Seismic monitoring of Nature's Heat Geothermal Reservoir in Kwintsheul (Netherlands)

Naranjo, David; Draganov, Deyan; Polychronopoulou, Katerina; De Bas, Mathieu ; Weemstra, Cornelis

Publication date
2022

Document Version
Final published version

Citation (APA)
Naranjo, D., Draganov, D., Polychronopoulou, K., De Bas, M., & Weemstra, C. (2022). *Seismic monitoring of Nature's Heat Geothermal Reservoir in Kwintsheul (Netherlands)*. Paper presented at European Geothermal Congress 2022, Berlin. https://www.egec.org/wp-content/uploads/2023/02/Naranjo-Microseismic-monitoring-of-Natures-Heat-Geothermal-Project-432_ExtAbstract.pdf

Seismic monitoring of Nature's Heat Geothermal Reservoir in Kwintsheul (Netherlands)

David Naranjo[1], Deyan Draganov[1], Katerina Polychronopoulou[2], Mathieu de Bas[3], and Cornelis Weemstra[1,4]

[1] Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands
[2] Seismotech S.A., Marousi, Greece
[3] Gastreatment Services BV (GtS), Bergambacht, The Netherlands
[4] Royal Netherlands Meteorological Institute, De Bilt, The Netherlands

Corresponding author: d.f.naranjohernandez@tudelft.nl

Keywords: Passive seismology, seismic monitoring, Dutch geothermal doublet.

ABSTRACT

In 2018, the geothermal project Nature's Heat started its operations to supply heat to 64 hectares of greenhouses in Kwintsheul, Netherlands. The operation involves the extraction and reinjection of geothermal fluids at a depth of about 2.4km. Several studies suggested that geothermal operations in these parts of The Netherlands are unlikely to generate felt seismic events (M>2.0); nevertheless, adequate seismic monitoring techniques are essential to guarantee sustainable and safe use of the Dutch subsurface. Between July and October 2019, Delft University of Technology, Seismotech (Greece), and Gastreatment Services BV installed a passive seismic network to monitor the seismic activity over Nature's Heat geothermal reservoir. The seismic network consists of 30 three-component short-period seismic sensors placed at inter-station distances of approximately 150 m along two crossing lines. A challenge for seismic monitoring systems in urban areas is the high level of background noise. In Kwintsheul, anthropogenic noise dominates the spectrograms at frequencies higher than 2 Hz. Despite these high background-noise levels, a seismic event of ML = 0.0 (duration magnitude Md 0.16) was recorded by all seismometers of the array on July 14, 2019. To understand the relation of the event and improve the safety of the geothermal operation, we are developing a probabilistic monitoring and inversion scheme. This study aims to improve the seismic network's detection and hypocentre-determination capabilities and verifies via template matching if the detected seismic event is repeating over time (possibly at the background noise level).

1. INTRODUCTION

Over the next few decades, geothermal energy will cover an increasingly larger portion of the heat demand in The Netherlands. One condition to steer the growth in the right direction is to improve the efficiency and safety of geothermal operations. In addition, public support plays an essential role in developing large-scale geothermal projects. Societal acceptance partly depends on assessing and managing the risks associated with geothermal operations. One key risk factor is the potential occurrence of induced seismicity. This risk is due to the injection and extraction of fluids in the subsurface, which may change the stresses in the underground structures (Buijze et al., 2020). Concerns about induced seismicity could lead to the suspension or cancellation of large-scale geothermal projects. In particular, if the seismicity is not adequately evaluated and discussed with all parties involved (e.g., Kim et l., 2018; Seithel et al., 2019).

To improve the safety of geothermal operations, it is essential to understand the underground geological structures where the injection and extraction processes occur. In terms of efficiency, one wants to identify the most permeable layers such that sufficient heat can be extracted during the operation. In terms of safety, one wants to avoid fault zones that could potentially trigger unwanted seismicity. A powerful tool to identify key underground geological faults is passive seismic monitoring. By using passive seismic monitoring, it is possible to detect microseismic events that could be related to tensile cracking or active faults. With this tool, it is also possible to characterise the geothermal field's seismicity and its temporal evolution, which could be related to the injection and production of the geothermal operation.

In 2018, a geothermal doublet started operating in Kwintsheul, Netherlands, to supply heat to 64 hectares of greenhouses. This kind of geothermal operation requires extraction and reinjection of fluids. Nature's Heat geothermal operation is located in a system of inactive normal faults associated with the West Netherlands Basin (WNB). In section 2, the setup of the geothermal operation and the WNB is further explained. The geothermal reservoir used in this project has shown to possess suitable hydraulic parameters that allow the fluid's circulation. Several authors suggested that geothermal operations at this depth are unlikely to generate felt seismicity in the WNB (e.g., Buijze et al., 2020). Notwithstanding, reinjection of cold water in regions with pre-existing fault systems may well affect the underground stress conditions. Therefore, it is essential to monitor subsurface operations to ensure that the injection of fluids does not trigger felt seismicity.

The national seismic network, operated by the Royal Netherlands Meteorological Institute (KNMI), has been used to detect seismicity all over The Netherlands since 1993 (KNMI, 1993). The seismic network and the magnitude of completeness of the associated earthquake catalogue are shown in Figure 1. In Kwintsheul, the magnitude of completeness of this catalogue exceeded M_L 1.0 until 2020 (Muntendam-Bos et al., 2020), meaning that only earthquakes above M_L 1.0 can reliably be recorded. For the purpose of monitoring subsurface operations, it is beneficial to record events of lower magnitudes as they can be precursors of stronger seismic events (e.g., Eyre et al., 2019; Deichmann et al., 2014).

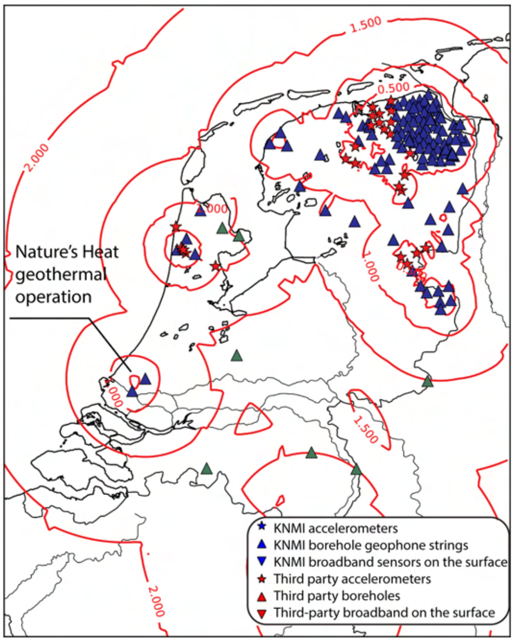

Figure 1: Overview of the seismic stations and magnitude of completeness (red contours) of KNMI's seismic network in 2020 (Ruigrok & Dost, 2019). Modified from Muntendam-Bos et al. (2022).

To monitor the operation of Nature's Heat project, Delft University of Technology, Seismotech (Greece), and Gastreatment Services BV installed a temporary seismic network over the geothermal reservoir that consisted of 30 stand-alone three-component short-period seismological stations. The objectives of installing a temporary seismic monitoring network at Kwintsheul are multi-fold. The main goal is to characterise the local seismicity and analyse whether there are any active seismic zones in the area. By characterising the local seismicity (or lack of seismicity), we intend to investigate whether there is a relationship between the production and injection operations carried out on-site and the local seismicity. In this way, the operator will have more confidence that their geothermal doublet is running efficiently and safely.

2. NATURE'S HEAT GEOTHERMAL OPERATION

The geothermal operation of Nature's Heat is an initiative of 9 horticultural companies that currently operate commercial greenhouses in Kwintsheul. Heating systems are necessary for commercial greenhouses to extend their growing season without depending on the weather. Initially, only natural-gas combined heat and power (CHP) plants were used to produce the heat necessary for the greenhouses. In 2015, the horticultural companies took the initiative to develop a geothermal-based heating system to offset the highly volatile natural-gas prices. The substitution of a gas-based heating system resulted in a consumption reduction of approximately 22 million m³ of natural gas and an emission reduction of 40 million kg of CO2 per year (Nature's heat, n.d). The installation of the geothermal doublet started in 2015, and the operation started on March 21, 2018.

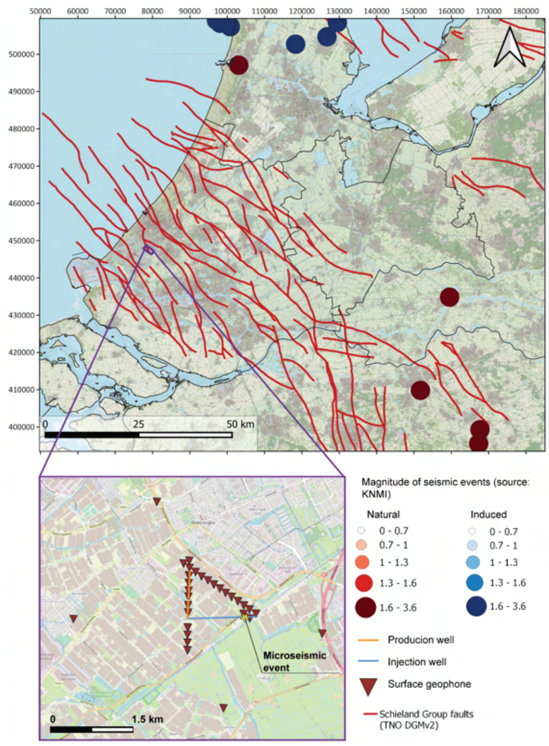

Figure 2: Location of Nature's Heat geothermal operation (purple), main geological faults of the West Netherlands Basin (WNB), and regional seismicity. The seismic monitoring network and the detected microseismic event can be seen in the inset.

The geothermal doublet of Nature's Heat injects and extracts fluids at a depth of approximately 2400 m, corresponding to the Lower Cretaceous. The location of the injection and production wells can be seen in Figure 2. These are deviated wells. Borehole data reveal that injection and production occur within the Delft Sandstone Member (i.e., 'the reservoir'). This member is overlain by the Rodenrijs Claystone Member. At reservoir depth, the separation between the two wells is approximately 1500 m.

3. GEOLOGICAL SETTING

Nature's Heat geothermal operation is located in the province of South Holland, Netherlands, in an area that hosts the WNB. The location of Nature's Heat project in relation to the WNB is shown in Figure 3. The WNB is a 60-km-wide transtensional basin that, together with the Ruhr Valley Graben and the Broad Fourteens Basin, forms a failed rift system (Boersma et al., 2021). The normal faults associated with the WNB display a NW-SE trend (Duin et al., 2006), as shown in Figure 2 (red lines). Permian to Tertiary deposits correspond to the first 5 km of the WNB characterised by a connected fault network of WNW-ESE to NNW-SSE striking features (Worum et al., 2005; Boersma, 2021). The faults associated with the WNB are not manifested at the surface.

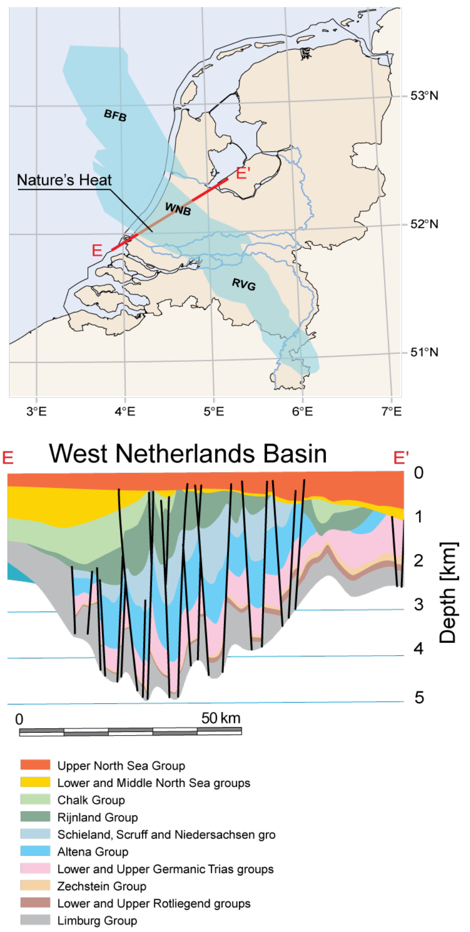

Figure 3: Cross-section of the WNB and location of Nature's Heat geothermal operation. Modified from Duin et al. (2006).

According to the complete earthquake catalogue of the Netherlands, the WNB has no reported seismic activity. The closest seismic events, shown in Figure 2, can be classified into two main groups. To the North, the seismicity corresponds to the recorded seismic events around Bergermeer's gas storage system. To the Southeast, the seismic events correspond to natural seismicity associated with the Ruhr Valley Graben. These two sets of events are unrelated to the geological and seismotectonic setting of Nature's Heat geothermal operations.

4. TEMPORARY PASSIVE SEISMIC NETWORK

For monitoring the geothermal operation of Nature's Heat project, a temporary passive seismic network was installed in Kwintsheul, Netherlands. The network was operational between July 22, 2019, and November 9, 2019, with a total recording time of approximately 4 months. The network consisted of 30 three-component short-period seismic sensors that sampled the wavefield at 250 samples per second. An impression of the deployment of the sensors is given in Figure 4.

Figure 4: Installation of the seismic sensors that monitored the geothermal operation of Nature's Heat project in Kwintsheul, The Netherlands.

The passive seismic network effectively consists of two different geometries. The first one has two crossing lines, each comprising 13 stations. These cover an area of approximately 3.8 km^2. These stations were installed with an average interstation distance of 150 m. The two crossing lines are intended to characterise the local seismicity and facilitate beamforming and array-processing techniques. The second geometry consists of an outer ring of 4 peripheral stations, which covers an area of 18 km^2 around the geothermal doublet's injection point. This second geometry augments the azimuthal coverage of the passive seismic network for improved depth resolution of the possible microseismic events. The Network's geometry and location of the geothermal doublet can be seen in the inset in Figure 2.

5. PERFORMANCE OF THE SEISMIC NETWORK

5.1 AMBIENT SEISMIC NOISE

For evaluating the performance of a passive seismic network, it is essential to characterise the background seismic noise of the different stations. The background seismic noise adversely affects the ability to distinguish the seismic signals of interest (e.g., surface displacement due to induced seismic events). The noise can be due to natural Earth vibrations (e.g., microseisms), cultural sources, instrumental glitches, or a combination of these (Peterson, 1993).

One-week spectrograms for stations KW03 and KW07 are shown in Figure 5. Station KW03 is located next to the surface location of the geothermal doublet. Station KW07 is on the same seismic line as KW03 but at a greater distance from the geothermal doublet. The frequency spectrum of both stations shows diurnal variations of the ambient seismic noise. The variations are more substantial for station KW07 than for station KW03. Both frequency spectra show narrow-band continuous noise at around 3 Hz. Stations closer to the location of the geothermal doublet show dominant ambient seismic noise at frequencies between 2 Hz and 20 Hz. In contrast, stations further away from the geothermal doublet show dominant noise also at higher frequencies - between 2 Hz and 50 Hz.

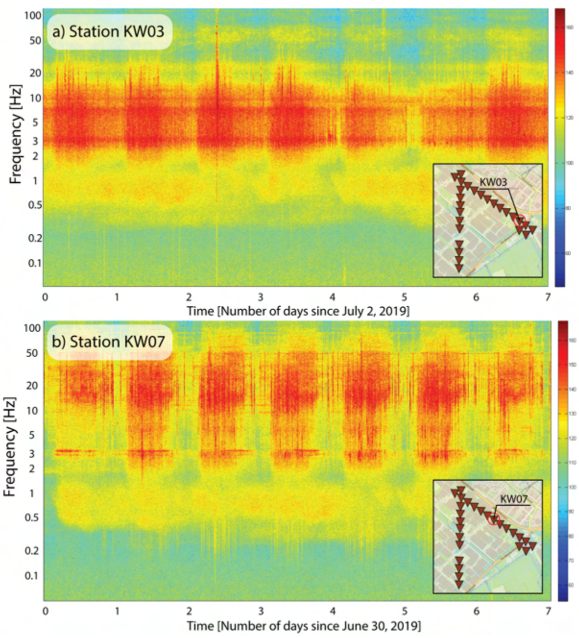

Figure 5: Spectrograms of stations (a) KW03 and (b) KW07. The red circles in the insets indicate the positions of the stations along the lines.

The standard approach for quantifying the background seismic noise is the computation of power spectral densities or PSDs (McNamara & Buland, 2004). In particular, a PSD's probability density function (PDF) is often computed to estimate the true seismic-noise variation at a given station. The PDF provides the probability of a specific noise level being recorded by a specific station at a specific frequency. These results can then be compared with the standard new low-noise model (NLNM) and the new high-noise model (NHNM) of Peterson (1993). Both reference models serve as a standard of seismic background noise and, as such, provide an estimate of the quality of the seismic recordings.

The PSDs of the three components of station KW03 are shown in Figure 6. For most stations and periods higher than 10 s, the noise levels are significantly above the NSMN model of Peterson (1993). For periods above 2 s and below 7 s, the noise levels are below the NHNM with a probability of 18 %. The relatively high seismic noise levels in the Kwintsheul area represent a challenge for processing and interpretation of the recordings by the passive seismic network. These high noise levels are most likely related to cultural noise from operations in and near the greenhouses. Additionally, the passive seismic network is located close to various roads and urban areas, making the detection of microseismic events an even more challenging task.

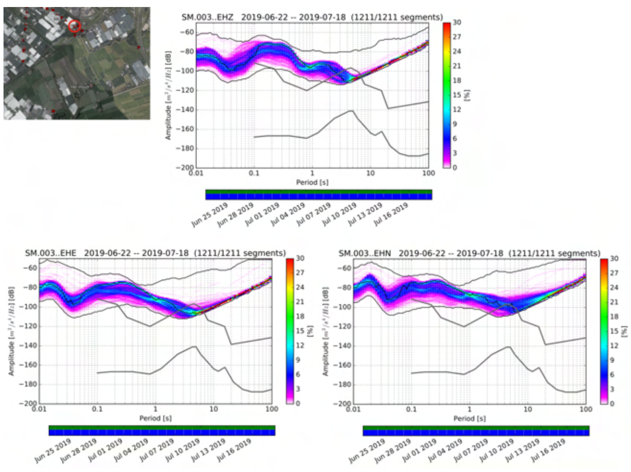

Figure 6: Power Spectral Densities of the vertical (EHZ, top), east (EHE, bottom left), and North (EHN, bottom right) components of station KW03. The red circle in the inset indicates the position of the station.

5.2 DETECTED SEISMIC EVENT

In order to assess the seismicity of the survey area, we analysed the continuous passive seismic dataset. The analysis consisted of two distinct steps: event detection, which is applied to the whole dataset using an energy-based algorithm (Leontarakis et al., 2015); and phase picking, which follows in case of the detection of an earthquake, resulting in an estimation of the P- and S-wave onset times at each station, based on the statistical characteristics of the detected signals (Lois et al., 2013). The picked travel times are then used to estimate the hypocentral location of the detected event.

Data analysis of the Kwintsheul dataset resulted in the detection and location of a single weak event, which was recorded by the totality of the stations of the passive seismic network on July 14, 2019. The unfiltered waveforms of the weak event are shown in figure 7. For this microseismic event, we performed event location using an iterative linearized least-squares procedure (based on HYPO71 – Lee and Lahr, 1972) and a coarse velocity model of the subsurface based on regional data (1D P-wave velocity model and homogeneous Vp/Vs ratio of 2.6). We estimated the event's magnitude (ML) to be 0.0 (duration magnitude Md 0.16) and its depth of occurrence at 2.46 km, close to the injection point of Nature's Heat geothermal operation. However, the location procedure is heavily affected by the velocity model assumed for the conversion of times to distances, which in this case is characterised by significant uncertainty (especially in terms of the Vp/Vs ratio value). This increases the overall ambiguity of the solution and thus must be taken into consideration before definite conclusions on the nature of the recorded event (tectonic or induced) can be drawn.

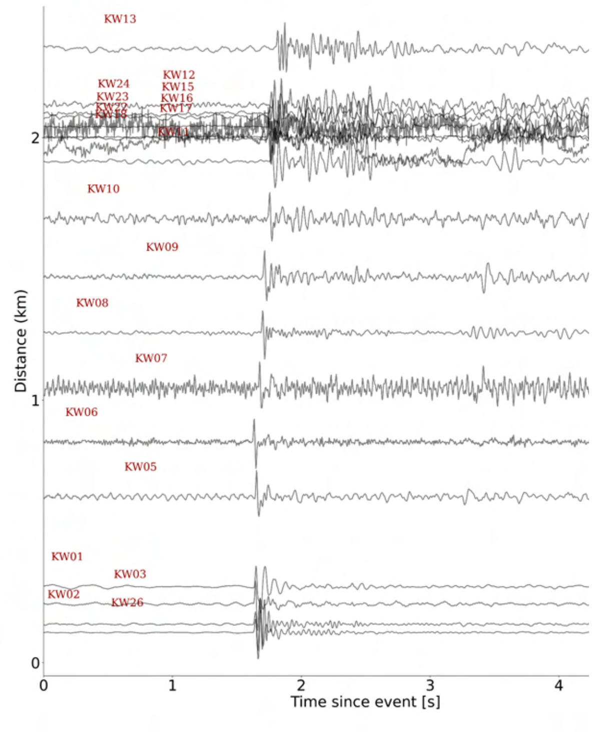

Figure 7: Raw waveforms of the Md 0.14 microseismic event recorded in Kwintsheul, Netherlands.

6. PROPOSED ANALYSIS

We are currently developing an optimised seismic monitoring scheme to improve our detection and source-characterisation techniques.

6.1 BEAMFORMING

To improve the detection capabilities of the passive seismic network, we are implementing a beamforming algorithm. The goal of applying beamforming is to separate coherent signals from noise. Assuming plane waves, beamforming systematically evaluates all differential travel times to infer the slowness vector (and hence back azimuth and horizontal velocity) that best describes the recorded waveforms (Rost and Thomas, 2002). That is, aligning the individual single-station recordings according to this slowness vector will cause them to sum constructively. The corresponding best-beam amplitude serves as a criterion to further analyse a specific time window for the presence of P and S waves (in case of incoherent noise, the best-beam amplitude will not exceed a predefined threshold). The implementation and processing of the data using the beamforming technique are currently under development.

6.2 EVENT CHARACTERISATION

To improve the source characterisation, we will use a probabilistic moment-tensor inversion algorithm. The results of the moment-tensor inversion can improve the hypocentre localization and estimate the focal mechanism of the microseismic event. In this way, we might be able to identify the nature of the microseismic event in a better way (tectonic or induced).

For the velocity model, we use a 1D Vp profile extracted from the seismic velocity model (VELMOD) for the entire Netherlands area (Van Dalfsen et al., 2006). We estimated the Vp/Vs ratio for the different velocity layers based on known Vp/Vs ratios in other areas using the Digital Geological Model (DGM) of The Netherlands. The latter model is a set of layers for the top and base of geological sections in The Netherlands. The velocity model is shown in figure 8a, while figure 8b shows the hypothetical ray paths from the detected seismic event. Plotting the ray paths is crucial when analysing the velocity model because it can show whether some layers defocus the seismic energy.

The methodology for performing a probabilistic moment-tensor inversion requires comparing synthetic waveforms with field observations. For the forward modelling of synthetic waveforms, we are using the Pyrocko package (*Heimann et al.*, 2017). The forward modelling requires the computation of Green's functions. For that purpose, we use a pre-computed Green's function database handled by the related Pyrocko-GF software library (*Heimann et al.*, 2019). This significantly accelerates the performance of the Monte Carlo sampler. Specifically, we compute Green's functions using the orthonormal propagator method QSEIS *Wang* (1999). Preliminary synthetic waveforms for a synthetic event are shown in figure 9. As the inversion requires sampling high-dimensional posterior distributions, we will test different probabilistic approaches. This work is still under active development.

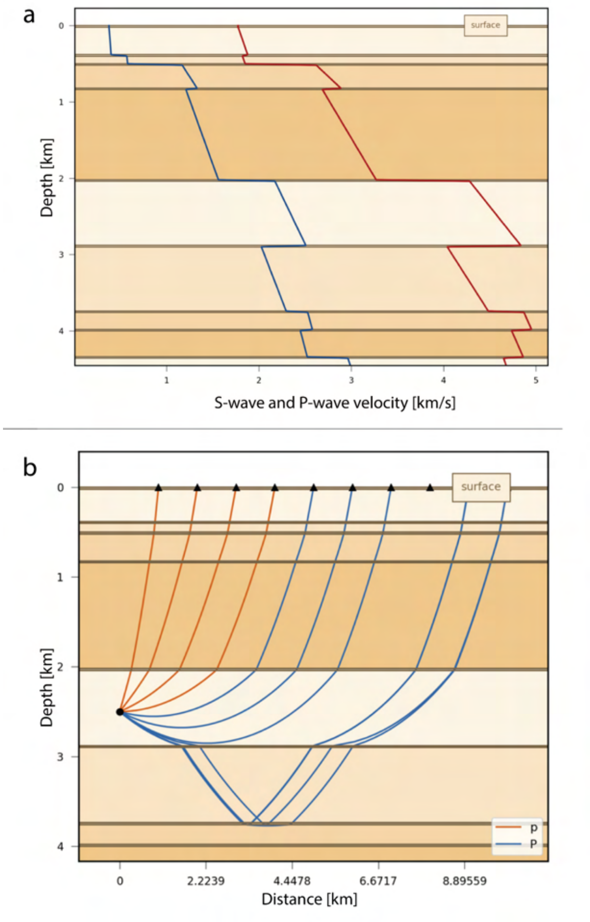

Figure 8: a) P- and S-wave velocity model in Kwintsheul's area. b) Hypothetical ray paths of the Md 0.14 event detected by the temporal passive seismic network.

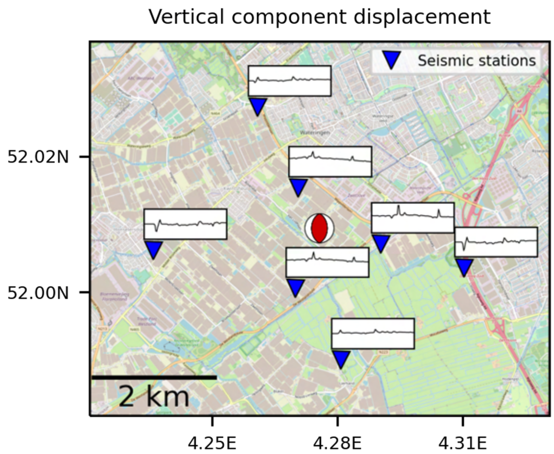

Figure 9: Synthetic waveforms for a hypothetical reverse-fault seismic event.

7. CONCLUSIONS

A temporary passive seismic network was deployed for 4 months in Kwintsheul, Netherlands, to monitor Nature's Heat geothermal operation. Although several authors described the West Netherlands Basin as an inactive fault system, a small (ML 0) event was recorded on July 14, 2019. As expected, the spectrograms and power spectral densities of the seismic stations showed high levels of ambient seismic noise. The ambient noise comes from a combination of sources, including traffic, industrial activity, and machinery. These high levels of ambient seismic noise can interfere with the network's ability to detect earthquakes and other seismic events. Considering the results of the analysis so far, it is possible to conclude that Nature's Heat geothermal operation was running safely during the acquisition and that there was no evidence of triggering significant seismicity for the duration of the monitoring period. It is, however, needed to monitor the geothermal operation and improve the detection and localization methods of the seismic network to ensure a sustainable operation.

REFERENCES

Nature's Heat (n.d.), Over Nature's heat, Geothermie project Nature's Heat. Available from: https://www.naturesheat.nl/over-nature-s-heat/ (Accessed April 21, 2022)

Boersma, Q., Bruna, P., De Hoop, S., Vinci, F., Moradi Tehrani, A., & Bertotti, G. (2021). The impact of natural fractures on heat extraction from tight Triassic sandstones in the West Netherlands Basin: A case study combining well, seismic and numerical data. Netherlands Journal of Geosciences, 100, E6. doi:10.1017/njg.2020.21

Buijze, Loes & Bijsterveldt, Lonneke & Cremer, Holger & Jaarsma, Bastiaan & Paap, Bob & Veldkamp, J.G. & Wassing, Brecht & Van Wees, J. & van Yperen, Guido & ter Heege, Jan. (2020). Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands. Netherlands Journal of Geosciences. 98. 10.1017/njg.2019.6.

Deichmann N, Kraft T, Evans KF (2014) Identification of faults activated during the stimulation of the Basel geothermal project from cluster analysis and focal mechanisms of the larger magnitude events. Geothermics 52:84–97. https://doi.org/10.1016/j.geothermics.2014.04.001

Donselaar, M. E., Groenenberg, R. M., & Gilding, D. T. (2015). Reservoir geology and geothermal potential of the Delft Sandstone Member in the West Netherlands Basin. In Proceedings world geothermal congress (p. 9).

Duin, E.J.T. & Doornenbal, J.C. & Rijkers, R.H.B. & Verbeek, J.W. & Wong, Theo. (2006): Subsurface structure of the Netherlands - Results of recent onshore and offshore mapping. Netherlands J. Geosci.. 85. (Geologie en Mijnbouw), 85-4: 245-276. 10.1017/S0016774600023064.

Eyre, T., Eaton, D., Zecevic, M., D'Amico, D., & Kolos, D. (2019). Microseismicity reveals fault activation before Mw 4.1 hydraulic-fracturing induced earthquake. Geophysical Journal International, 218, 534–546.

Kim, K., Ree, J., Kim, Y., Kim, S., Kang, S.Y. & Seo, W., 2018a. Assessing whether the 2017 Mw 5.4 Pohang earthquake in South Korea was an induced event. Science (New York) 360(6392): 1007. doi:10.1126/science.aat6081.

KNMI (1993): Netherlands Seismic and Acoustic Network. Royal Netherlands Meteorological Institute (KNMI). Other/Seismic Network. 10.21944/e970fd34-23b9-3411-b366-e4f72877d2c5

Lee, W. H. K., & Lahr, J. C. (1972). HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes (p. 100). US Department of the Interior, Geological Survey, National Center for Earthquake Research.

Leontarakis K., Lois A., Pantazopoulos A. and Polychronopoulou K. (2015) A comprehensive methodology for automated analysis of seismic records and its contribution to a Passive Seismic Tomography survey in Delvina, SW Albania. 85th SEG meeting, New Orleans, USA, Expanded Abstracts, 18 - 23.

Lois A., Sokos E., Martakis N., Paraskevopoulos P. and Tselentis G-A. (2013) A new automatic S-onset detection technique: Application in local earthquake data. Geophysics 78(1), KS1–KS11.

McNamara, D. E., & Buland, R. P. (2004). Ambient noise levels in the continental United States. Bulletin of the Seismological Society of America, 94(4), 1517–1527.

Muntendam-Bos, A., Hoedeman, G., Polychronopoulou, K., Draganov, D., Weemstra, C., Van der Zee, W., . . . Roest, H. (2022). An overview of induced seismicity in the Netherlands. Netherlands Journal of Geosciences, 101, E1. doi:10.1017/njg.2021.14

Peterson (1993). Observation and modelling of seismic background noise, US Geol. Surv. Tech. Rept. 93-322, 1–95.

Kramers, L., Van Wees, J.D., Pluymaekers, M.P.D., Kronimus, A. & Boxem, T. (2012). Direct heat resource assessment and subsurface information systems for geothermal aquifers: the Dutch perspective. Netherlands Journal of Geosciences/Geologie en Mijnbouw 91(4): 637–649. doi: 10.1017/S0016774600000421.

Ruigrok, E., & Dost, B. (2019). Seismic monitoring and site-characterisation with near-surface vertical arrays. Near Surface Geoscience Conference and Exhibition, 1–5. https://doi.org/10.3997/2214-4609.201902455

Spetzler, J. (2019). Westland Geothermal Project [PowerPoint slides]. Royal Netherlands Meteorological Institute. Ministry of infrastructure and the environment.

Van Dalfsen, W., Doornenbal, J., Dortland, S., & Gunnink, J. (2006). A comprehensive seismic velocity model for the Netherlands based on lithostratigraphic layers. Netherlands Journal of Geosciences - Geologie En Mijnbouw, 85(4), 277-292. doi:10.1017/S0016774600023076

Weemstra, C., 2019. Passive seismic measurements at the Nature's Heat Geothermal site in Kwintsheul, Netherlands [PowerPoint slides]. Energy Geotechnics: mechanics of the energy transition, October 3, 2019, Delft. Available at: http://homepage.tudelft.nl/2n5j1/booklet.pdf

Worum, G., Michon, L., Van Balen, R.T., Van Wees, J.D., Cloetingh, S. & Pagnier, H. (2005). Pre-Neogene controls on present-day fault activity in the West Netherlands Basin and Roer Valley Rift System (southern Netherlands): role of variations in fault orientation in a uniform low-stress regime. Quaternary Science Reviews, 24(3–4): 473–488. doi: 10.1016/j.quascirev.2004.02.020.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956965.