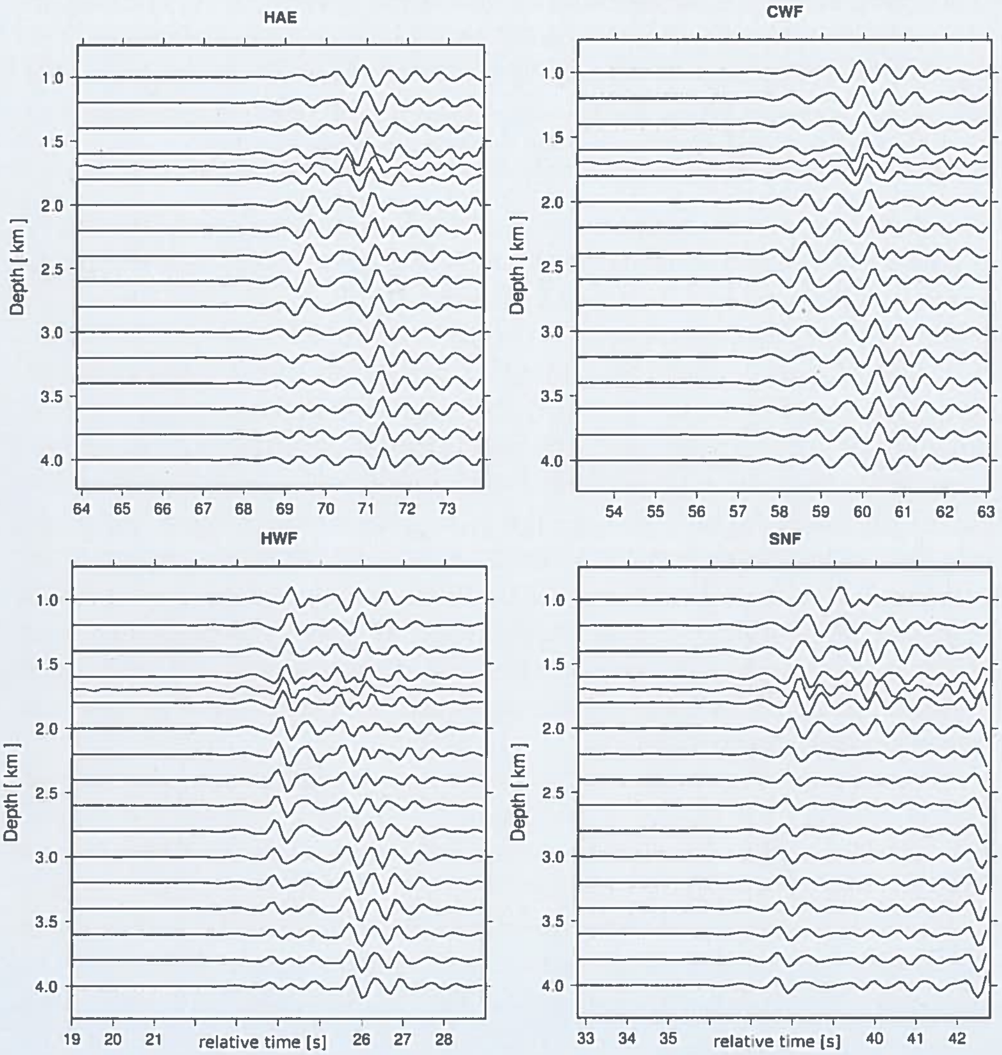


Figure 9: Modelling of depth phases at regional distances. Synthetic seismograms are shown in black, observations in red. Modelling has been done for frequencies ranging from 0.75 to 2.25 Hz. The assumed source mechanism was strike = 160°, dip = 80°, rake = -30°. The traces have been scaled individually. The observed traces have been manually shifted by best guess. The horizontal axis gives relative time in seconds.

5 Models of peak ground velocity

The 9 September 2001 earthquake was felt in the epicentral area of Bergermeer and the induced ground shaking locally caused some damage. The epicentral intensity was IV+ [Haak et al., 2001] Areas of strongest ground shaking were observed in the central western and north-western part of the small city of Bergermeer [see Fig. 8 in Haak et al., 2001].

Intensity scales, which quantify local damage to building and structures, are related to ground shaking parameters as peak ground velocity, peak ground acceleration and/or ground shaking duration. We used the source mechanism and the Green function database to simulate the ground shaking in the epicentral area. The synthetic seismograms have been analysed and peak ground velocities and and Arias intensities were extracted. **It is important to not overinterprete the deterministic simulations of seismograms, since thbis is not a probabilisitc hazard map.** The ground motion depend on many factors, as e.g. the earthquake source model, the uppermost soil structure and the velocity model and intrinsic attenuation. Peak-to-peak value will also depend on the frequency range chosen (often values are taken at $3\,Hz$). So, a deterministic simulation as presented here may be useful for parameteric studies, e.g. to investigate the amplification factor of depth or earthquake magnitude, but should not be taken to replace a proper hazard analysis.
Fig. 10 shows the distribution of simulated peak ground velocities for assuming different source depths between 1 and 4 km. The source mechanism and the seismic moment (M_W 3.4) were held constant. Intensities of V are associated with peak ground velocities of $\approx 25\,mm/s$ ($\log_{10}$ in m/s is -1.6), intensities VI with peak ground velocities of $\approx 47\,mm/s$ ($\log_{10}$ in m/s is -1.3), and intensities VII with $\approx 87\,mm/s$ ($\log_{10}$ in m/s is -1.0). The simulation of a source at $2\,km$ depth in Fig. 10 indicates that largest peak ground velocities slightly below $100\,mm/s$ occurred in a small patch at the epicenter, which would indicate an epicentral intensity of about VII. The patch of largest ground shaking is outside the urban areas. The predicted peak ground velocities in the central and norther western part of Bergermeer indicate intensities VI to V, which resembles well the level of and number of damage reports in these areas. The result may be interpreted in such a way, that the velocity model and frequency range chosen ($0.5-5\,Hz$) simulated realistic ground motions for the Bergermeer area and may be used for parameter studies. For instance, the peak ground velocity increases and decreases if the source is placed shallower or deeper than $2\,km$, respectively (Fig. 10). However, as noted by 10.2.e. , the dominant

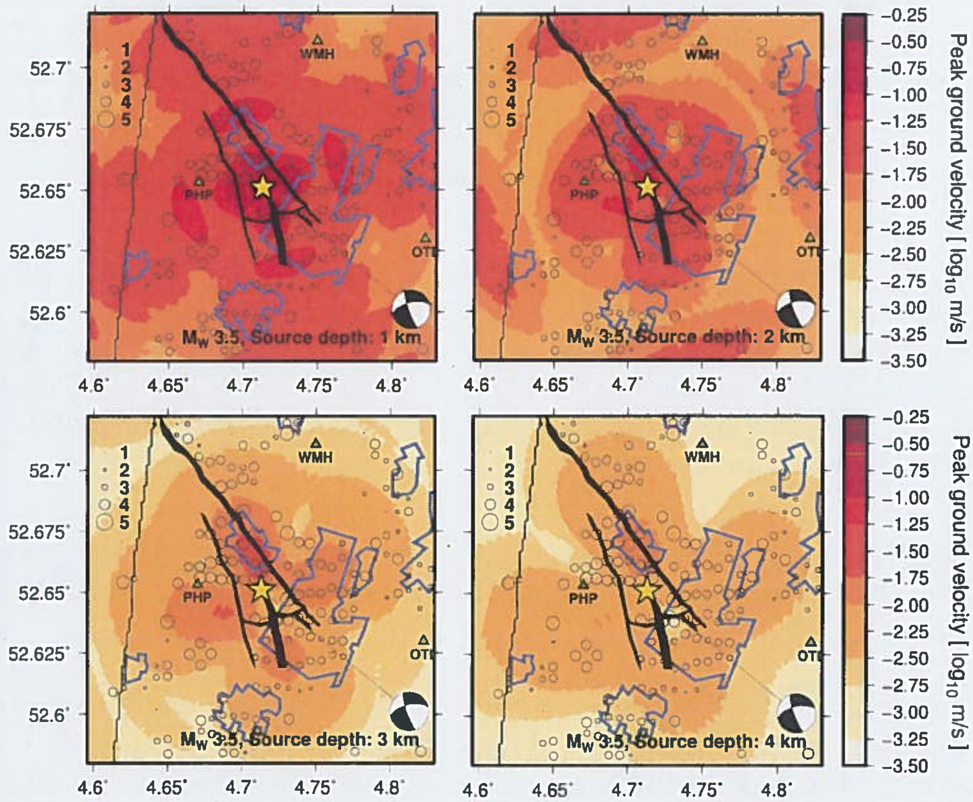


Figure 10: Shakemaps of peak ground velocity for different assumed source depths. The modelling has been done for frequencies between 0.5 and 5 Hz and for a source mechanism with the following parameters: strike = 160°, dip = 80°, rake = -30°, depth = 2 km, M_W = 3.4. Open circles denote observed intensities and blue lines enclose populated areas. The coast is indicated by black solid line. Faults at 2 km depth are inidicated by black lines. Green triangles indicate borehole stations PHP, WMH and OTL, and the star marks the location of the event.

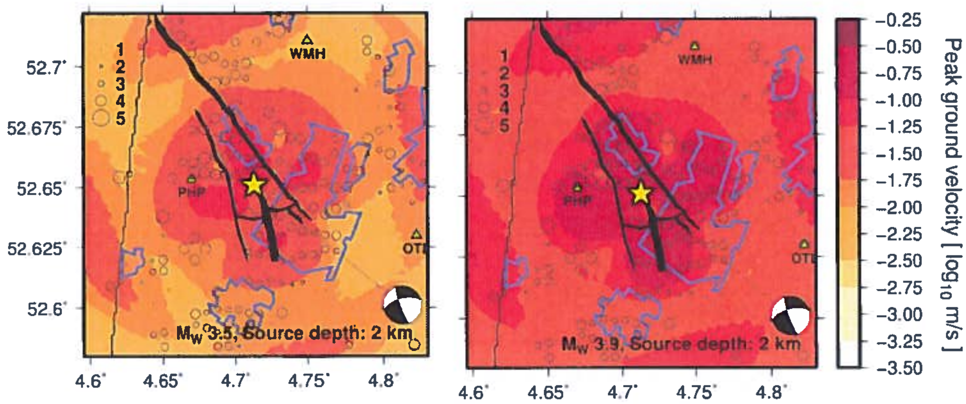


Figure 11: Peak ground velocity is shown in colour. The frequency range is between 0.5 and 5 Hz. *Left sub-figure:* The same simulation as in Fig. 10 for a depth of $2\,km$, but for the uppermost 100 m replaced by a soft layer with v_P = 1500 m/s, v_S = 500 m/s, Q_p = 200, and Q_s = 50. *Right sub-figure:* The same simulation as in Fig. 10 but for a moment magnitude of M_W 3.9 instead of M_W 3.4.

frequency of S-waves is around $10\,Hz$, so that our conversion of ground velocity in between $0.5 - 5\,Hz$ may not be realistic and has to be taken by care.

Fig. 11 shows the influence of a soft layer at the surface and the effect of moment magnitude scaling. The influence of the soft layer is not very drastic. The predicted peak ground velocity increases slightly but would still be in the range of observed patterns of intensities.

Stronger or weaker earthquakes at the same location would amplify or attenuate the peak ground velocities. A simulation of an hypothetic earthquake in only $2\,km$ depth with 0.5 magnitude units larger (i.e. M_W 3.9 instead of M_W 3.4) would predict maximal peak ground velocities in the range of $560\,mm/s$ (factor 5.6), which might be associated with intensities $VIII$ (Fig. 11). On the other side, a earthquake of strength M_W 2.9 in 2 km depth instead of M_W 3.4 would predict a factor 5.6 smaller ground velocities, which would be below the critical level for damage everywhere.

Peak ground velocities tell nothing about the duration of ground motion. In Fig. 12 we extracted Arias intensities from simulated seismograms. Arias intensities better parametrise the expected energy and duration of ground

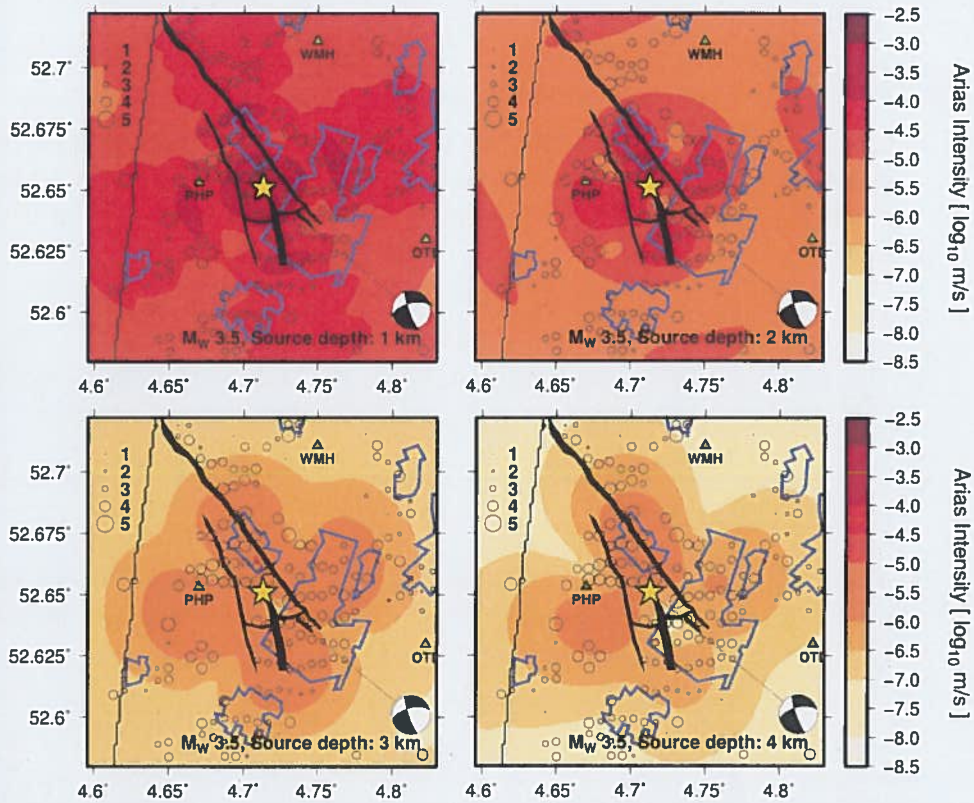


Figure 12: Shakemaps of Arias intensities determined by forward modelling for different assumed source depths. Arias intensities are shown in colour. The modelling has been done between 0.5 and 5 Hz for a source mechanism with the following parameters: strike = 160°, dip = 80°, rake = -30°, depth = 2 km, M_W = 3.4. Open circles denote observed intensities and blue lines enclose populated areas. The coast is indicated by black solid line. Faults at 2 km depth are inidicated by black lines. Green triangles indicate borehole stations PHP, WMH and OTL, and the star marks the location of the event.

motion and often resemble better the pattern of expected damage. In our case, the pattern of Arias intensities is very similar to the patter of peak ground velocities and does not provide new insights or conclusion.

Summary of 5:

1. The simulation of peak ground velocities and Arias intensities can explain the pattern of reports of strong ground shaking and damage in Bergermeer and the surrounding, if the earthquake was in $2\,km$ depth.

2. The maximal epicentral intensity of about VI+ is reproduced.

3. The reverse faulting radiation pattern of Haak et al. [2001] would explain the distribution of stronger and weaker ground motion.

4. The pattern of ground shaking confirms the epicentral location by Haak et al. [2001].

5. The forward modelling indicates that a soft layer of $100\,m$ thickness has only a weak amplification effect. The effect of a stronger magnitude event in only $2\,km$ depth is considerable.

Table 2: Source parameters estimated by Haak et al. (2001). The seismic moment M_0 has here been transformed to moment magnitude M_W by using the Kanamori (1977) relation, i.e. $M_W = \frac{2}{3}\log_{10} M_0 - 10.7$, where M_0 is given in $dyne \cdot cm$.

	9 September	10 September
lat/lon	no new location	$52.663° \pm 0.011°$/ $4.710° \pm 0.013°$
depth	≈ 1.5 to $2.2\,km$	$2.2 \pm 1.2\,km$
moment magnitude M_W	3.45 ± 0.2	-
strike/dip/rake . (errors $\approx$ $\pm 15°$).	$200°$/ $80°$ / $-90°$ or $160°$/ $80°$ / $-30°$	-

6 Conclusions

The 9 September 2001 Alkmaar earthquake has been re-analysed for its depth, seismic moment (moment magnitude), and the radiation pattern of the energetic body waves. Amplitude spectra and waveforms at European stations were included in the full waveform analysis. While epicenter, source depth and moment magnitude is reasonably well constrained from waveform data, the source mechanism was more difficult to resolve. The focal solution given by Haak et al. [2001] for the 10 September 2001 event cannot explain very well the P wave amplitude measured for the 9 September earthquake. The solution derived from amplitude spectra and the comparison of waveforms is, however, not consistent with first motion polarities and may indicate a complex rupture.
Additionally, peak ground velocity and Arial intensities were simulated and compared to observed ground shaking proxies (macroseismic intensities). These simulations were used to evaluate the relative ground motion parameter if an earthquake would occur at a similar location but at a slightly different depth or with slightly different magnitude. Important results comprise (see also Table 2):

1. Waveform modeling confirms that the eartquake was shallow. The time delay of depth phases at regional distances indicate that the hypocenter was in between 1.5 - 2.2 km depth.

2. The moment magnitude constrained by P and S wave amplitude spectra inversion is $M_W = 3.45 \pm 0.2$.

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A Station list

station	latitude	longitude	elevation	depth	distance	azimuth
NL.DBN.	52.1017	5.1767	0	0	69	153
nb.HWF.0	53.0718	6.3516	0	0	120	66
nb.HWF.1	53.0718	6.3516	0	-44	120	66
nb.HWF.2	53.0718	6.3516	0	-94	120	66
nb.HWF.3	53.0718	6.3516	0	-144	120	66
nb.HWF.4	53.0718	6.3516	0	-194	120	66
nb.ENV.1	52.8953	6.6338	0	-33	132	77
nb.ENV.2	52.8953	6.6338	0	-83	132	77
nb.ENV.3	52.8953	6.6338	0	-133	132	77
nb.ENV.4	52.8953	6.6338	0	-183	132	77
nb.VBG.1	52.5447	6.6704	0	-39	133	94
nb.VBG.2	52.5447	6.6704	0	-89	133	94
nb.VBG.3	52.5447	6.6704	0	-139	133	94
nb.VBG.4	52.5447	6.6704	0	-189	133	94
nb.ENM.1	53.4076	6.4823	0	-49	146	54
nb.ENM.2	53.4076	6.4823	0	-99	146	54
nb.ENM.3	53.4076	6.4823	0	-149	146	54
nb.ENM.4	53.4076	6.4823	0	-199	146	54
nb.ZLV.0	53.0931	6.75	0	0	146	69
nb.ZLV.1	53.0931	6.75	0	-49	146	69
nb.ZLV.2	53.0931	6.75	0	-99	146	69
nb.ZLV.3	53.0931	6.75	0	-149	146	69
nb.ZLV.4	53.0931	6.75	0	-199	146	69
nb.WDB.0	53.209	6.7349	0	0	149	65
nb.WDB.1	53.209	6.7349	0	-52	149	65
nb.WDB.2	53.209	6.7349	0	-102	149	65
nb.WDB.3	53.209	6.7349	0	-152	149	65
nb.WDB.4	53.209	6.7349	0	-202	149	65
NL.WTSB.	51.966	6.799	43	0	161	117
nb.VLW.0	52.9694	7.0982	0	0	165	77
nb.VLW.1	52.9694	7.0982	0	-43	165	77
nb.VLW.2	52.9694	7.0982	0	-93	165	77
nb.VLW.3	52.9694	7.0982	0	-143	165	77
nb.VLW.4	52.9694	7.0982	0	-193	165	77
nb.FSW.1	53.2146	7.1204	0	0	174	68
nb.FSW.2	53.2146	7.1204	0	-75	174	68
nb.FSW.3	53.2146	7.1204	0	-150	174	68
nb.FSW.4	53.2146	7.1204	0	-225	174	68
nb.FSW.5	53.2146	7.1204	0	-300	174	68
GR.IBBN.	52.3072	7.7566	140	0	210	99
NL.VKB.	50.8669	5.7847	0	0	212	159
BE.EBN.	50.797	5.678	80	0	217	162
GR.BUG.	51.4406	7.2693	85	0	221	127
NL.HGN.	50.764	5.9317	135	0	226	158
BE.SKQ.	50.649	4.08	63	0	227	-169

BE.LCH.	50.639	5.607	100	0	232	164
BE.STI.	50.584	5.567	226	0	237	165
BE.SNF.	50.508	4.282	108	0	240	-173
BE.MEMB.	50.609	6.006	250	0	244	158
BE.BOU.	50.389	3.945	80	0	257	-168
BE.HEY.	50.357	5.568	195	0	262	167
BE.RCH.	50.156	5.228	191	0	280	172
BE.DOU.	50.1	4.59	0	0	284	-178
BE.KLB.	50.1	6.109	0	0	300	161
BE.WLF.	49.6646	6.1526	295	0	347	163
GR.TNS.	50.2225	8.4473	815	0	375	135
GR.CLZ.	51.8416	10.3724	680	0	397	101
GR.BSEG.	53.9353	10.3169	40	0	400	67
GR.MOX.	50.6447	11.6156	455	0	527	112
GR.STU.	48.7708	9.1933	360	0	535	142
GR.BFO.	48.3301	8.3296	589	0	545	151
GR.GRFO.	49.6909	11.2203	384	0	561	123
GR.CLL.	51.3077	13.0026	230	0	588	101
GR.RGN.	54.5477	13.3214	15	0	607	66
GR.RUE.	52.4759	13.78	40	0	615	88
GR.BRG.	50.8732	13.9428	296	0	667	104
GR.FUR.	48.1629	11.2752	565	0	683	134
GR.WET.	49.144	12.8782	613	0	694	121
GR.GEC2.	48.8451	13.7016	1132	0	762	120

B Channel orientations and gain

The following list describes the orientation of each channel at each station by giving azimuth and dip of the respective instument component. The table also lists the gain for each channel, which should be a constant approximation for the corresponding transfer function. The gain factor is given in counts/(m/s). If the gain value listed is zero, the complete transfer function of the channel has been used. Pole-zero representations of the complete transfer functions of the instruments are listed in appendix C.

channel	azimuth	dip	gain
NL.DBN..BHE	90	0	0.
NL.DBN..BHN	0	0	0.
NL.DBN..BHZ	0	-90	0.
nb.HWF.0.SH1	0	0	0.
nb.HWF.0.SH2	90	0	0.
nb.HWF.0.SHZ	0	-90	0.
nb.HWF.1.SH1	346	0	0.
nb.HWF.1.SH2	76	0	0.
nb.HWF.1.SHZ	0	-90	0.
nb.HWF.2.SH1	77	0	0.

```
nb.HWF.2.SH2  167    0  0.
nb.HWF.2.SHZ    0  -90  0.
nb.HWF.3.SH1  162    0  0.
nb.HWF.3.SH2  252    0  0.
nb.HWF.3.SHZ    0  -90  0.
nb.HWF.4.SH1   19    0  0.
nb.HWF.4.SH2  109    0  0.
nb.HWF.4.SHZ    0  -90  0.
nb.ENV.1.SH1  142    0  0.
nb.ENV.1.SH2  232    0  0.
nb.ENV.1.SHZ    0  -90  0.
nb.ENV.2.SH1  157    0  0.
nb.ENV.2.SH2  247    0  0.
nb.ENV.2.SHZ    0  -90  0.
nb.ENV.3.SH1   27    0  0.
nb.ENV.3.SH2  117    0  0.
nb.ENV.3.SHZ    0  -90  0.
nb.ENV.4.SH1  131    0  0.
nb.ENV.4.SH2  221    0  0.
nb.ENV.4.SHZ    0  -90  0.
nb.VBG.1.SH1  340    0  0.
nb.VBG.1.SH2   70    0  0.
nb.VBG.1.SHZ    0  -90  0.
nb.VBG.2.SH1  294    0  0.
nb.VBG.2.SH2  204    0  0.
nb.VBG.2.SHZ    0  -90  0.
nb.VBG.3.SH1  104    0  0.
nb.VBG.3.SH2  194    0  0.
nb.VBG.3.SHZ    0  -90  0.
nb.VBG.4.SH1   90    0  0.
nb.VBG.4.SH2  180    0  0.
nb.VBG.4.SHZ    0  -90  0.
nb.ENM.1.SH1  122    0  0.
nb.ENM.1.SH2  212    0  0.
nb.ENM.1.SHZ    0  -90  0.
nb.ENM.2.SH1  177    0  0.
nb.ENM.2.SH2  267    0  0.
nb.ENM.2.SHZ    0  -90  0.
nb.ENM.3.SH1  164    0  0.
nb.ENM.3.SH2  254    0  0.
nb.ENM.3.SHZ    0  -90  0.
nb.ENM.4.SH1   91    0  0.
nb.ENM.4.SH2  181    0  0.
nb.ENM.4.SHZ    0  -90  0.
nb.ZLV.0.SH1    0    0  0.
nb.ZLV.0.SH2   90    0  0.
nb.ZLV.0.SHZ    0  -90  0.
nb.ZLV.1.SH1  244    0  0.
nb.ZLV.1.SH2  334    0  0.
```

```
nb.ZLV.1.SHZ     0  -90  0.
nb.ZLV.2.SH1   313    0  0.
nb.ZLV.2.SH2    43    0  0.
nb.ZLV.2.SHZ     0  -90  0.
nb.ZLV.3.SH1    42    0  0.
nb.ZLV.3.SH2   132    0  0.
nb.ZLV.3.SHZ     0  -90  0.
nb.ZLV.4.SH1   310    0  0.
nb.ZLV.4.SH2    40    0  0.
nb.ZLV.4.SHZ     0  -90  0.
nb.WDB.0.SH1     0    0  0.
nb.WDB.0.SH2    90    0  0.
nb.WDB.0.SHZ     0  -90  0.
nb.WDB.1.SH1   274    0  0.
nb.WDB.1.SH2     4    0  0.
nb.WDB.1.SHZ     0  -90  0.
nb.WDB.2.SH1    52    0  0.
nb.WDB.2.SH2   142    0  0.
nb.WDB.2.SHZ     0  -90  0.
nb.WDB.3.SH1   311    0  0.
nb.WDB.3.SH2    41    0  0.
nb.WDB.3.SHZ     0  -90  0.
nb.WDB.4.SH1    70    0  0.
nb.WDB.4.SH2   160    0  0.
nb.WDB.4.SHZ     0  -90  0.
NL.WTSB..BHE    90    0  0.
NL.WTSB..BHN     0    0  0.
NL.WTSB..BHZ     0  -90  0.
nb.VLW.0.SH1     0    0  0.
nb.VLW.0.SH2    90    0  0.
nb.VLW.0.SHZ     0  -90  0.
nb.VLW.1.SH1    22    0  0.
nb.VLW.1.SH2   112    0  0.
nb.VLW.1.SHZ     0  -90  0.
nb.VLW.2.SH1    72    0  0.
nb.VLW.2.SH2   162    0  0.
nb.VLW.2.SHZ     0  -90  0.
nb.VLW.3.SH1   303    0  0.
nb.VLW.3.SH2    33    0  0.
nb.VLW.3.SHZ     0  -90  0.
nb.VLW.4.SH1   269    0  0.
nb.VLW.4.SH2   359    0  0.
nb.VLW.4.SHZ     0  -90  0.
nb.FSW.1.SH1    53    0  0.
nb.FSW.1.SH2   143    0  0.
nb.FSW.1.SHZ     0  -90  0.
nb.FSW.2.SH1   204    0  0.
nb.FSW.2.SH2   294    0  0.
nb.FSW.2.SHZ     0  -90  0.
```

```
nb.FSW.3.SH1   11    0  0.
nb.FSW.3.SH2  101    0  0.
nb.FSW.3.SHZ    0  -90  0.
nb.FSW.4.SH1  214    0  0.
nb.FSW.4.SH2  304    0  0.
nb.FSW.4.SHZ    0  -90  0.
nb.FSW.5.SH1  278    0  0.
nb.FSW.5.SH2    8    0  0.
nb.FSW.5.SHZ    0  -90  0.
GR.IBBN..BHE   90    0  5.98802e+08
GR.IBBN..BHN    0    0  5.98802e+08
GR.IBBN..BHZ    0  -90  5.98802e+08
NL.VKB..HHE    90    0  0.
NL.VKB..HHN     0    0  0.
NL.VKB..HHZ     0  -90  0.
GR.BUG..BHE    90    0  5.98802e+08
GR.BUG..BHN     0    0  5.98802e+08
GR.BUG..BHZ     0  -90  5.98802e+08
NL.HGN..BHE    90    0  0.
NL.HGN..BHN     0    0  0.
NL.HGN..BHZ     0  -90  0.
GR.TNS..BHE    90    0  5.98802e+08
GR.TNS..BHN     0    0  5.98802e+08
GR.TNS..BHZ     0  -90  5.98802e+08
GR.CLZ..BHE    90    0  5.98802e+08
GR.CLZ..BHN     0    0  5.98802e+08
GR.CLZ..BHZ     0  -90  5.98802e+08
GR.BSEG..BHE   90    0  5.98802e+08
GR.BSEG..BHN    0    0  5.98802e+08
GR.BSEG..BHZ    0  -90  5.98802e+08
GR.MOX..BHE    90    0  5.98802e+08
GR.MOX..BHN     0    0  5.98802e+08
GR.MOX..BHZ     0  -90  5.98802e+08
GR.STU..BHE    90    0  6.13497e+08
GR.STU..BHN     0    0  6.13497e+08
GR.STU..BHZ     0  -90  6.13497e+08
GR.BFO..BHE    90    0  5.98802e+08
GR.BFO..BHN     0    0  5.98802e+08
GR.BFO..BHZ     0  -90  5.98802e+08
GR.GRFO..BHE   90    0  1.04712e+09
GR.GRFO..BHN    0    0  9.76562e+08
GR.GRFO..BHZ    0  -90  9.88142e+08
GR.CLL..BHE    90    0  5.98802e+08
GR.CLL..BHN     0    0  5.98802e+08
GR.CLL..BHZ     0  -90  5.98802e+08
GR.RGN..BHE    90    0  5.98802e+08
GR.RGN..BHN     0    0  5.98802e+08
GR.RGN..BHZ     0  -90  5.98802e+08
GR.RUE..BHE    90    0  5.98802e+08
```

```
GR.RUE..BHN      0     0   5.98802e+08
GR.RUE..BHZ      0   -90   5.98802e+08
GR.BRG..BHE     90     0   5.98802e+08
GR.BRG..BHN      0     0   5.98802e+08
GR.BRG..BHZ      0   -90   5.98802e+08
GR.FUR..BHE     90     0   5.98802e+08
GR.FUR..BHN      0     0   5.98802e+08
GR.FUR..BHZ      0   -90   5.98802e+08
GR.WET..BHE     90     0   5.98802e+08
GR.WET..BHN      0     0   5.98802e+08
GR.WET..BHZ      0   -90   5.98802e+08
GR.GEC2..BHE    90     0   2.65301e+10
GR.GEC2..BHN     0     0   2.65301e+10
GR.GEC2..BHZ     0   -90   2.65301e+10
```

C Station responses

This section contains a collection of the transfer functions which have been used. The transfer functions are given as pole-zero files in SAC format. These pole-zeros describe the the complete transfer function including gain factors from ground velocity in m/s to digitizer output in counts. For the german stations, displacement seismograms have been obtained by integration and division by the gain factor listed in appendix B.

Polezero file for station DBN

```
ZEROS 2
POLES 10
 -0.276     0.149
 -0.276    -0.149
 -6.13     30.81
 -6.13    -30.81
-17.45     26.12
-17.45    -26.12
-26.12     17.45
-26.12    -17.45
-30.82      6.09
-30.82     -6.09
CONSTANT 3.21E19
```

Polezero file for station HGN channel Z

```
ZEROS 2
POLES 9
 -0.0123    0.0123
 -0.0123   -0.0123
-62.8320    0.0000
-39.1440   49.1480
-39.1440  -49.1480
-14.0120   61.2500
-14.0120  -61.2500
-56.6120   27.2580
-56.6120  -27.2580
CONSTANT 3.15e21
```

Polezero file for station HGN channel N

```
ZEROS 2
POLES 9
 -0.0123    0.0123
 -0.0123   -0.0123
-62.8320    0.0000
-39.1440   49.1480
-39.1440  -49.1480
-14.0120   61.2500
-14.0120  -61.2500
-56.6120   27.2580
-56.6120  -27.2580
CONSTANT 3.13e21
```

Polezero file for station HGN channel E

```
ZEROS 2
POLES 9
 -0.0123    0.0123
 -0.0123   -0.0123
-62.8320    0.0000
-39.1440   49.1480
-39.1440  -49.1480
-14.0120   61.2500
-14.0120  -61.2500
-56.6120   27.2580
-56.6120  -27.2580
CONSTANT 3.10e21
```

Polezero file for station WTSB

```
ZEROS 9
-5907.0000  -3411.0000
-5907.0000   3411.0000
 -683.9000   -175.5000
 -683.9000    175.5000
 -555.1000      0.0000
 -294.6000      0.0000
  -10.7500      0.0000
POLES 20
   -0.0370      0.0370
   -0.0370     -0.0370
  -62.8320      0.0000
  -56.6120     27.2580
  -56.6120    -27.2580
  -14.0120     61.2500
  -14.0120    -61.2500
  -85.1100      0.0000
-6909.0000   9208.0000
-6909.0000  -9208.8000
-6227.0000      0.0000
-4936.0000   4713.0000
-4936.0000  -4713.0000
-1391.0000      0.0000
 -556.8000    -60.0500
 -556.8000     60.0500
  -98.4400   -442.8000
  -98.4400    442.8000
  -10.9500      0.0000
 -255.1000      0.0000
CONSTANT 1.031520e+37
```

Polezero file for station VKB

```
ZEROS 4
POLES 12
   4.15      4.71
   4.15     -4.71
  -0.666     0.701
  -0.666    -0.701
 -34.30    172.52
 -34.30   -172.52
 -97.71    146.26
 -97.71   -146.26
-146.26     97.72
-146.26    -97.72
```

```
-172.56     34.13
-172.56    -34.13
CONSTANT 3.24E26
```

Polezero file for the borehole stations ENM, FSW, WDB, HWF, ZLV, ENV, VBG, OTL, WMH, and PHP

```
ZEROS 6
  0.00  0.00
  0.00  0.00
  0.00  0.00
  0.00  0.00
-28.50  0.00
-28.50  0.00
POLES 14
 -19.99      19.99
 -19.99     -19.99
  -6.35       0.00
  -6.35       0.00
  -0.666      0.701
  -0.666     -0.701
 -34.30     172.52
 -34.30    -172.52
 -97.71     146.26
 -97.71    -146.26
-146.26      97.72
-146.26     -97.72
-172.56      34.13
-172.56     -34.13
CONSTANT 3.31E26
```

D Earth model

```
depth    vP         vS         density     QP       QS
  0.        1.880    1.08506   2.5       1324   600
   .830     1.880    1.08506   2.5       1324   600
   .830     2.496    1.44058   2.5       1324   600
   .933     2.496    1.44058   2.5       1324   600
   .933     3.242    1.87114   2.5       1324   600
  1.219     3.242    1.87114   2.5       1324   600
  1.219     3.383    1.95252   2.5       1324   600
  1.326     3.383    1.95252   2.5       1324   600
  1.326     3.505    2.02294   2.5       1324   600
```

2.070	3.505	2.02294	2.5	1324	600
2.070	4.706	2.7161	2.5	1324	600
2.400	4.706	2.7161	2.5	1324	600
2.400	4.903	2.8298	2.5	1324	600
3.0	4.903	2.8298	2.5	1324	600
3.0	5.8183	3.3592	2.6037	1340	600
7.1296	5.8183	3.3592	2.6037	1340	600
7.1296	5.8448	3.3745	2.6155	1340	600
8.7568	5.8448	3.3745	2.6155	1340	600
8.7568	5.8713	3.3898	2.6273	1340	600
10.3841	5.8713	3.3898	2.6273	1340	600
10.3841	5.8979	3.4052	2.6391	1340	600
12.0113	5.8979	3.4052	2.6391	1340	600
12.0113	6.2325	3.5988	2.7045	1340	600
13.6153	6.2325	3.5988	2.7045	1340	600
13.6153	6.2742	3.623	2.7238	1340	600
15.2194	6.2742	3.623	2.7238	1340	600
15.2194	6.3159	3.6471	2.7431	1340	600
16.8234	6.3159	3.6471	2.7431	1340	600
16.8234	6.3576	3.6712	2.7623	1340	600
18.4274	6.3576	3.6712	2.7623	1340	600
18.4274	6.3993	3.6954	2.7816	1340	600
20.0315	6.3993	3.6954	2.7816	1340	600
20.0315	6.6922	3.8637	2.9453	1340	600
22.0393	6.6922	3.8637	2.9453	1340	600
22.0393	6.8349	3.9461	2.9543	1340	600
24.0472	6.8349	3.9461	2.9543	1340	600
24.0472	6.9777	4.0286	2.9633	1340	600
26.0551	6.9777	4.0286	2.9633	1340	600
26.0551	7.1204	4.111	2.9723	1340	600
28.063	7.1204	4.111	2.9723	1340	600
28.063	7.2632	4.1934	2.9814	1340	600
30.0709	7.2632	4.1934	2.9814	1340	600
30.0709	8.3465	4.8189	3.3214	1340	600
41.1325	8.3465	4.8189	3.3214	1340	600
41.1325	8.3243	4.7506	3.3158	1340	600
56.2655	8.3243	4.7506	3.3158	1340	600
56.2655	8.2653	4.6057	3.3104	1340	600
71.3986	8.2653	4.6057	3.3104	1340	600
71.3986	8.2534	4.5465	3.3077	1340	600
96.2716	8.2534	4.5465	3.3077	1340	600
96.2716	8.2888	4.5731	3.3076	1340	600
121.144	8.2888	4.5731	3.3076	1340	600
121.144	8.3342	4.5984	3.3078	1340	600
147.241	8.3342	4.5984	3.3078	1340	600
147.241	8.3898	4.6225	3.3084	1340	600
173.337	8.3898	4.6225	3.3084	1340	600
173.337	8.459	4.6439	3.3098	1340	600
193.438	8.459	4.6439	3.3098	1340	600

193.438	8.5416	4.6626	3.312	1340	600
213.539	8.5416	4.6626	3.312	1340	600
213.539	8.6625	4.7155	3.3121	1340	600
245.236	8.6625	4.7155	3.3121	1340	600
245.236	8.8217	4.7943	3.31	1340	600
276.933	8.8217	4.7943	3.31	1340	600
276.933	9.0353	4.9	3.3105	1340	600
329.587	9.0353	4.9	3.3105	1340	600
329.587	9.3033	5.0327	3.3135	1340	600
382.241	9.3033	5.0327	3.3135	1340	600
382.241	9.4907	5.1255	3.3159	1340	600
403.014	9.4907	5.1255	3.3159	1340	600
403.014	9.5976	5.1785	3.3178	1340	600
423.787	9.5976	5.1785	3.3178	1340	600
423.787	10.085	5.4676	3.5155	1340	600
456.553	10.085	5.4676	3.5155	1340	600
456.553	10.2474	5.5655	3.5179	1340	600
489.319	10.2474	5.5655	3.5179	1340	600
489.319	10.4198	5.6693	3.5311	1340	600
525.622	10.4198	5.6693	3.5311	1340	600
525.622	10.6022	5.7792	3.5553	1340	600
561.925	10.6022	5.7792	3.5553	1340	600
561.925	10.7845	5.8891	3.5794	1340	600
598.227	10.7845	5.8891	3.5794	1340	600
598.227	10.9596	5.9946	3.6002	1340	600
631.067	10.9596	5.9946	3.6002	1340	600
631.067	11.1273	6.0956	3.6177	1340	600
663.907	11.1273	6.0956	3.6177	1340	600
663.907	11.2949	6.1966	3.6351	1340	600
696.747	11.2949	6.1966	3.6351	1340	600
696.747	12.0649	6.66	3.9274	1340	600
709.03	12.0649	6.66	3.9274	1340	600
709.03	12.1696	6.7437	3.9309	1340	600
742.451	12.1696	6.7437	3.9309	1340	600
742.451	12.3231	6.8664	3.9195	1340	600
775.871	12.3231	6.8664	3.9195	1340	600
775.871	12.4765	6.9892	3.9081	1340	600

E Waveform comparison for different source mechanism

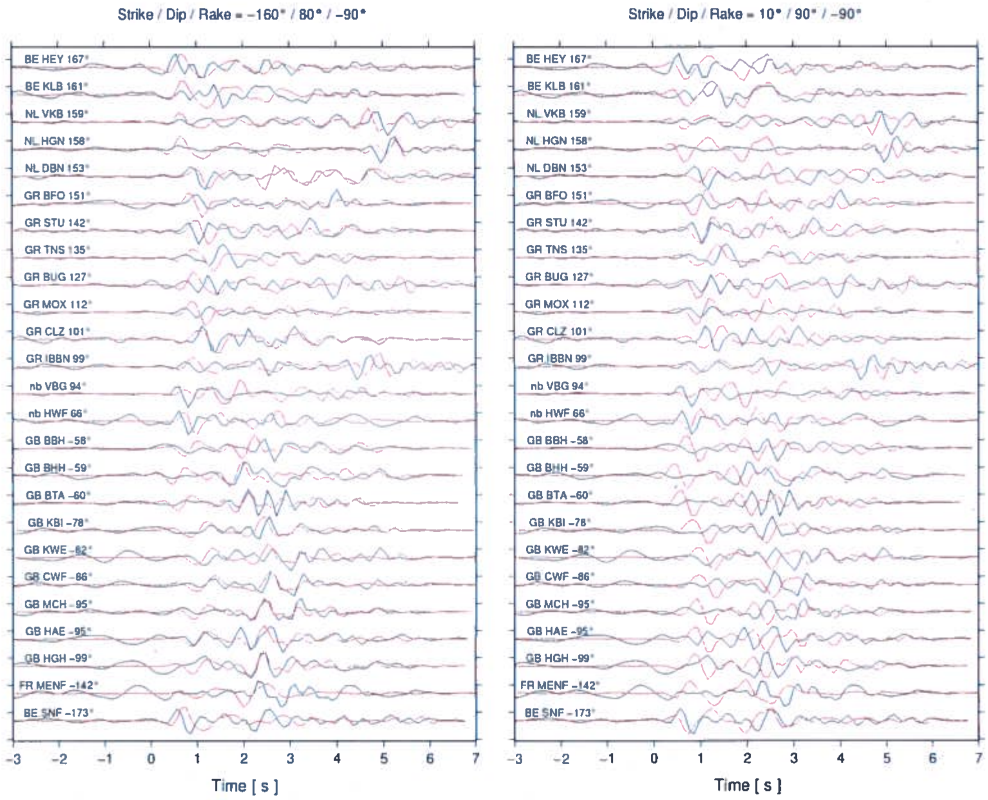


Figure 13: Comparison similar to Fig. 7. Strike, dip and rake are indicated in the figure heading.

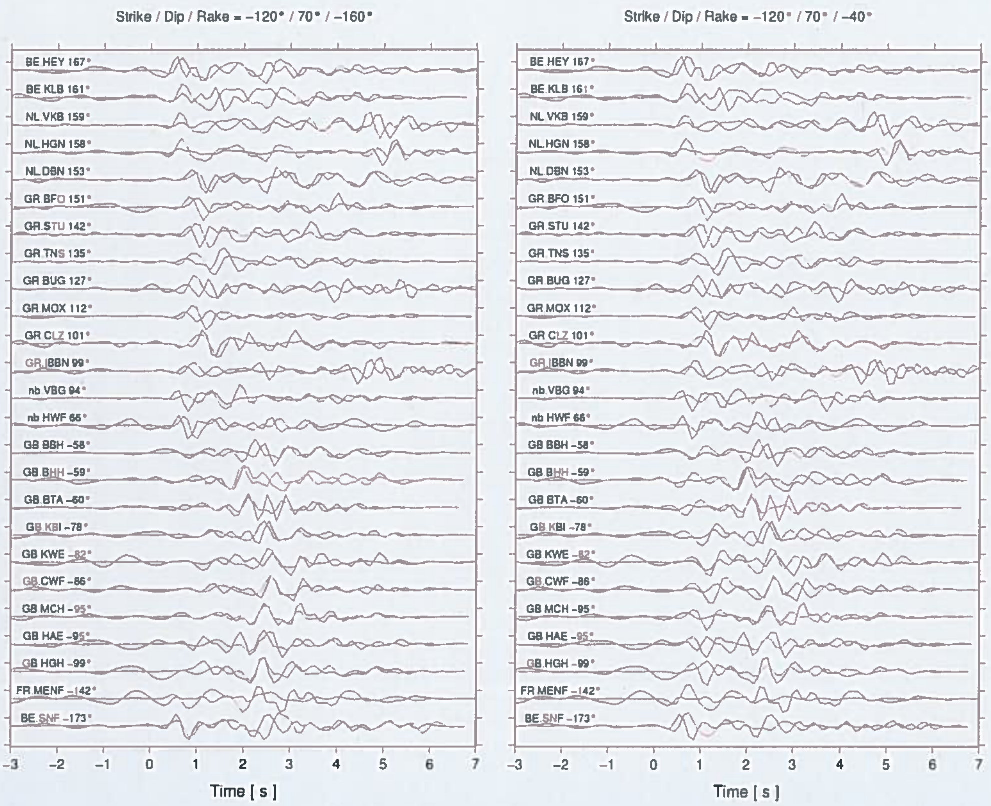


Figure 14: Comparison similar to Fig. 7. Strike, dip and rake are indicated in the figure heading.

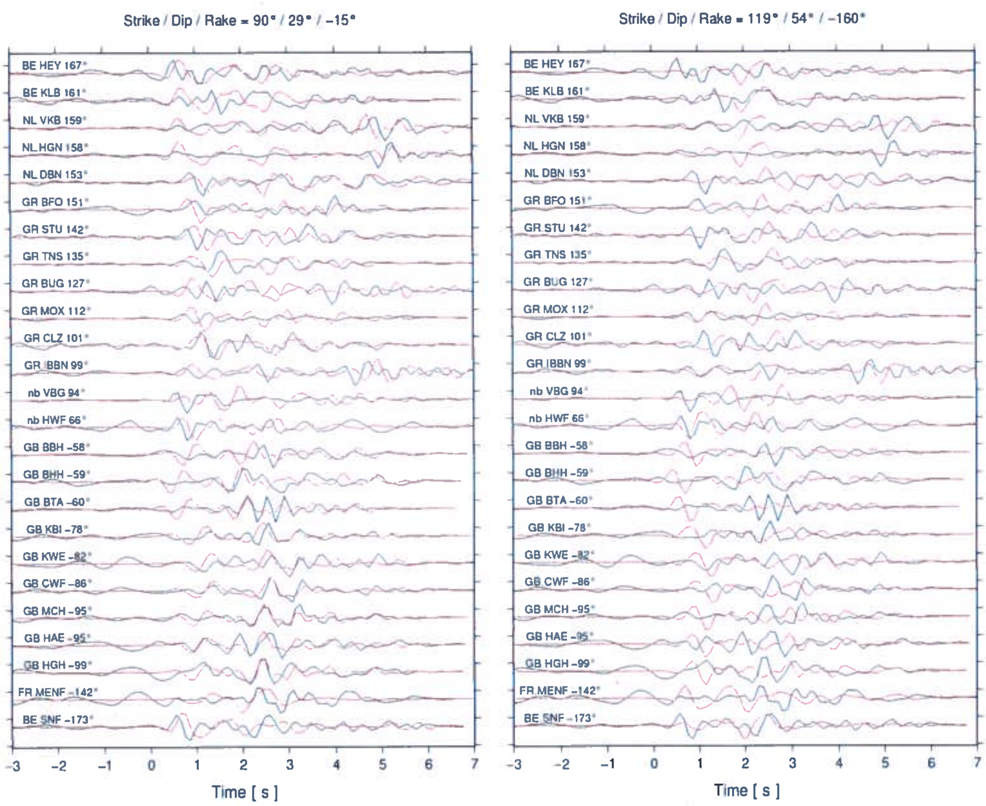


Figure 15: Comparison similar to Fig. 7. Strike, dip and rake are indicated in the figure heading.

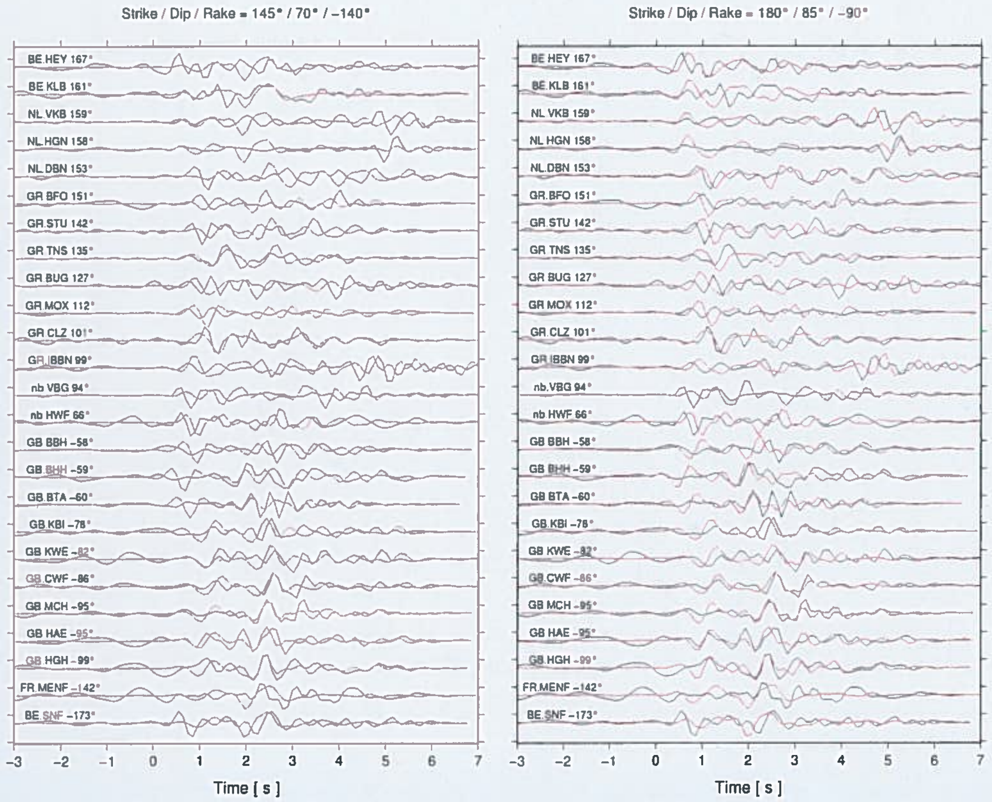


Figure 16: Comparison similar to Fig. 7. Strike, dip and rake are indicated in the figure heading.

Source parameter study of the 2001 earthquakes at Alkmaar in Bergen, The Netherlands

TAQA Meeting, 16 December 2010

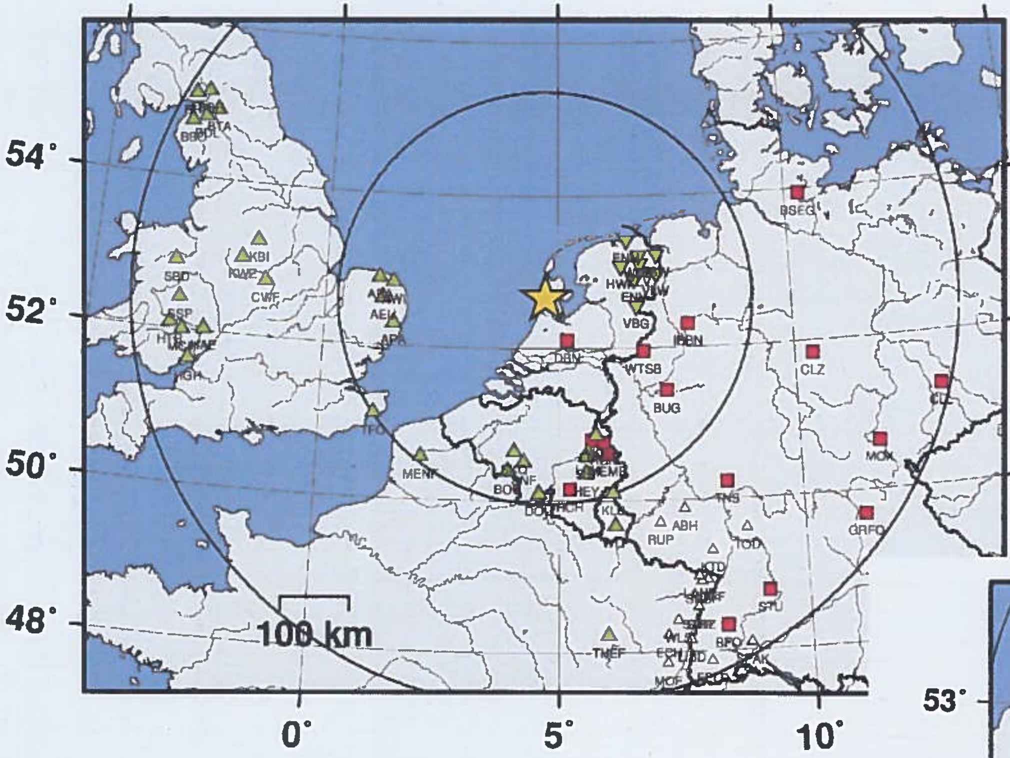
10.2.e. [redacted] 10.2.e. [redacted], Institut für Geophysik, Universität Hamburg

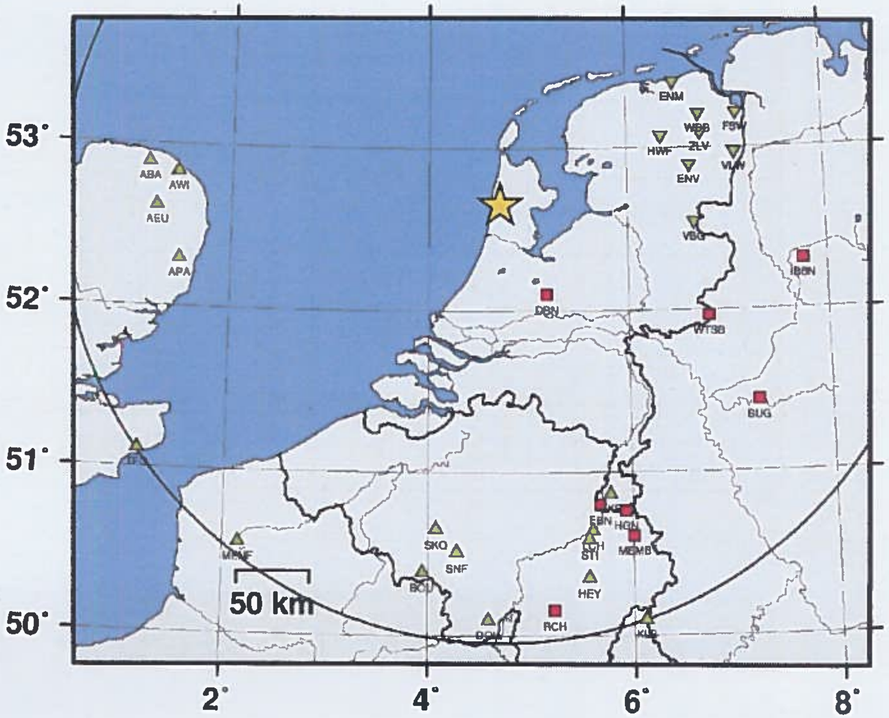
goals

A. can source parameters be confirmed
- depth (& epicentre locations)
- strength
- reverse faulting or different mechanism

B. prediction of ground motion
- peak ground acceleration for different source locations
- comparison to felt intensities

Stations used (colored symbols)





source parameter of Haak et al. (2001)

	9 september	10 september
origin time (UTC)	$\approx$ 6:58 12s	$\approx$ 4:30 14s
lat/lon	52.651° / 4.713°	52.653° / 4.712°
depth	$2.0 \pm 0.2\,km$	$2.0 \pm 0.2\,km$
Epicentral Intensity I_0	VI+	IV-V
magnitude M_L	3.5	3.2
moment magnitude M_W	3.49	3.17
strike/dip/rake	130° / 66° / 73°	-

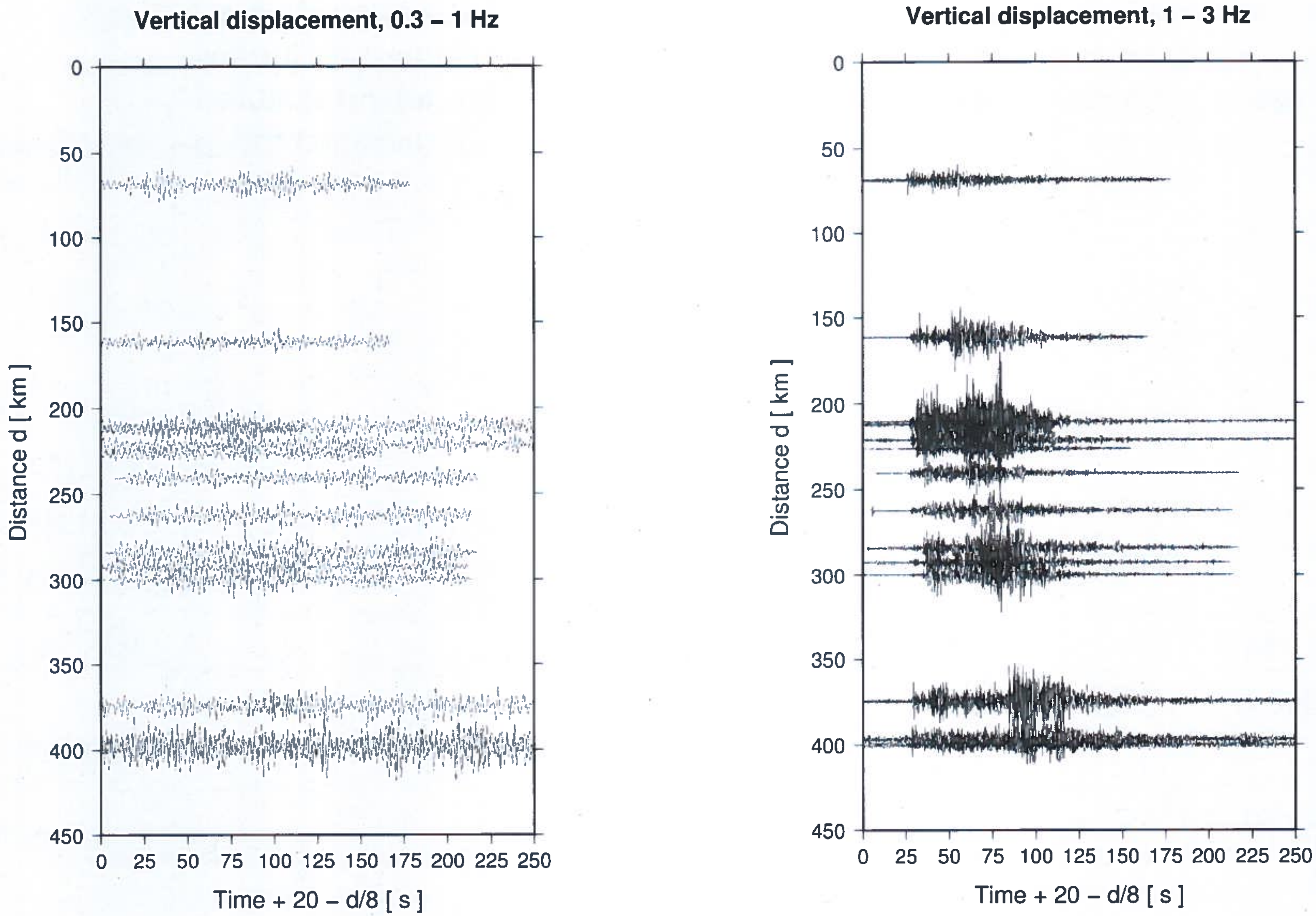
comment:
- depth and absolute location is difficult
- seismic moment is controverse
- reverse slip is difficult to explain with geomechanical modeling

source parameter derived here

	9 September	10 September
lat/lon	no new location	$52.663° \pm 0.011°$/ $4.710° \pm 0.013°$
depth	≈ 1.5 to $2.2\,km$	$2.2 \pm 1.2\,km$
moment magnitude M_W	3.45 ± 0.2	-
strike/dip/rake . (errors $\approx \pm 15°$).	$200°/\ 80°\ /\ -90°$ or $160°/\ 80°\ /\ -30°$	-

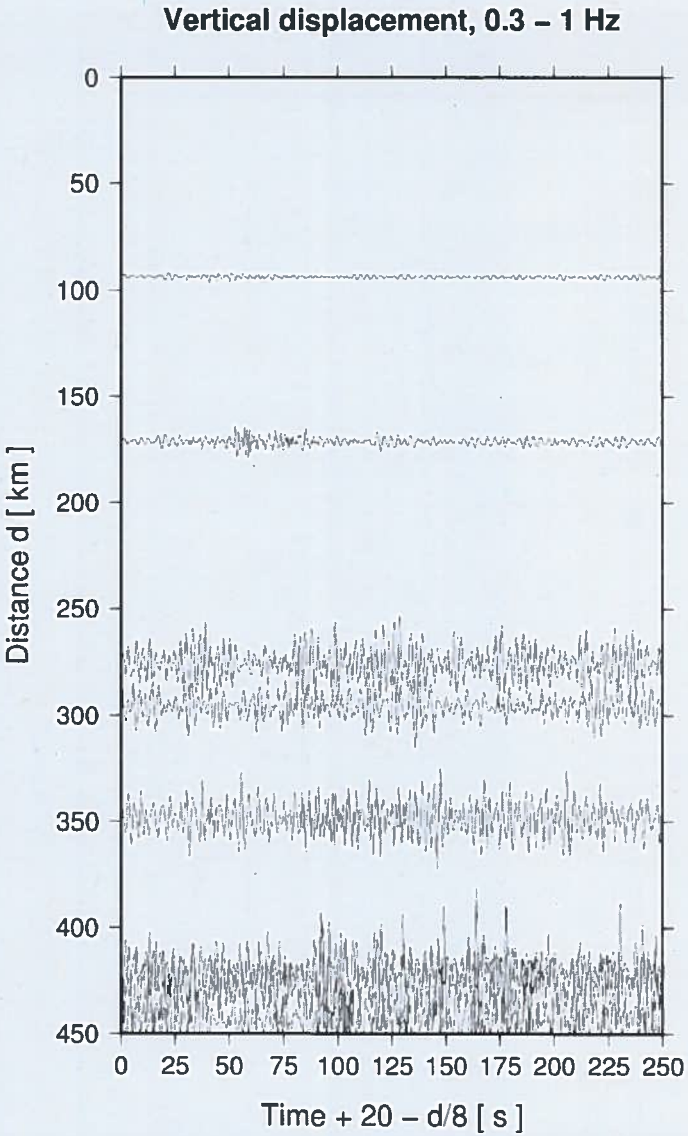
comment: - depth confined by depth phase modelling
- moment magnitude confined by amplitude spectra inversion of P and S phases
- source mechanism is inconsistent to Haak et al. first motion study.

Record sections at low and high frequencies

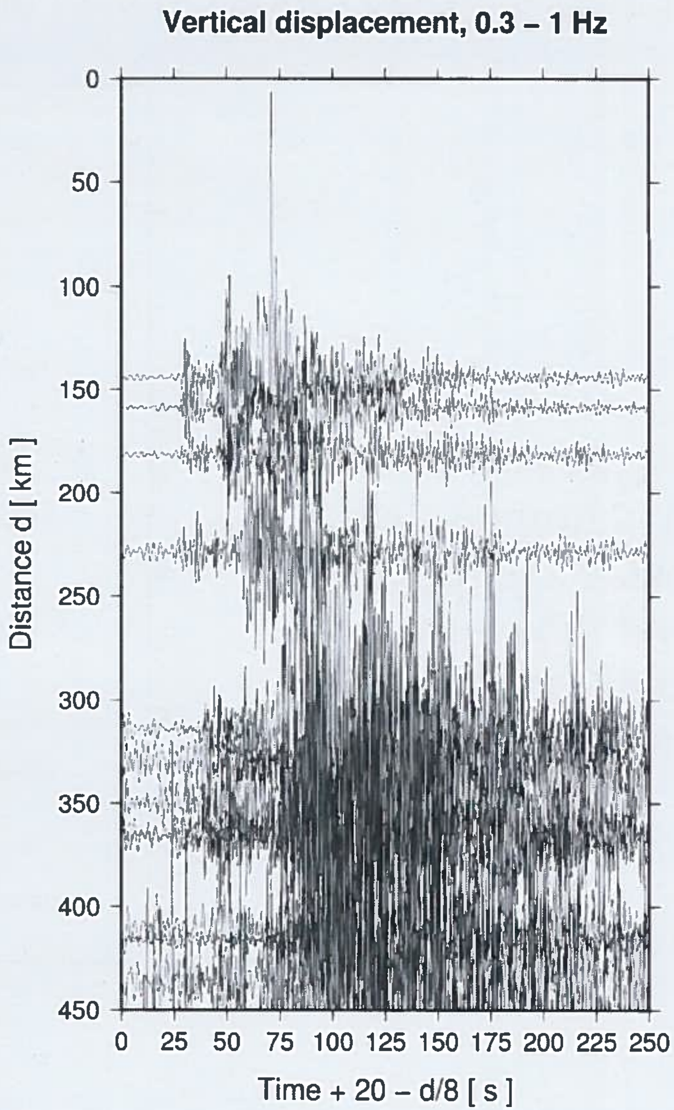


x 4

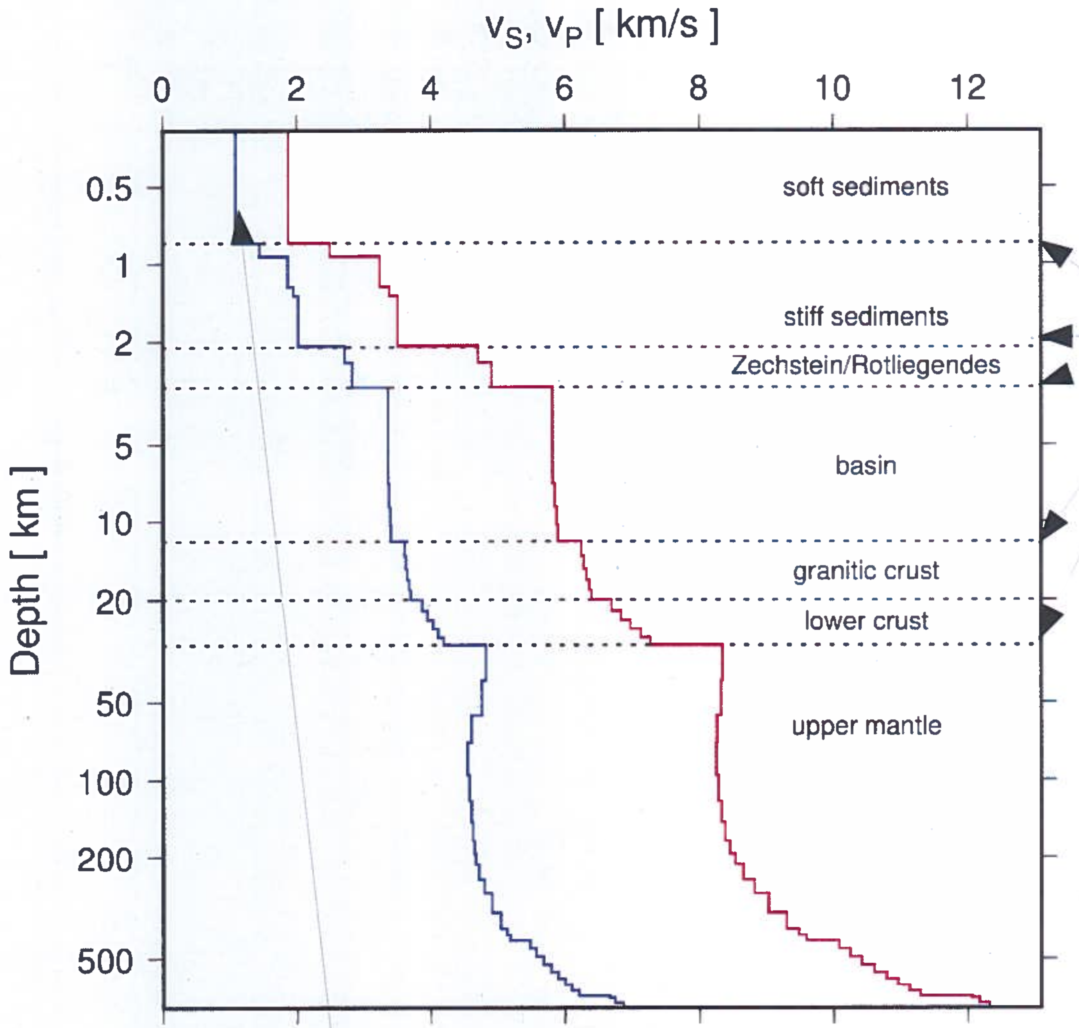
Mw 3 (Basel 2006)



Mw 3.8 (Saarbrücken 2008)



velocity model



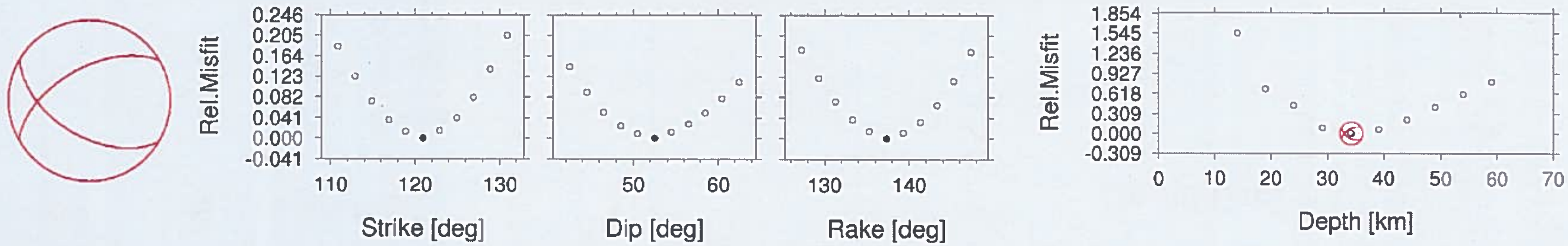
Velocity contrasts may produce secondary phases with different polarities, which make seismogram interpretation at high frequencies difficult!

S-wave velocities in uppermost 100 meters should be revised by including more realistic vp/vs relations (e.g. Castagnia relations)

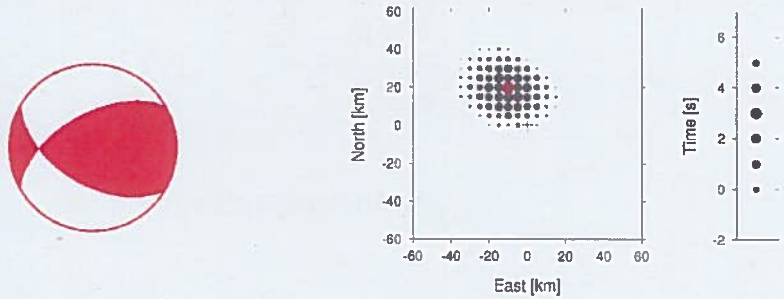
multi-step amplitude spectra / full waveform inversion

Step 0 Data pre-processing (displacements, quality evaluation)

Step 1 Focal mechanism, Depth, M_0 (from amplitude spectra)



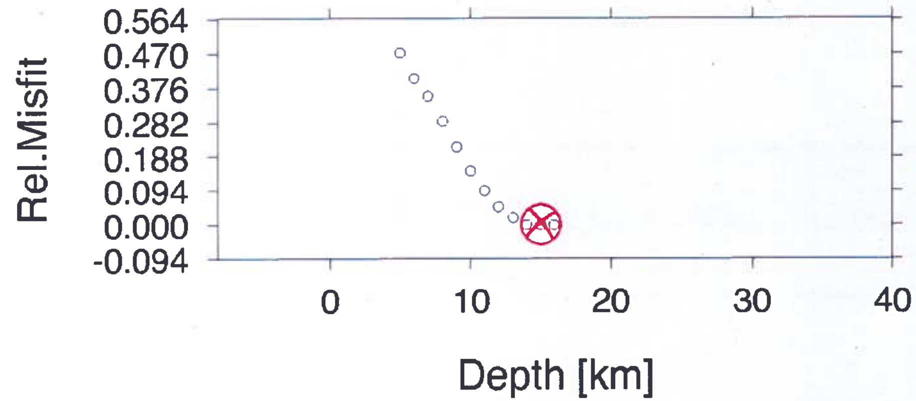
Step 2 sense of slip, centroid location, apparent duration (from waveforms)

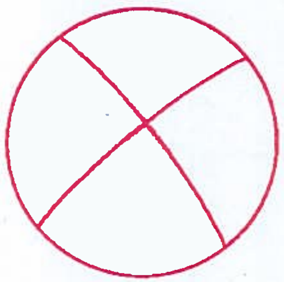


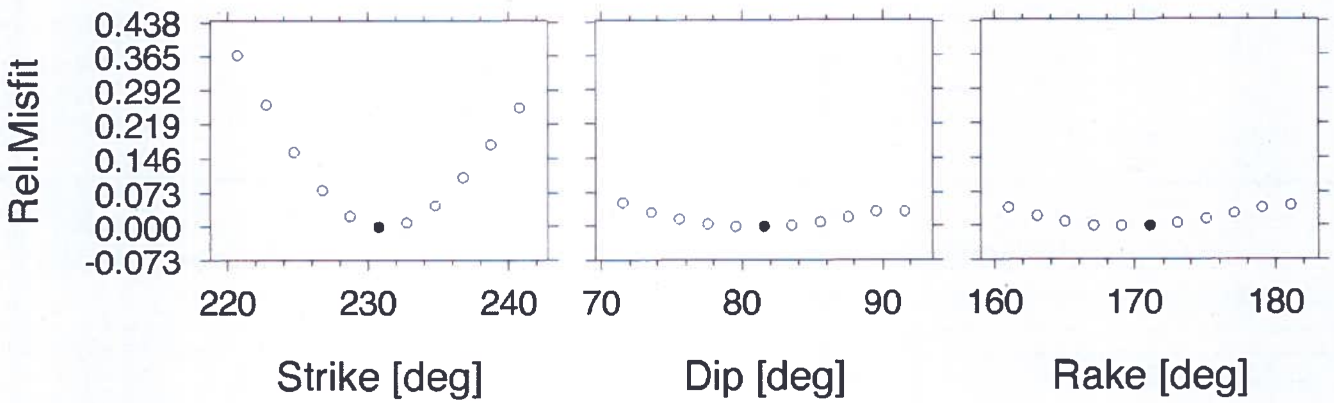
CMT inversion, KINHERD-KIWI project (Uni Hamburg, Uni Potsdam, GFZ, BGR)

Example: Koblenz earthquake

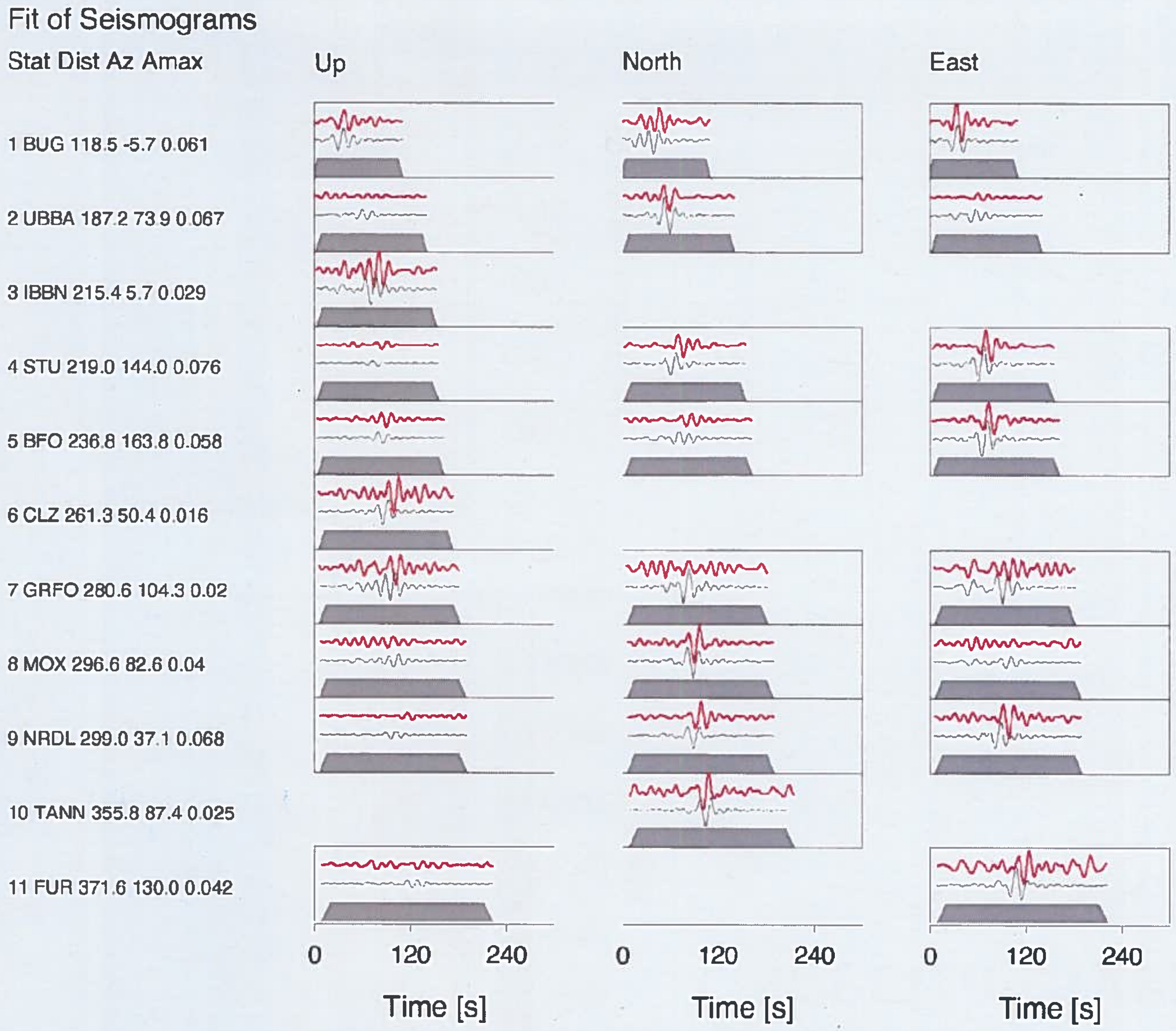
Event	koblenz	/scratch/local2/simone/KINI		
Lat Lon	50.38 N 7.44 E			
Strike	230	230	322	322
Dip	81	81	81	81
Rake	171	-8	8	-171
M_0	3.58E+14Nm			
M_w	3.6			
Depth	15.9km			
Duration	1.0s			
Misfit	0.352			
Method	Amplitude spectra			
Components	une			
Phases	Whole trace			
Bandpass	0.035 - 0.1 Hz			
Traces	26 (11 stations)			

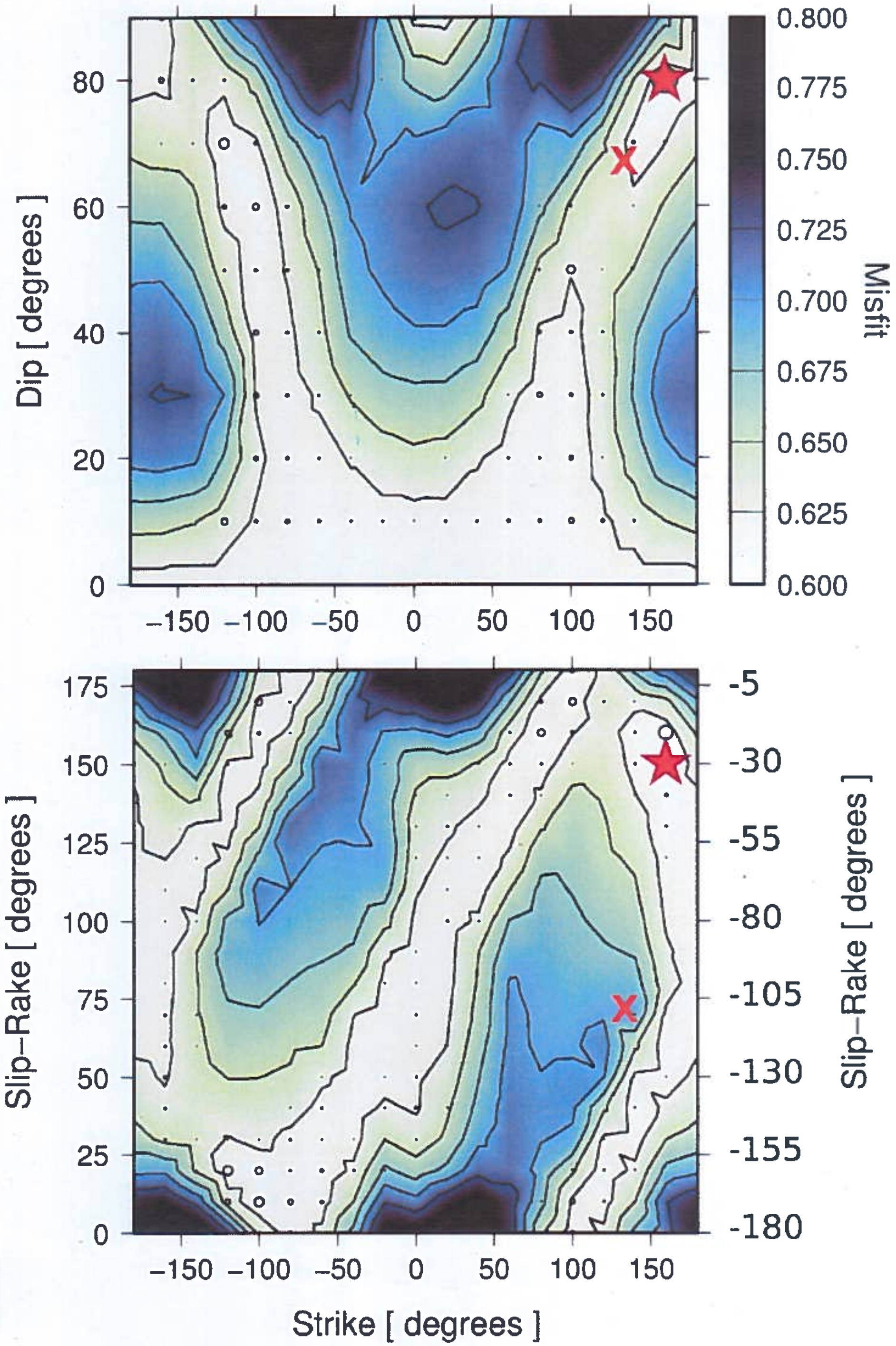






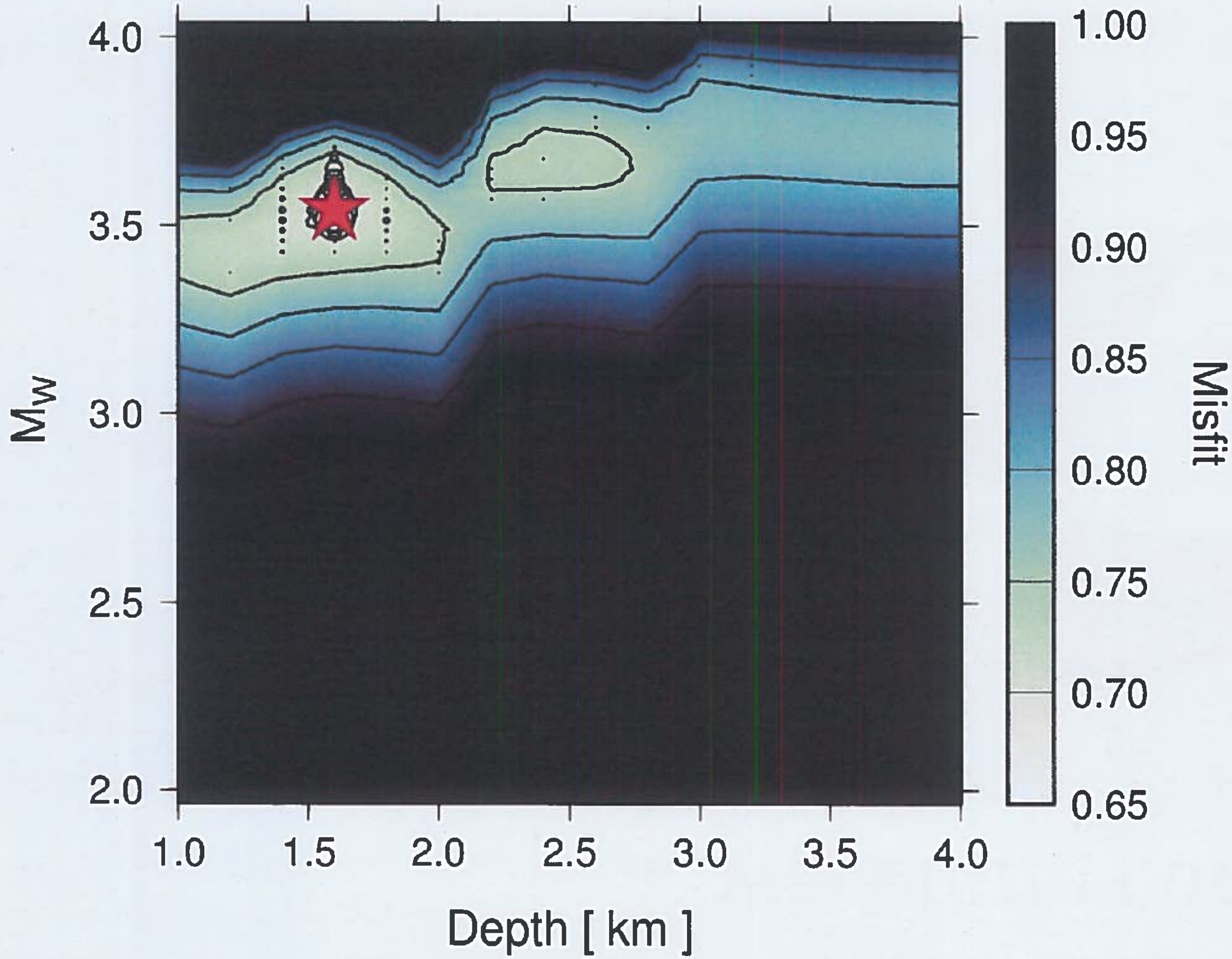
Example: Koblenz earthquake



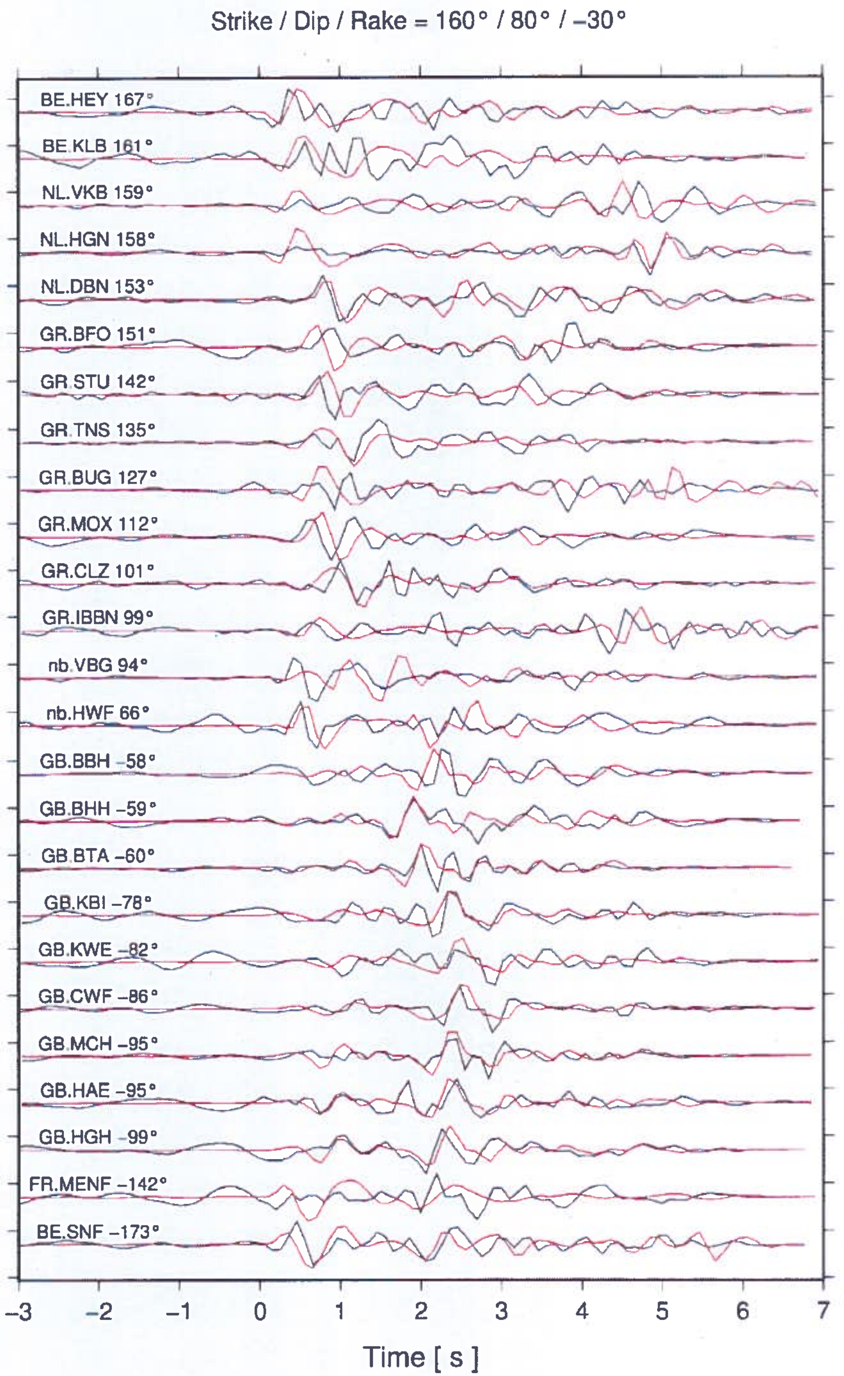


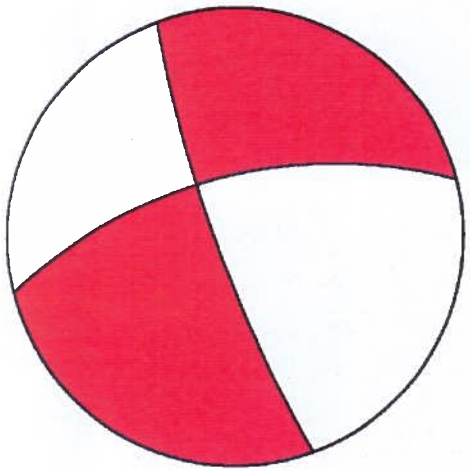
body wave amplitude spectra inversion

seismic moment (moment magnitude Mw)

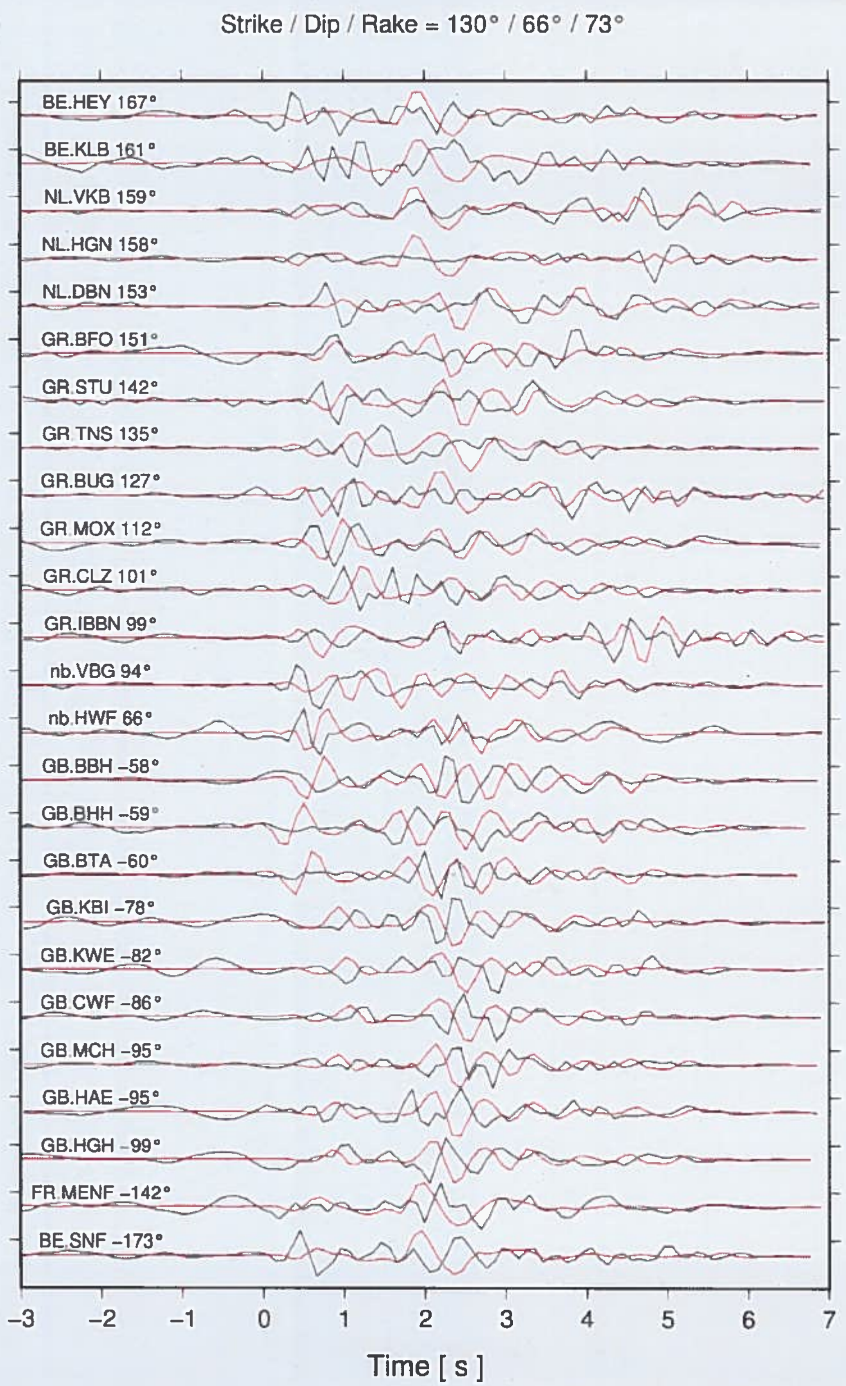


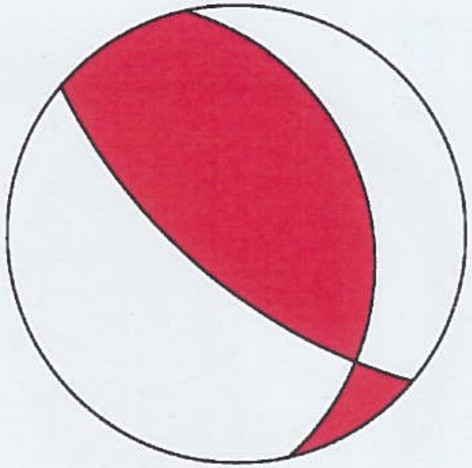
regional distance waveform comparison

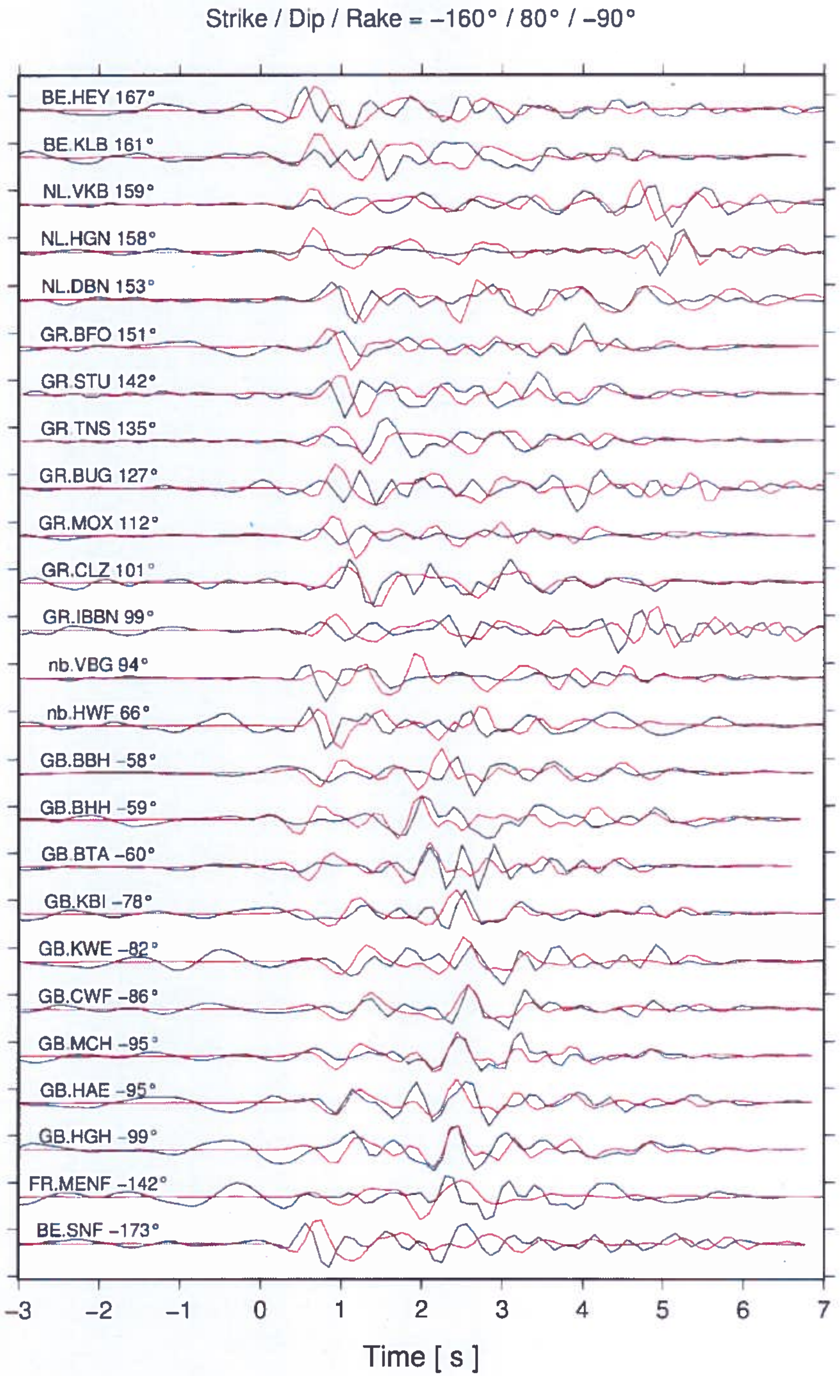




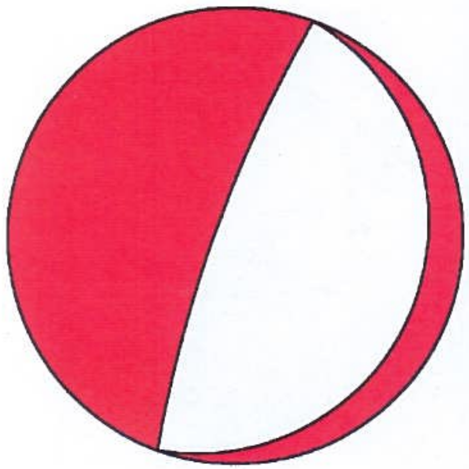
regional distance waveform comparison







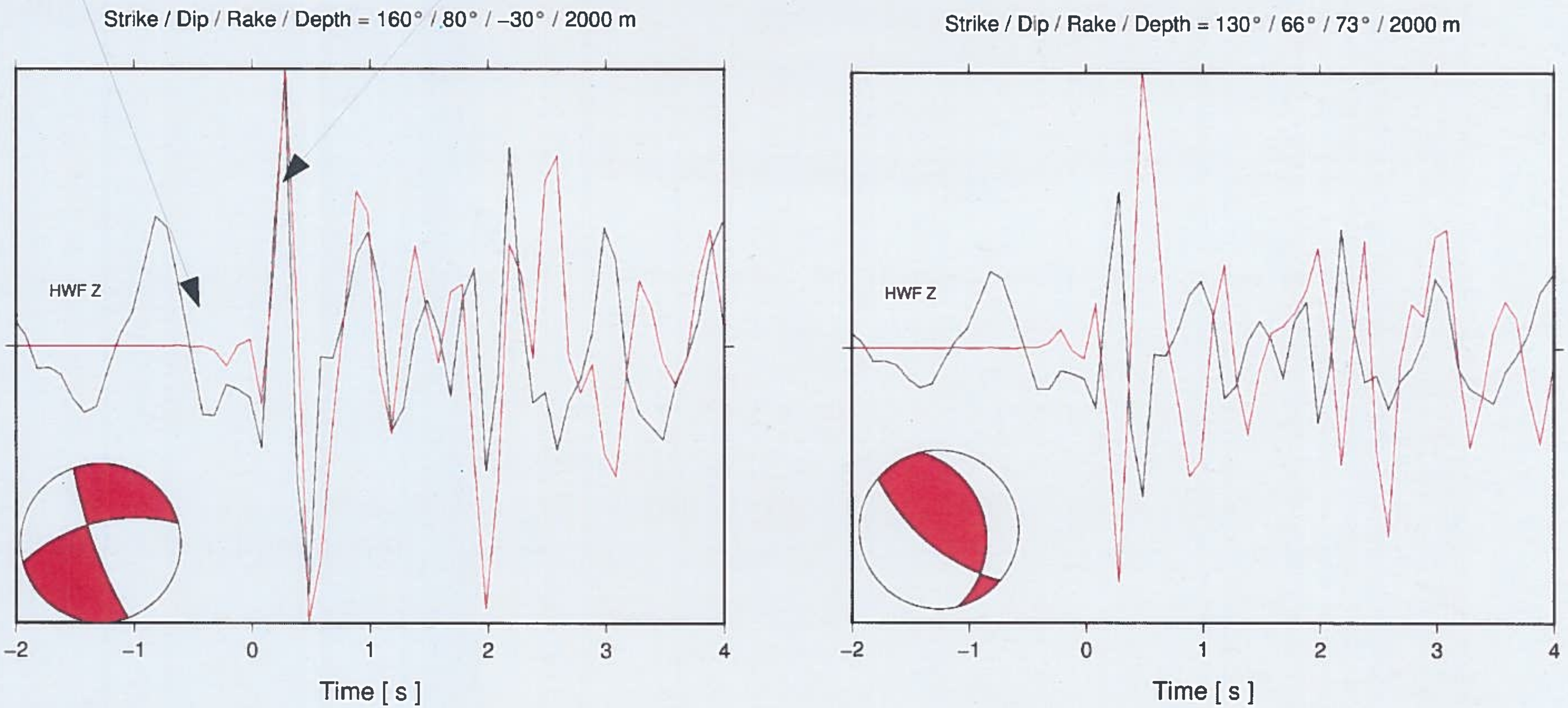
regional distance waveform comparison



Borehole array HWF in 120 km distance

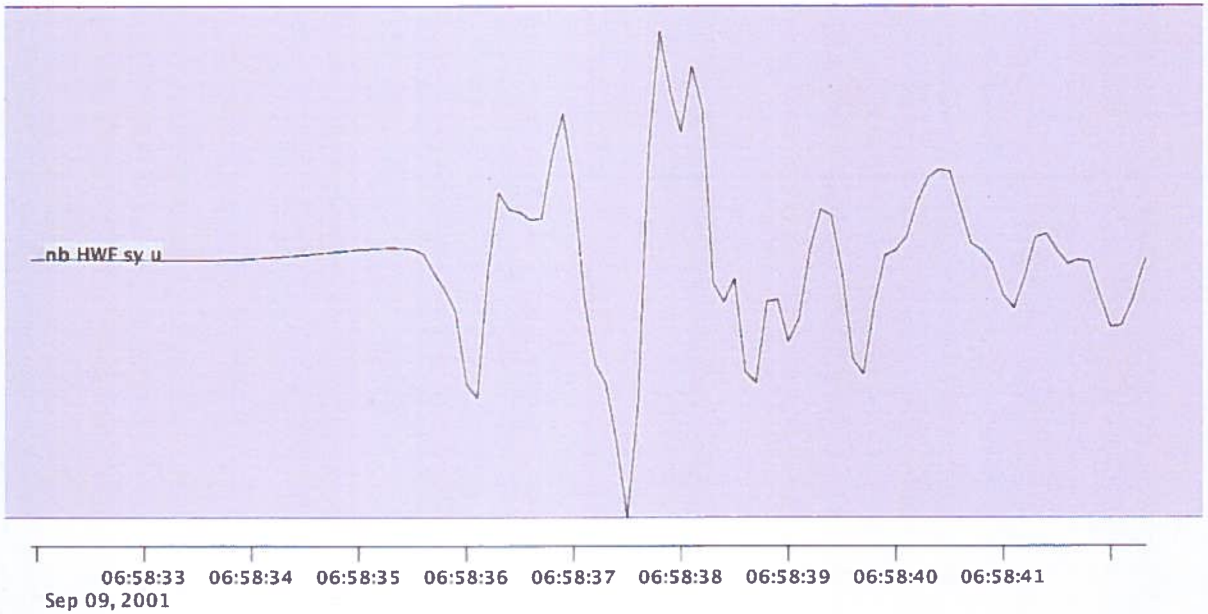
strong positive 2nd onset (possibly a waveform effect if hp filters (0.7 Hz) need to be taken

weak negative first onset

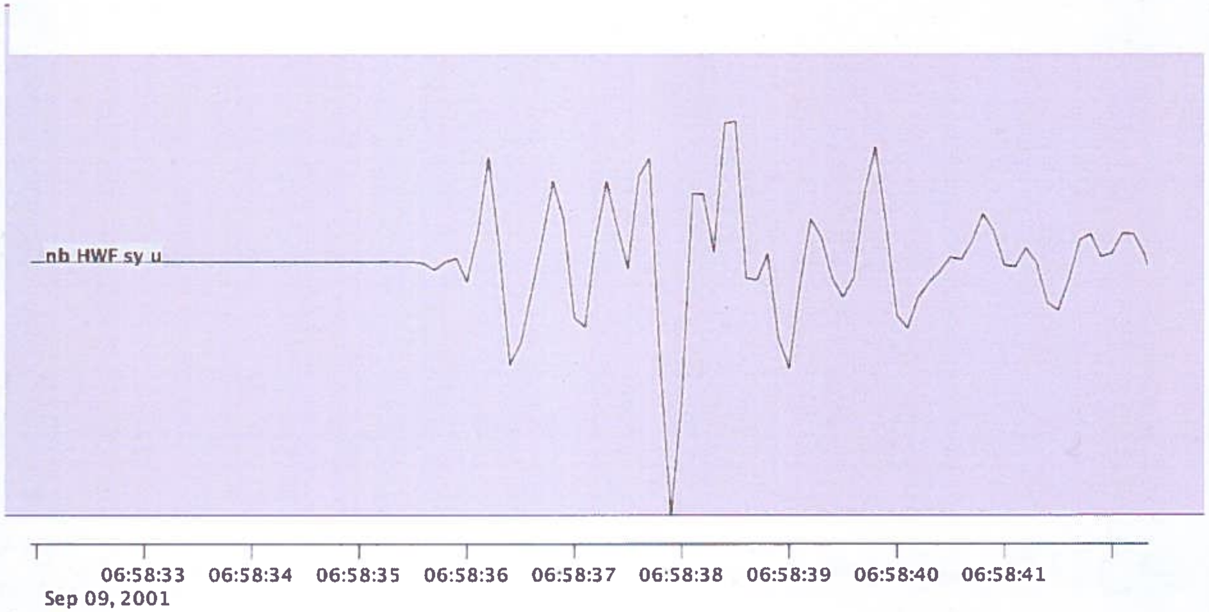


Borehole array HWF: synthetic raw data

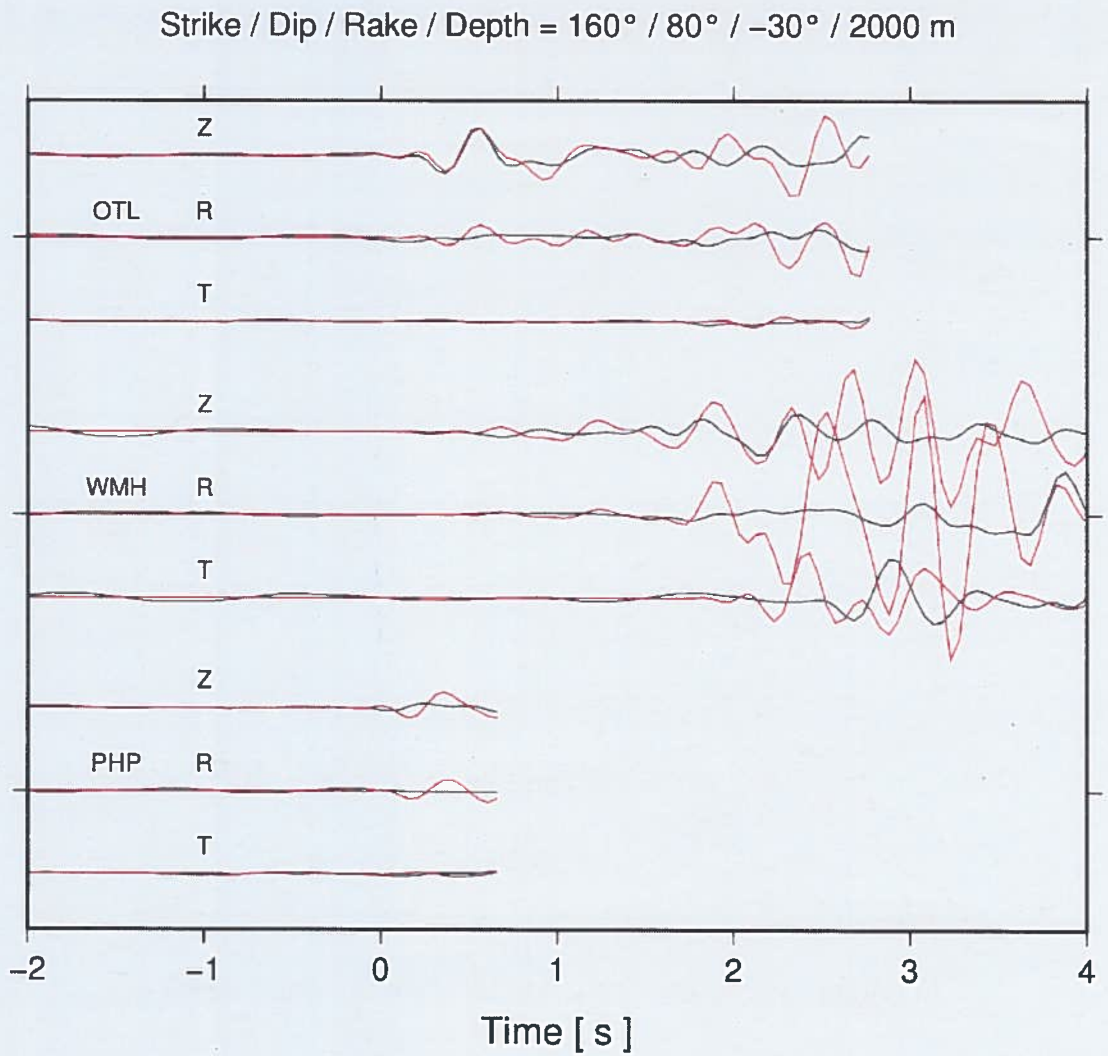
Unfiltered displacement

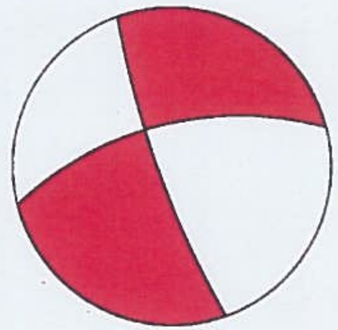


high pass at 1 Hz



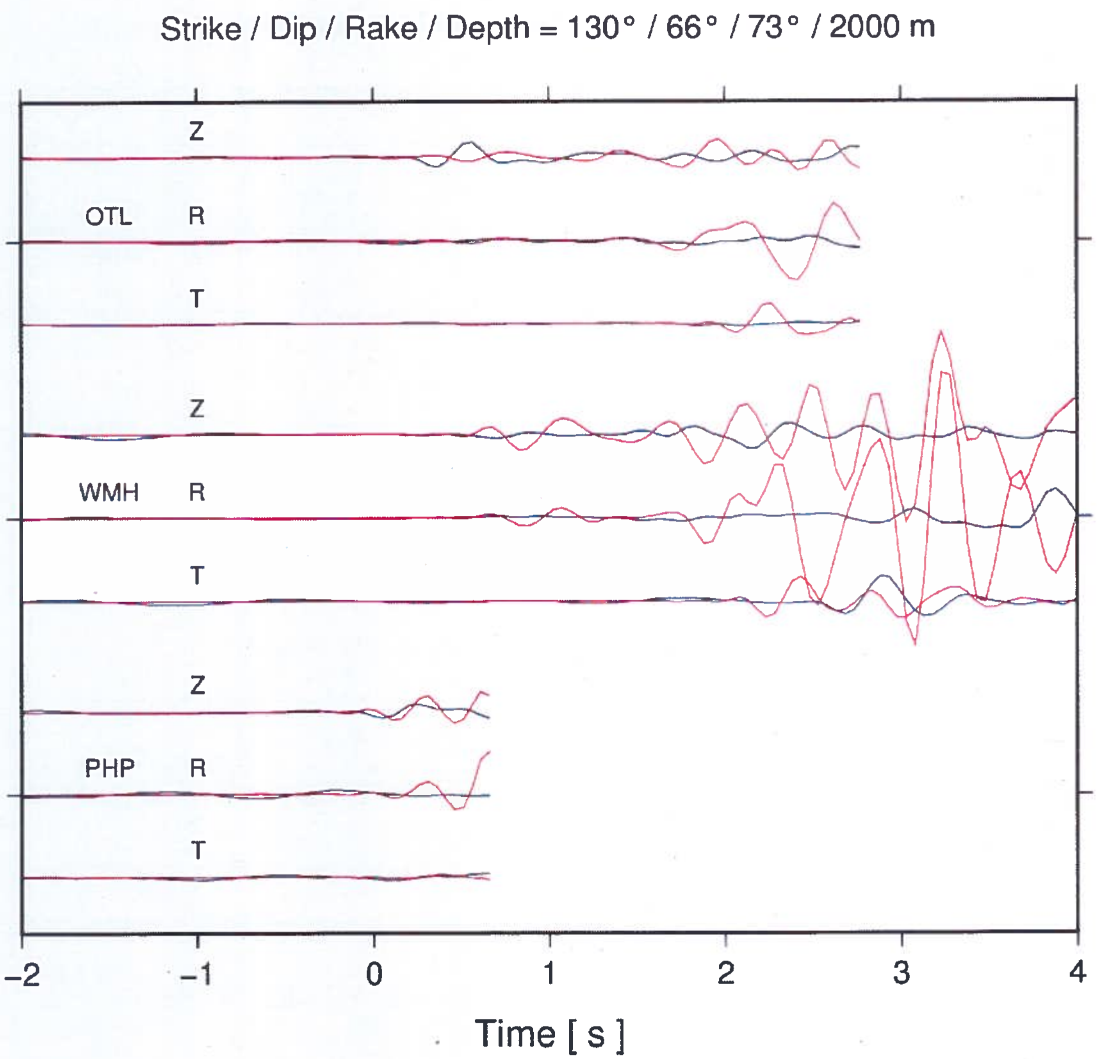
10 Sep 2010: closeby borehole arrays

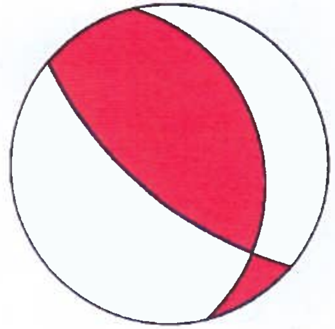




PHP is clipped with the first onset! S-waves on OTL are clipped!

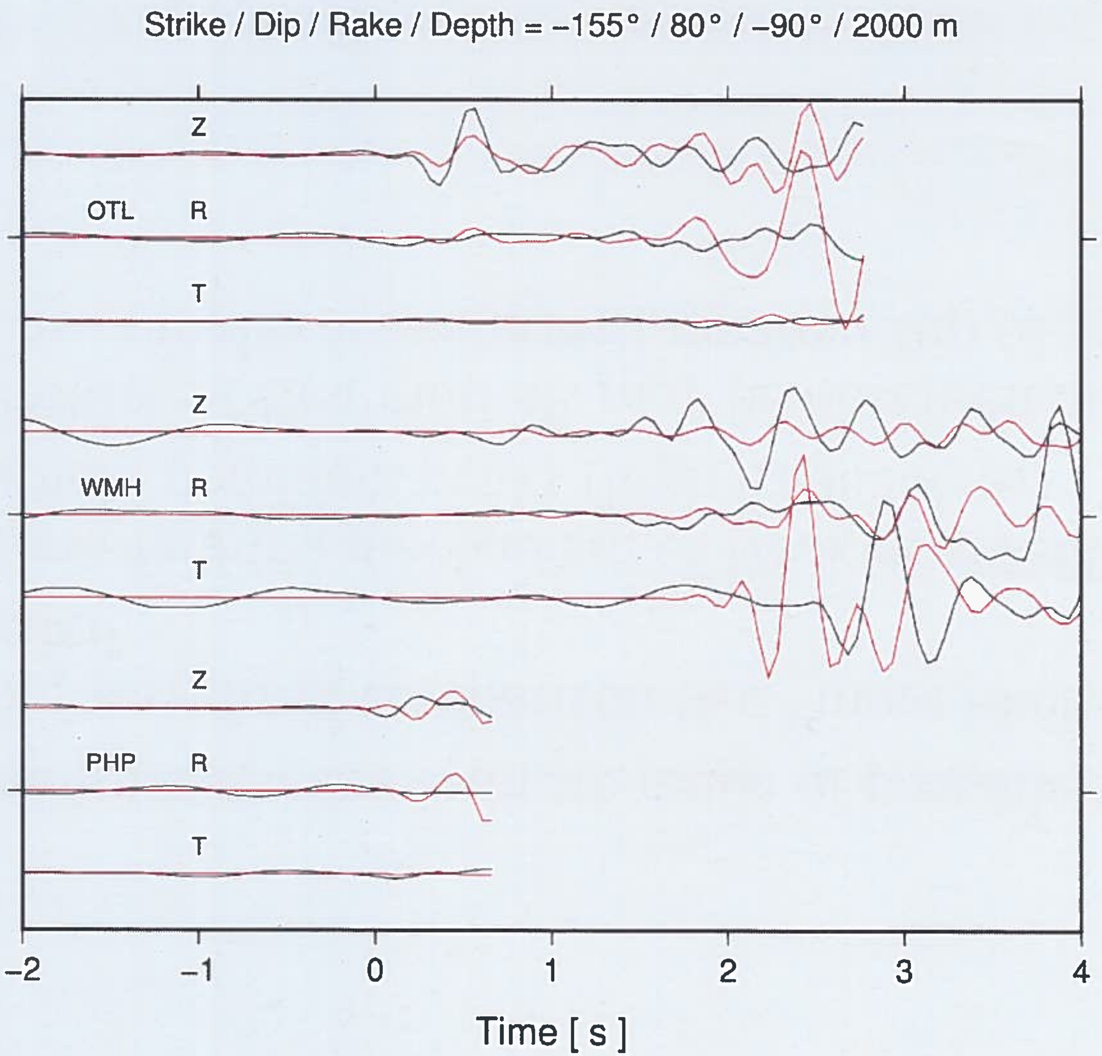
10 Sep 2010: closeby borehole arrays

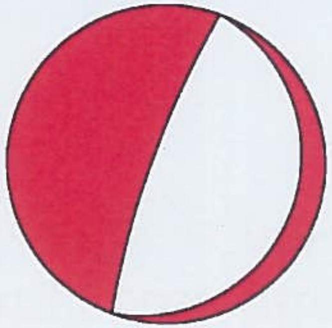




PHP is clipped with the first onset! S-waves on OTL are clipped!

10 Sep 2010: closeby borehole arrays





PHP is clipped with the first onset! S-waves on OTL are clipped!

preliminary conclusion

- Amplitude spectra indicate range of possible solutions
- From waveform comparison two “more likely” solutions are identifed
- reverse faulting mechanism of Haak et al (2001) has difficulties to explain dominant peaks (high frequencies)
- Polarities of first motions may be obscured in high pass filtered data by complex waveforms (apparent flip of polarities is possible)

conclusion

- Moment magnitude of Mw 3.45 is confirmed
- Source mechanism was possible oblique strike slip, but is difficult to finally constrain

Depth from waveform and traveltime

1. Traveltime location of the 10 September 2001 event
2. Depth phase modeling in regional distances

Arrival time location using arrival times, time differences and slowness

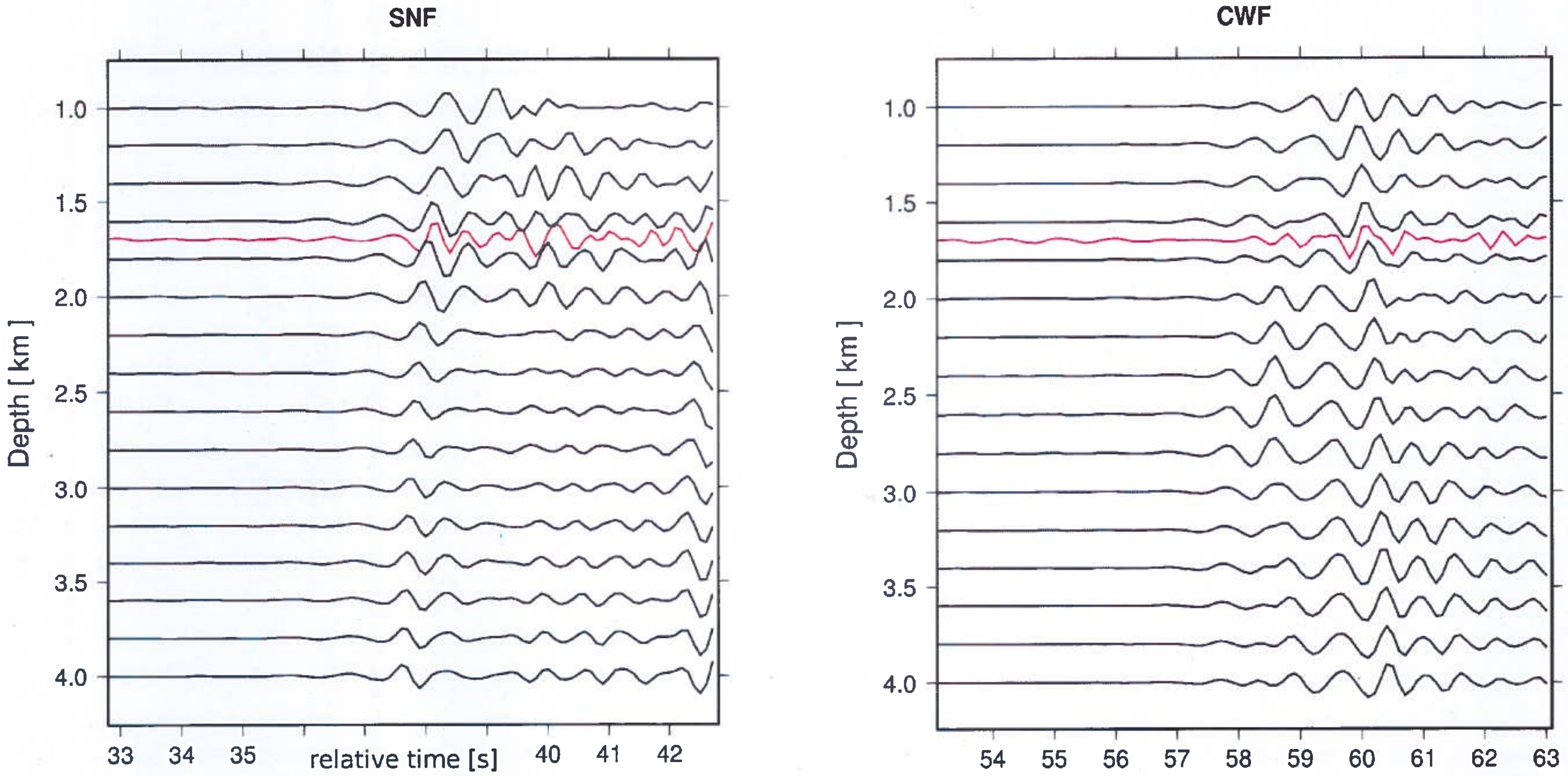
Weighted misfit of input data		L1
10 onset times	:	6.916
3 ray parameters	:	0.894
3 travel-time differences	:	2.229
16 misfit over all	:	4.908

Source time : 2001 09 10 04 30 15.898 +/- 0.455 [s]

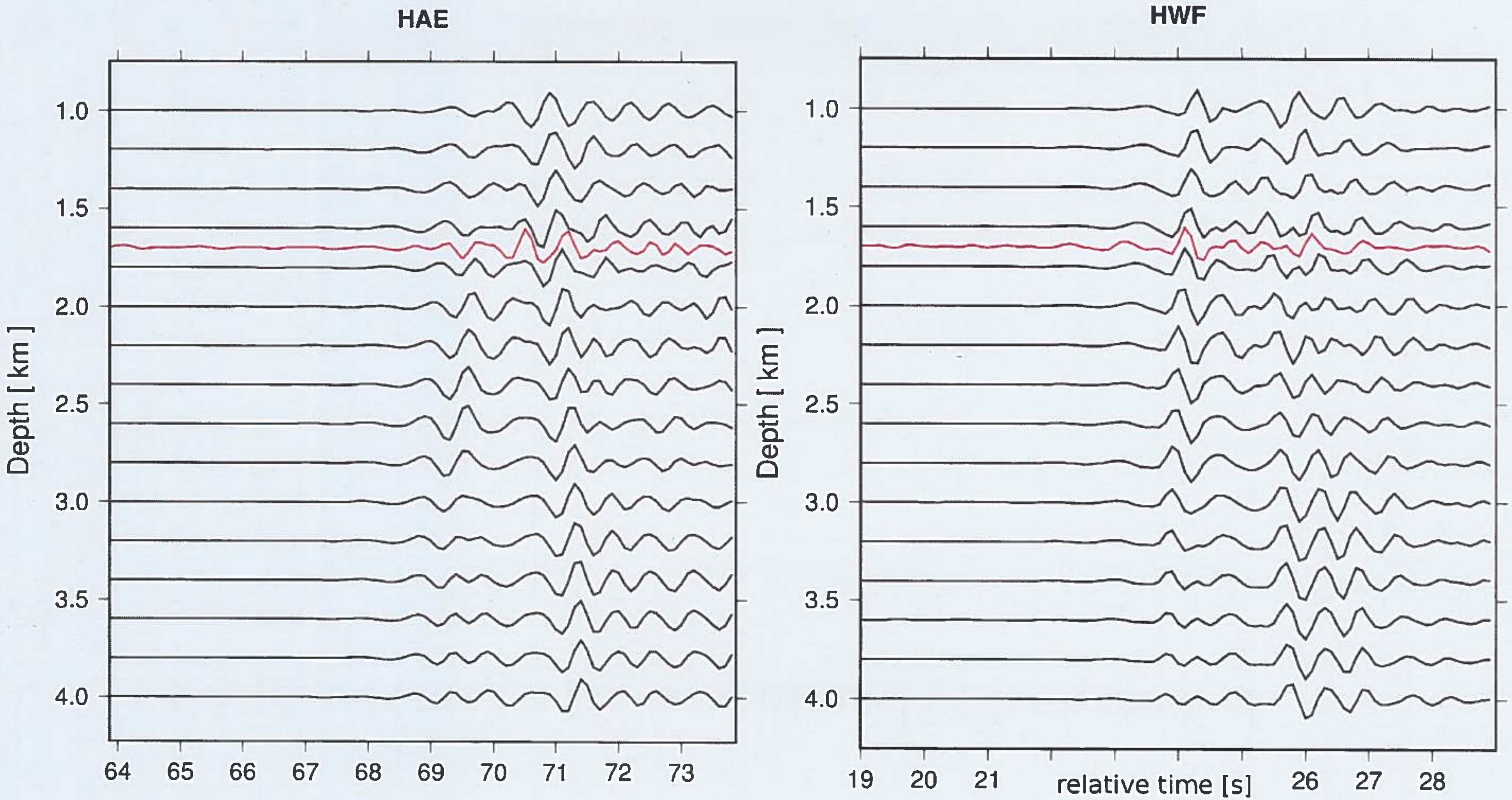
Epicenter lat:	52.6629	+/-	0.0106	[deg]
Epicenter lon:	4.7104	+/-	0.0127	[deg]
Source depth :	2.20	+/-	1.17	[km]

Hypocenter location confirmed within confidence intervals

Regional distance depth phases



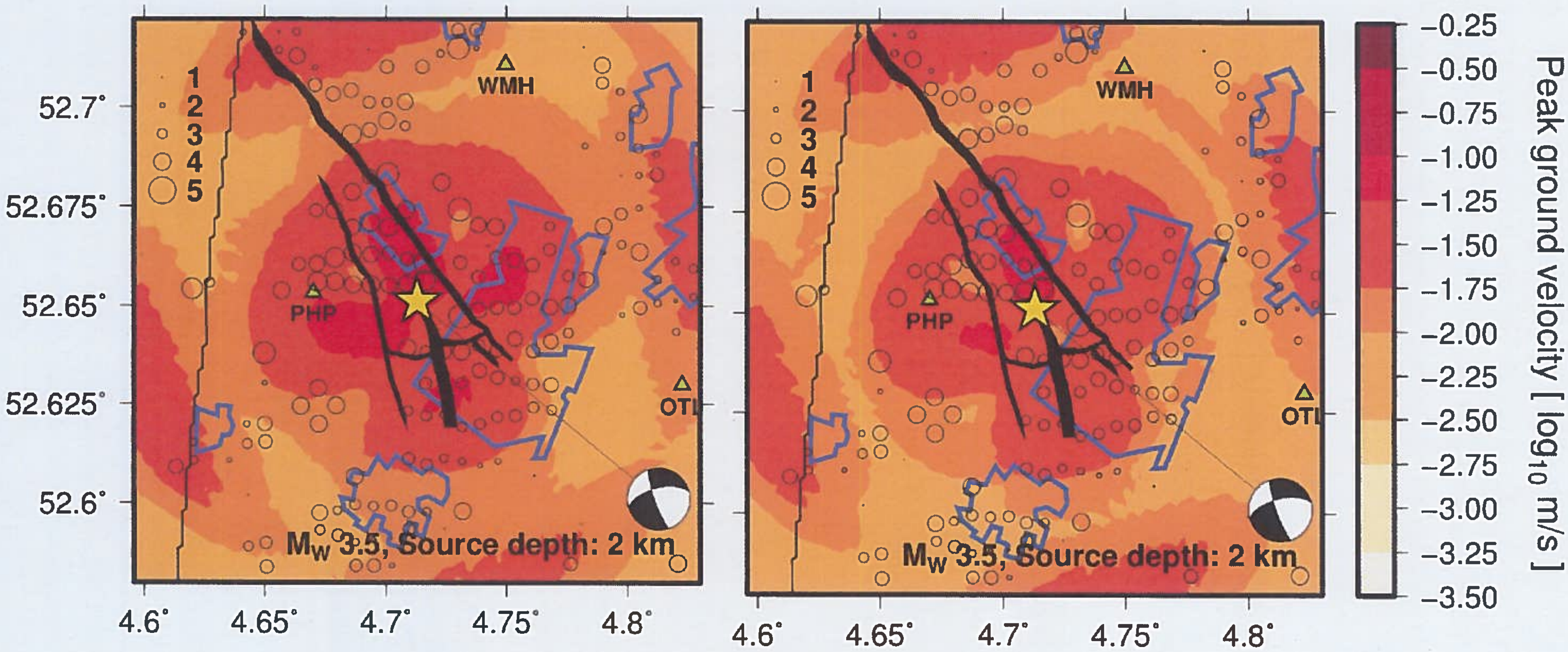
Regional distance depth phases



conclusion

- A depth of about 2 km is confirmed by both methods

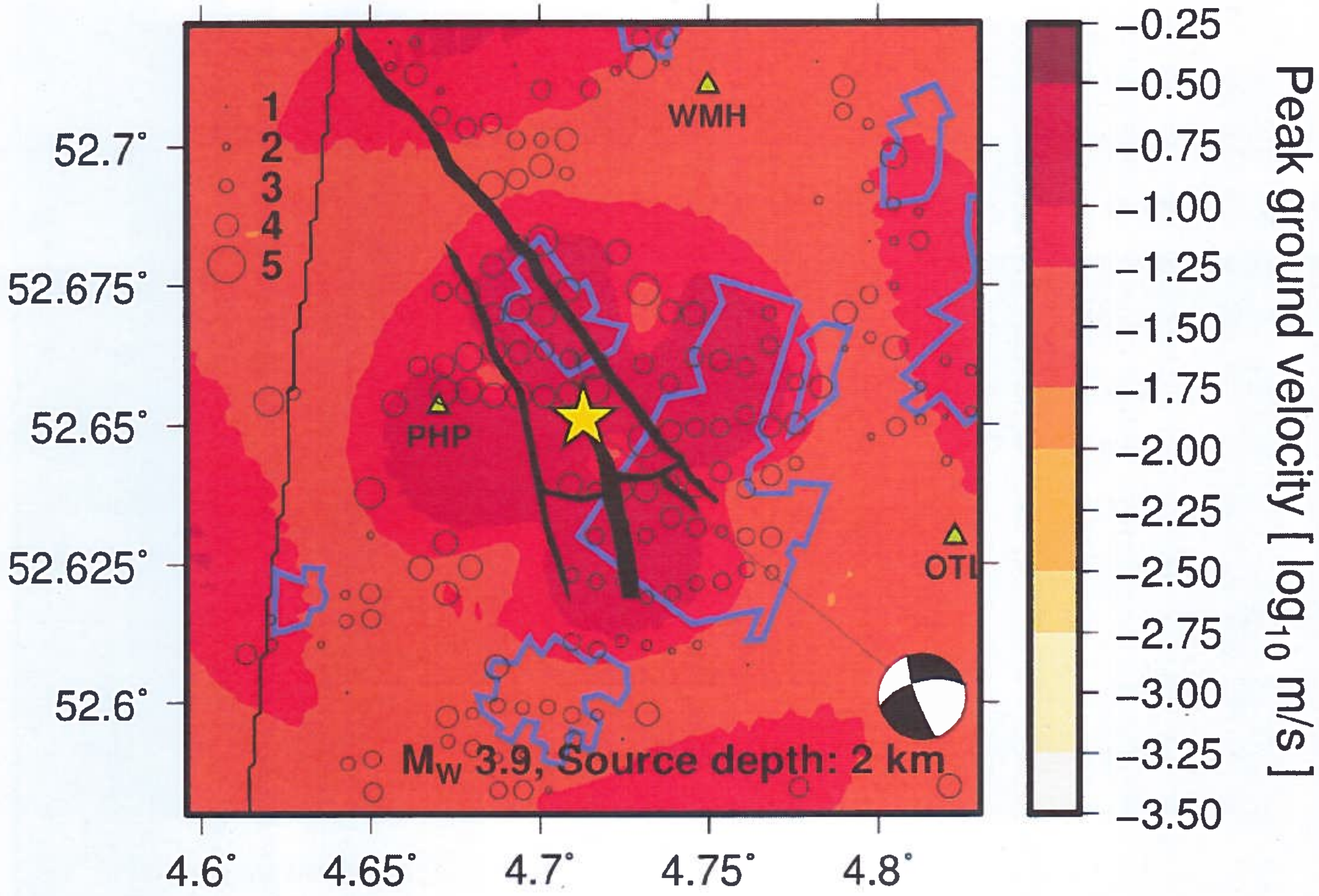
Simulation of "peak ground velocity"



soft layer on top

without soft layer

Simulation of Mw 3.9 event



maximal intensities of VIII are predicted (without soft layer)

conclusions

- Synthetic peak ground velocity can reproduce pattern of highest ground motion and epicentral intensity
- Influence of low velocity layer of 100 m thickness not very strong
- The epicentral location is confirmed
- Ground velocity will scale with factor 5.6 if moment magnitude is increased by 0.5 units

Stop here

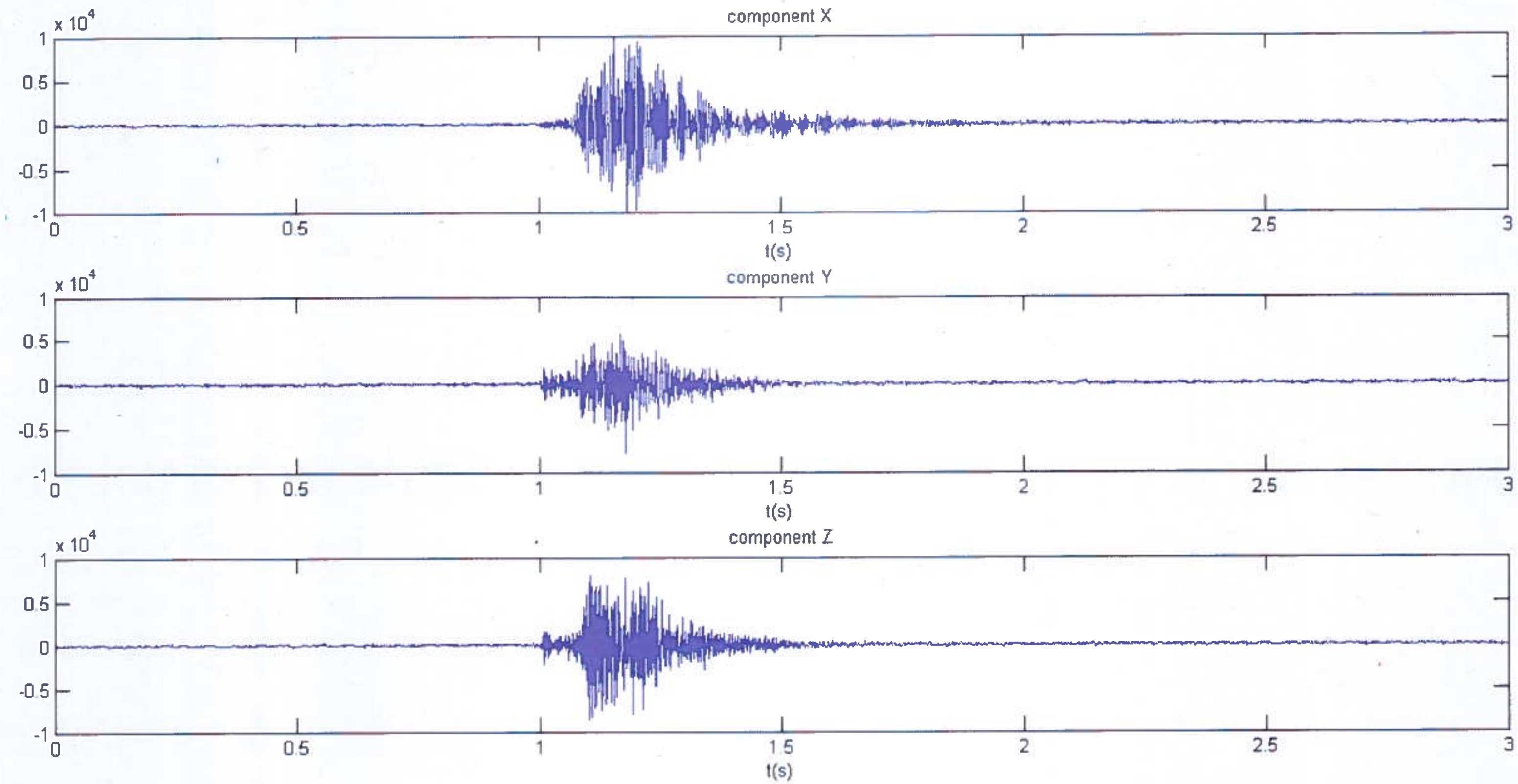
Micro-Seismicity Test

10.2.e. [redacted] (PhD student, MINE project)

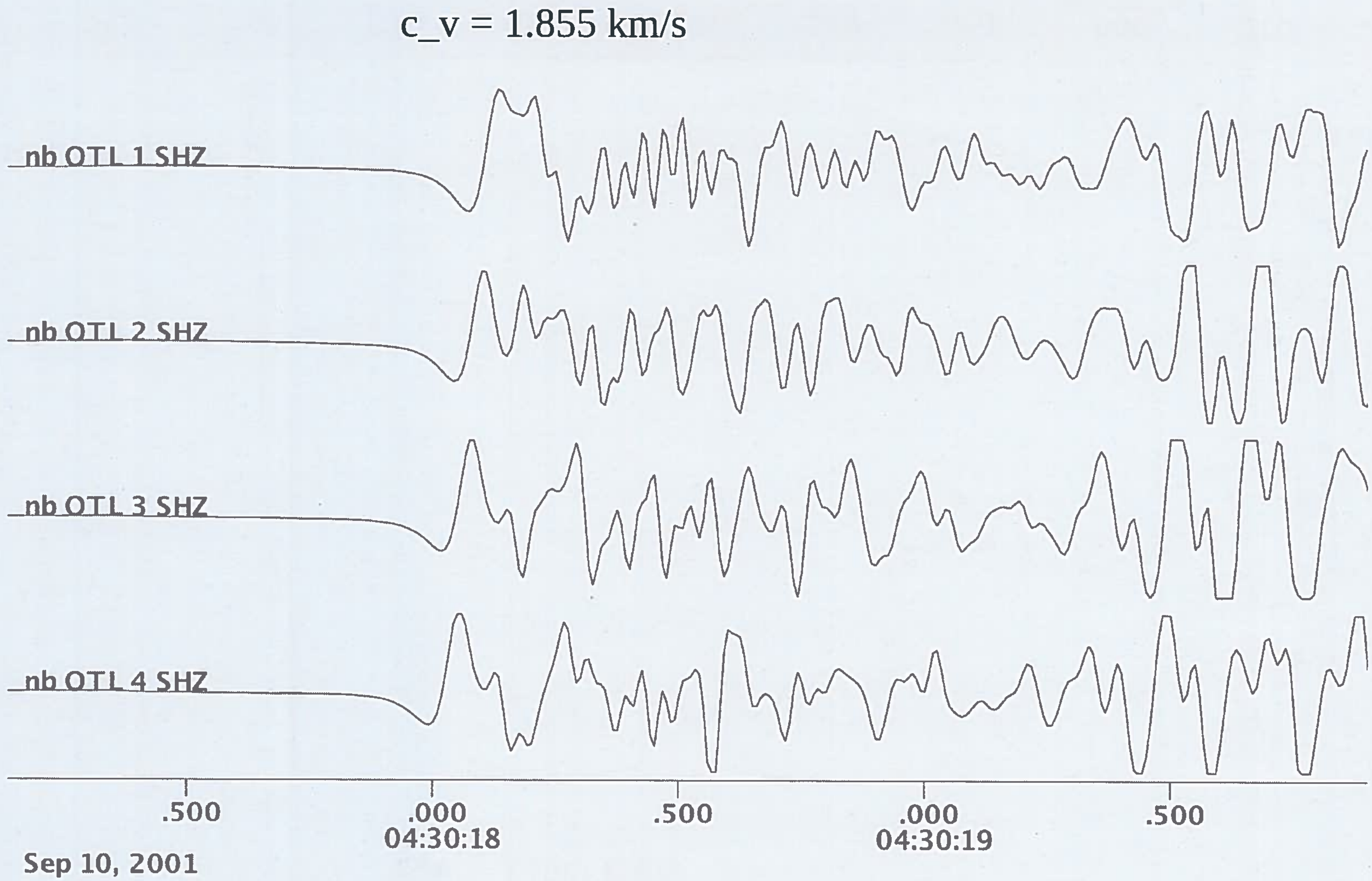
started to test automatic triggering tools (LTA/STA, semblance)

Universität Hamburg · Zentrum für Marine und Atmosphärische Wissenschaften · Bundesstrasse 53 · D-20146 Hamburg · Germany

Micro-Seismicity Test

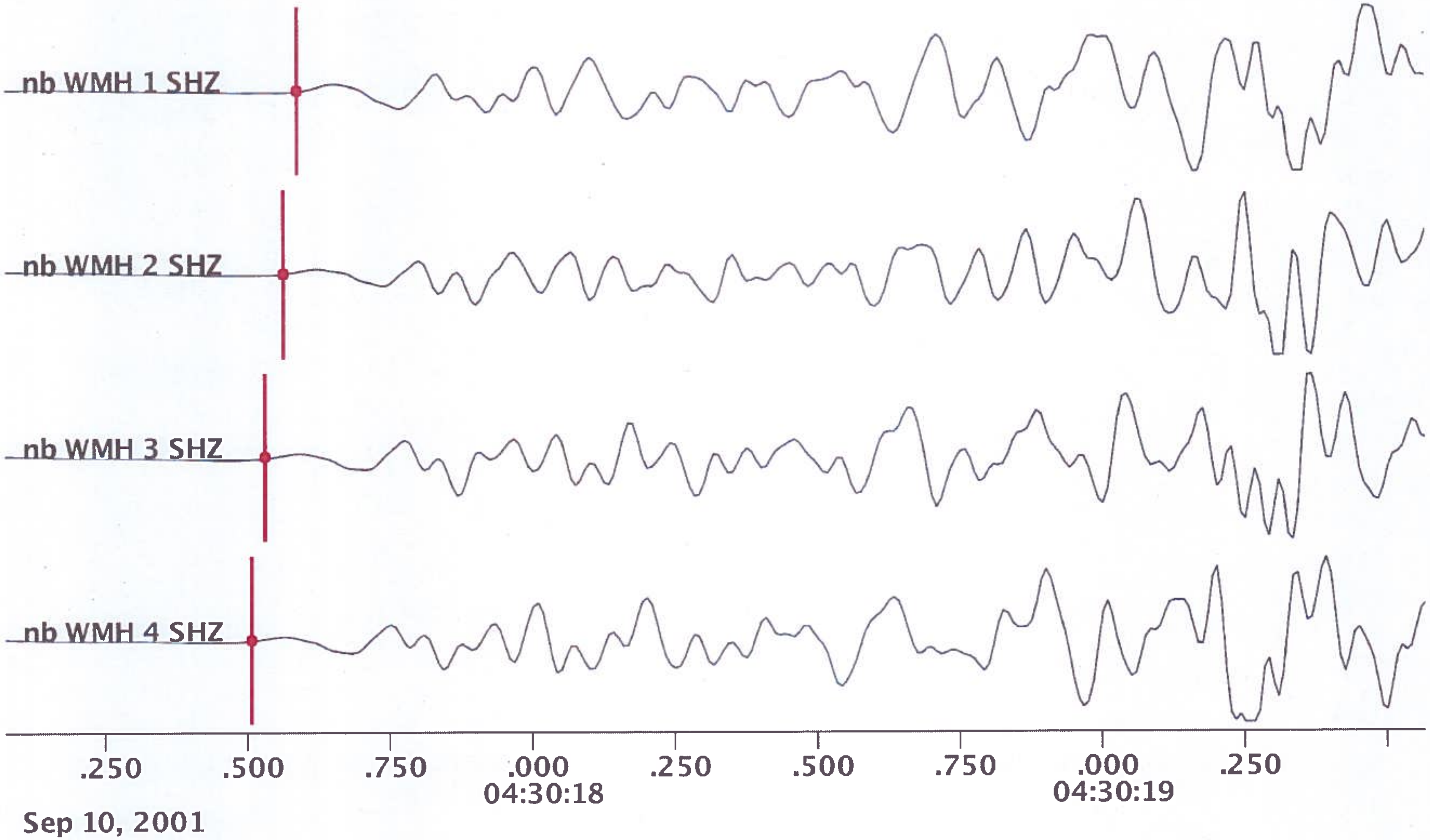


Slowness estimate from borhole arrays



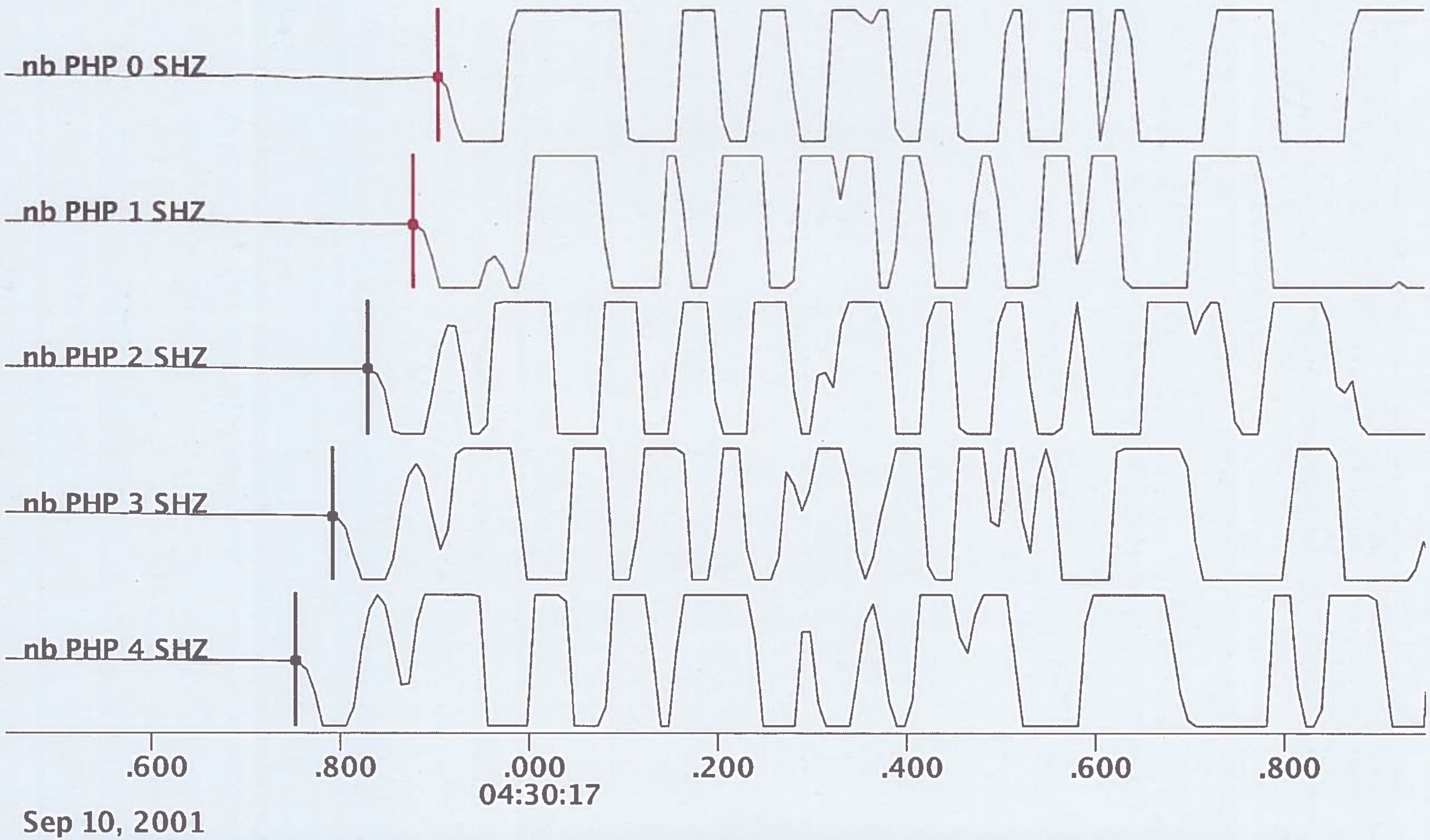
Slowness estimate from borhole arrays

c_v = 1.849 km/s



Slowness estimate from borhole arrays

c_v = 1.637 km/s



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Fachbereich Geowissenschaften
Institut für Geophysik
Prof. Dr. 10.2.e.

Dr. 10.2.e.
TAQA Energy B.V.
Prinses Margietplantsoen 40
Postbus 11550
2502 AN Den Haag, The netherlands

17. Februar 2011

10.2.e.

Dear 10.2.e

in your mail from 2 Feb 2011 you asked 10.2.e. and me about our common interpretation of the source mechanism of the 2001 Alkmaar earthquakes, since a full report has not been finished so far.

The source mechanism study shows that a fault with a strike of 130-160 degrees and a dip of 60-80 degrees was active during the 9. September 2001 Alkmaar Earthquake. After contacting 10.2.e. we can give you the following conclusions.

There is some uncertainty with respect to the movement on this fault plane. Waveform modeling results seems to indicate a strike-slip movement with a small vertical component. The vertical movement refers to minor normal or minor reverse movement that has occurred as an element of the overall strike-slip movement. However, further modeling will be required to find a more definite solution. The uncertainty on the movement on the fault plane has no effect on the estimate of the maximum magnitude, since this has been determined on the basis of other information (statistics and available fault length). 10.2.e.

10.2.e.

10.2.e.

Prof. Dr. 10.2.e.
INSTITUT FÜR GEOPHYSIK
Bundesstraße 55 · 20146 Hamburg

Dr. 10.2.e.
KNMI, Utrecht, The Netherlands