Project acronym and title:

SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

REPORT ON ADDRESSING METHODS TO ESTABLISH BASELINE LEVELS POST OPERATIONAL ACTIVITY

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Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for best practice for unconventional hydrocarbon production and geological CO2 storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

Executive report summary

Establishing a baseline for natural seismicity after the start of subsurface operations is no simple task, and best practice methods have yet to be created. In the SECURe project (Subtask 2.1.4.) a microseismic monitoring network has been established around the active natural gas storage facility in the Gassum Formation near Stenlille, Denmark. The Gassum Formation is a sandstone of Upper Triassic – Lower Jurassic age. A similar monitoring network was deployed near Dybvad, Denmark, approximately 200km from Stenlille, in 2014-2015. The geology and tectonic setting are similar at the two sites, and the natural seismicity is therefore expected to be similar as well. The measured natural background noise level is slightly lower near Stenlille. However, injection and production at the main pump dominate the recorded data at high frequencies at periods of high activity out to distances of approximately 3km. Preliminary data analysis has not yet detected any earthquakes near Stenlille. The natural seismicity is very low, and the relatively soft geology makes it challenging to detect small induced/triggered earthquakes. Based on the experience from the Dybvad network we do expect to be able to detect earthquakes down to a magnitude of 1.0, smaller during times of low or no pumping activity. The data analysis is ongoing. The approach being developed in SECURe will consist of microseismic monitoring around an active site, while experimenting with instruments in a range of distances from the well/storage facility, between 10 and 100 km, will help to establish best practice. These instruments are being installed during summer 2019.

Contents

1 Introduction

This report addresses methods to establish post operational baseline microseismological monitoring for CCS. We draw on GEUS' experience with a pre-operational seismological monitoring campaign carried out around a shale gas exploration drilling site near the small town of Dybvad in Vendsyssel (Northern part of Jutland, Denmark) and a post operational microseismological monitoring survey established as part of the SECURe project around the Stenlille natural gas storage facility located in the central part of Zealand, Denmark.

In general, a monitoring program of an injection site extends over a number of distinct operational phases, pre injection base line assessment, injection period data acquisition, injection stop and post injection monitoring.

Guidelines for CO2 geological storage e.g. European_Communities, 2011; ISO_TC265, 2017 includes an appropriate monitoring program as a key requirement and it has to address the following main objectives:

Site-specific geomechanical characterization of the storage unit, the primary seal, and of the overburden shall be conducted depending on the level of risk as determined by the project operator. Geomechanical characterization should include: evaluation of the natural seismicity and tectonic activity of the region where the prospective storage unit is to be located. Accordingly, the available information related to seismicity and tectonic activities should be collected and analysed. Characterization of the in situ stress regime (magnitude and orientation of principal stresses). Knowledge of the in situ stress regime in combination with the geomechanical modelling to assess the maximum (CO_2) injection pressure limits. Determination of rock mechanical properties of both storage unit and overlying seal and development of a mechanical geological model.

The applicability of a monitoring method may depend on site-specific characteristics, such as morphology, mineralogy, depth of the storage site, rock properties, natural plant cover, microclimate, etc. (Guidance document 2, 2011). To define these characteristics, geophysical and geochemical surveillance systems are required, which allow both continuous and periodic measurements. Reliable and robust sensor techniques are a necessary prerequisite for long-term data acquisition throughout the full life-cycle of the storage operation.

When monitoring and assessing the effects of utilizing the subsurface, it is desirable to know the environmental conditions (including gas fluxes and atmospheric composition, seismicity and groundwater chemistry) before activities commence. Deploying a network of seismographs may reveal microseismic activity, and in order to determine if the level of seismic activity is influenced by e.g. pumping it is useful to know the level of activity pre-operational. At existing sites, it is, however, not possible to measure at undisturbed conditions. Instead, a measured post-operational baseline can be compared with a baseline at an undisturbed site in a comparable geological setting.

There are currently no established methods for measuring a post-operational microseismic baseline, whereas pre-operational baselines are common e.g. Schoenball *et al.*, 2015; Wilson *et al.*, 2015. An increase in seismicity in a region of active subsurface operations is often taken as a clear indicator of induced and/or triggered seismicity e.g. Ellsworth, 2013; Grigoli *et al.*, 2017, but better post-operational methods need to be developed.

To establish a baseline for evaluation of the natural seismicity and tectonic activity in a region with prospectivity for underground storage or shale gas production all possible and available information related to these activities should be sampled and analysed.

This study utilizes two microseismicity surveys; a baseline monitoring survey of microseismicity within a radius of 10 km of a drilling site for a period of two years prior to drilling of the Vendsyssel-1 shale gas exploration well (Dybvad site); and an ongoing post injection microseismicity survey at the Stenlille gas storage site.

The two locations are selected due to similarity in geology especially in the overburden, i.e. strata above the target zones.

1.1 DYBVAD SITE:

The Dybvad monitoring network was established in 2014 to provide a pre-operational micro seismicity baseline prior to drilling the Vendsyssel-1 exploration well (Fig. 1). The exploration was abandoned after drilling the well down to the target, the Alumshale in the Paleozoic, as shale gas was discovered but in non-economical saturations.

The location in Northern Jutland, the Skagerrak-Kattegat area between Denmark, Sweden and Norway has no previous record of oil exploration or other activities which could have resulted in extensive mapping of the sub-surface. The data coverage is therefore scarce compared to regions in the Danish oil & gas province in the North Sea and the density of data is decreasing as one moves eastward in Skagerrak (Bergmo *et al.*, 2013).

The Alum Shale is overlain by several classic reservoirs in Lower Cretaceous, Jurassic, Triassic and Carboniferous formations. The upper Triassic Gassum Formation is overlain by thick marine mudstones of the Fjerritslev Formation, which is characterized by large lateral continuity, forming a highly competent cap rock unit probably making the Gassum Formation one of the most promising reservoirs for CO_2 storage in the study area. The sandstone of the Haldager Formation consists of fluvial and shallow marine sandstones interbedded with thin mudstones. The Haldager Formation sandstone is overlain by the marine mudstones of the Børglum Formation. Regional distribution of the mudstones with good sealing capacity above also makes the Haldager Sand Formation a good potential reservoir for CO_2 storage in the area (Bergmo *et al.*, 2013).

No salt structures occur in the Dybvad area, but local faulted blocks can potentially have formed stratigraphic traps (Mogensen *et al.*, 2003).

During the Vendsyssel-1 drilling GEUS carried out baseline monitoring of microseismicity within 10 km of the drilling site for a period of two years. A temporary network of six Broad Band seismographs continuously transmitted data in real-time to a server at GEUS, where processing of the data took place. The detection threshold for events was estimated to be magnitude 0.1 or smaller.

1.2 STENLILLE SITE:

The Stenlille natural gas underground storage facility is located 70 km SE of Copenhagen and has been in operation since 1989 (Fig.1). The storage facility has been re-developed over time in order to increase storage capacity.

The Stenlille structure is an anticlinal structure shaped by salt tectonics and with a vertical closure of approximate 35 m covering an area of 14 km2 (Fig. 2). The Upper Triassic – lower Jurassic Gassum Sandstone Formation forms the reservoir where gas is stored by displacing formation water. The top Gassum surface is located 1500-1600m below ground in the Stenlille area. The Gassum formation consists of cyclically interbedded sandstone and marine mudstone that were deposited as a result of changes in the depositional environment (Hamberg & Nielsen, 2000). The overlying 300 m thick Lower Jurassic Fjerritslev Formation, which consists of claystone, serves as a caprock for the sandstone reservoir.

The total estimated storage capacity of the Stenlille structure equals three billion normal cubic metres, and due to reservoir heterogeneities, gas is stored in several separate zones. The gas storage is at present operated by 14 wells for injection and withdrawal of gas and six wells used for observational purposes, most of them in the periphery of the structure, *cf*. Figure 2. (Laier & Øbro, 2009).

For safety reasons and to protect the environment it is necessary to monitor the storage operation carefully. No sign of gas leakage has been observed in a monitoring well located in a sand stringer 15 m above the gas reservoir. Other monitoring wells have been located in order to check for possible lateral escape of natural gas. A baseline study on naturally occurring hydrocarbons performed before the natural gas storage came into operation indicated the presence of only trace amounts hydrocarbon gases in the subsurface of the Stenlille area. Low concentrations of dissolved methane of bacterial origin were found in shallow groundwater that is used for water supply in the Stenlille area. After the start of injection of natural gas in 1989, no increase in methane concentration and no higher hydrocarbon gases were observed during the regular analysis of groundwater from 10 shallow wells located above the gas storage. However, a sudden increase in dissolved methane concentration from 0.02 to 27 mg/l was measured in a 130 m deep observation well after a minor gas leakage had been detected at a new deep drilling into the natural gas storage in 1995. Nonetheless, no increase in methane was observed in shallow groundwater at the same locality. Occasional higher concentrations of dissolved methane were encountered in shallow observation wells in low permeability layers. Stable isotope analyses and radiocarbon dating show that the gas does not originate from the underground gas storage because the methane was less than 300 years old, but it may have formed due to local microbial activity.

A pre-operational micro seismic baseline monitoring is obviously not possible at active sites. Instead micro seismic monitoring around an active site will be combined with baseline measurements in a comparable geological setting at a distance. As this has not been done before, it will be necessary to experiment with baseline instruments in a range of distances from the well/storage facility, between 10 and 100 km, to establish best practice.

2 A pre-operational microseismic monitoring network

GEUS established a microseismic baseline in the Gassum Formation near Dybvad during the period January 2014 to September 2015 (Figure 1). During the first part of the period there was no anthropogenic subsurface activity, towards the end test drilling took place. The Dybvad microseismic network consisted of 6 seismological surface stations placed at distances of approximately 1 km to 5 km from the test well location. The sites were equipped with Streckeisen STS-2 surface broadband seismometers. Continuous data were sampled at 100Hz and transmitted to GEUS in real time. The setup was chosen as to follow the GTV-Richtlinie 1101-1 from Vertrieb GTV Service GmbH, Albrechtstrasse 22, 10117 Berlin, Germany.

The recorded noise level on the temporary seismograph network near Dybvad was significantly higher than the noise level on GEUS’ regular network. This is not surprising as the constraints on where to deploy the temporary stations were quite narrow. A microseismic monitoring network is ideally installed within a few km of the site of interest, encircling the site by covering as many directions as possible. The faint signals from microseismic tremors do not propagate to great distances, although the exact propagation length depends on the local geology and can only be determined by field testing. The signal propagation has to be weight against local noise sources capable of dominating the recordings at frequencies of interest. For a permanent, national-level network it is possible to move the location of a station 20-50 km to obtain a more suitable geology (i.e. on chalk) and minimize cultural noise. A microseismic monitoring network is confined to the proximity of the site of interest, as the aim is to observe small local events which requires the stations to be within few km of the site to observe.

The baseline network did not record any events within 10km of the test drilling site during the 21 month long monitoring period. The 10 km circle from the test site was defined as the area of interest for microseismic activity. The closest event was a small earthquake with a Magnitude of 1.7 approximately 40 km from the site. During the lifetime of the temporary network the stations contributed to locating a total of 5 local events (defined as Denmark or border region), 48 regional events and 212 teleseismic events.

Figure 1. Location of the pre-operational microseismic monitoring network near Dybvad, active from January 2014 to September 2015 and the location of the Stenlille gas storage facility.

3 A post-operational microseismic monitoring network

During the period August to September 2018, GEUS established a microseismic monitoring network on the Gassum Formation around the Stenlille gas storage facility (Figure 2). The network builds on the same principles as the Dybvad network, currently consisting of 6 seismographs placed within 5 km of the main pumping facility. For the Stenlille network, Nanometrics Trillium seismometers from the DanSeis instrument pool were deployed. Continuous data sampled at 100 Hz are continuously transmitted to GEUS.

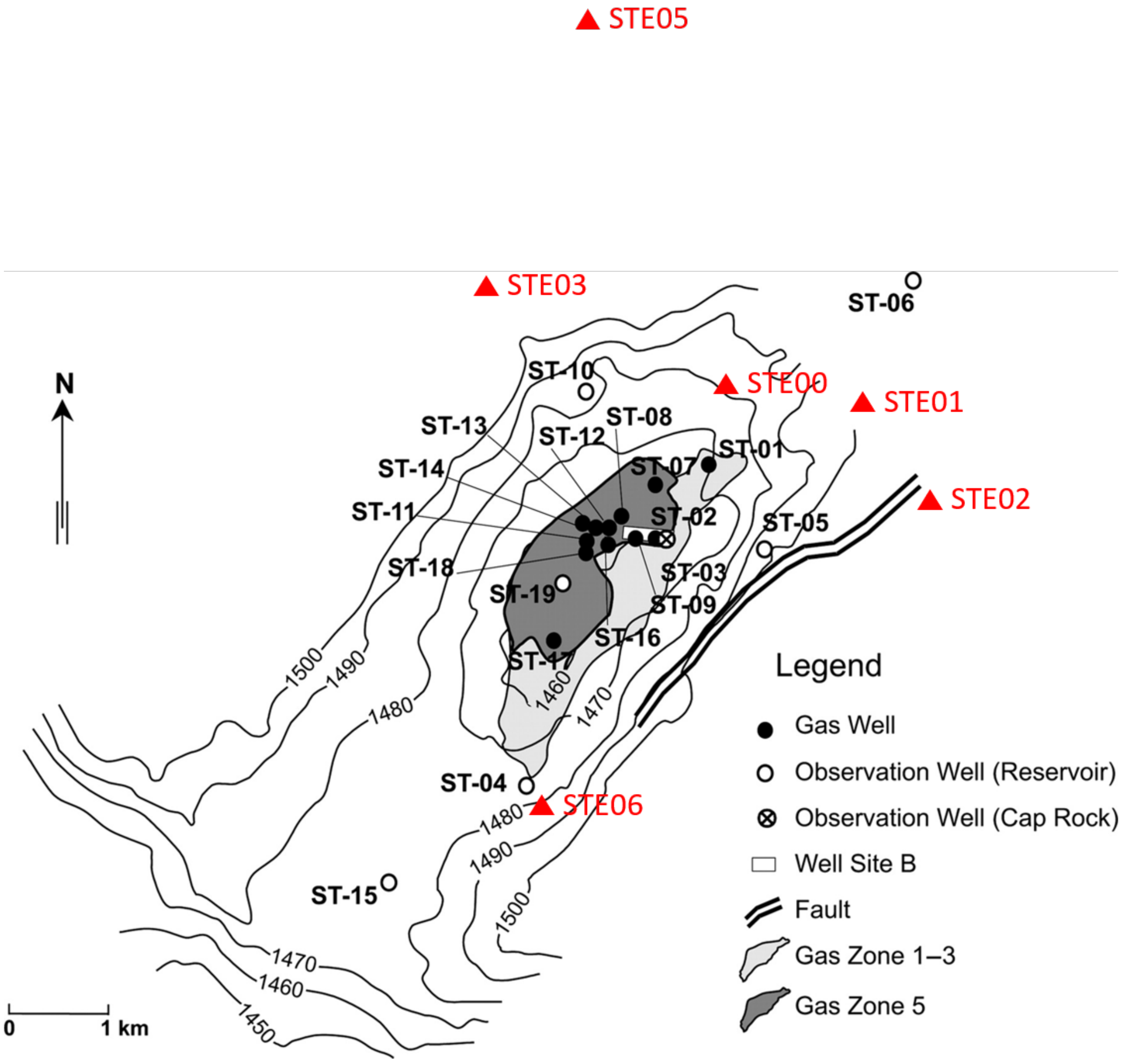

Figure 2. Well locations and extension of the different gas zones at the Stenlille gas storage facility. Contour lines indicate depth in metres to the top Gassum Formation. Red triangles are the deployed seismographs for the SECURe project. The seismographs in the network are within 5 km of the main pumping station. Modified from Laier & Øbro, 2009

3.1 PRELIMINARY DATA ANALYSIS

Since installation of the Stenlille monitoring network, data from the 6 stations have been continuously recorded and transmitted in real time to GEUS, where it is stored on our servers.

Preliminary analysis of the Stenlille data shows a high noise level, but slightly better than the Dybvad network. One of the original sites (STE04) was quickly abandoned and replaced by another (STE06) due to an unacceptable noise level high above the International High Noise model levels (see for example McNamara & Buland, 2004). The rest of the seismographs have noise levels below the international High Noise Model. Station. STE03 is included in the daily earthquake monitoring at the GEUS' seismic service as an extra quality control.

Several interesting features can be observed in the noise analysis of the stations. The most prominent feature is a characteristic noise on STE00, located at the main pumping station. During months of intense pumping activity, the high frequency part of the spectrum shows distinct bands of very high dB noise. The noise is clearly traceable at STE01 located 1.3 km from the main pump, whereas it is barely visible at STE03 located 3.2 km from the pump, see figures (3-5) below.

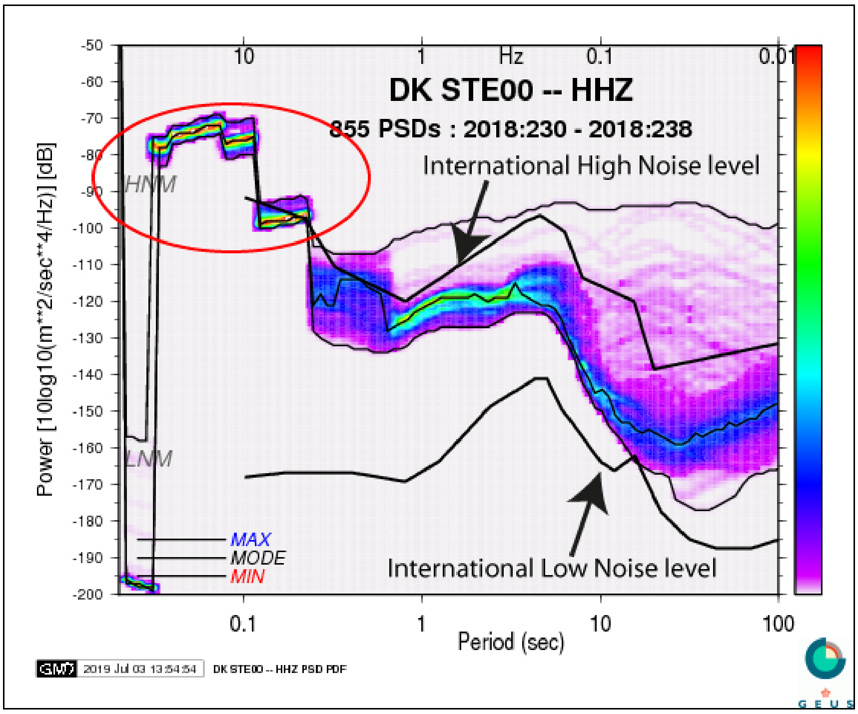

Figure 3. Noise analysis for the vertical component of STE00, located at the main pumping station, August 17-25, 2018. Bands of intense noise from the pumping is clearly visible (in red ellipse) in the high-frequency part of the spectrum. The International High and Low noise levels are marked.

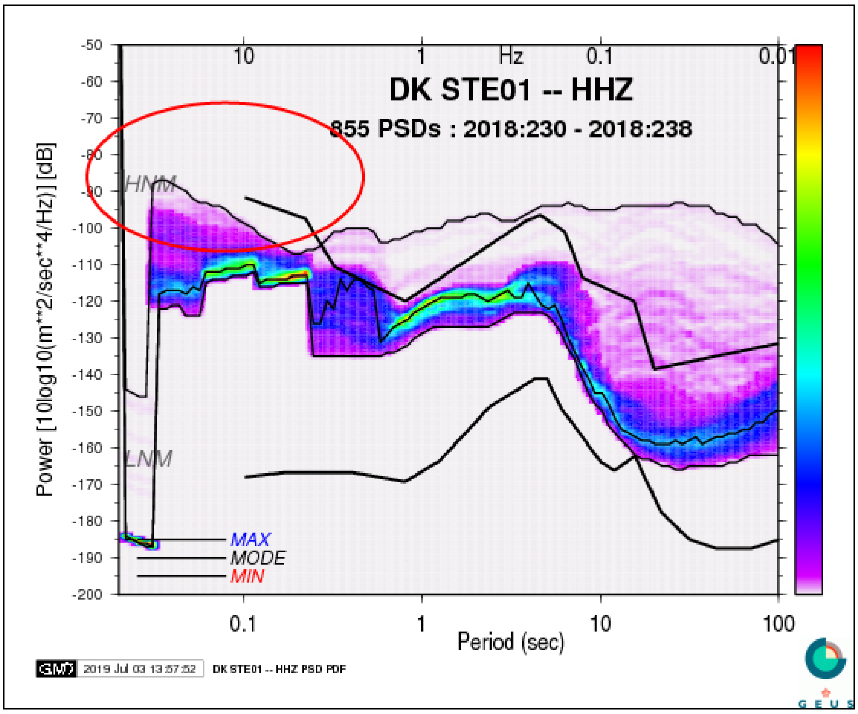

Figure 4. Noise analysis for the vertical component of STE01, located 1.3 km from the main pumping station, August 17-25, 2018. The high-frequency noise bands from the pumping are clearly visible, but the noise level is muted compared to STE00.

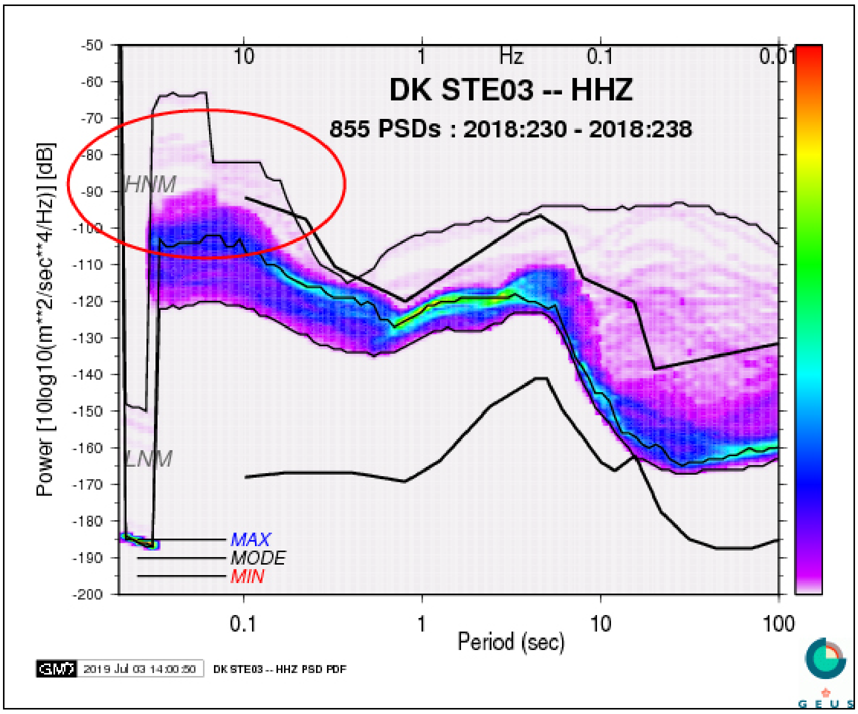

Figure 5. Noise analysis for vertical component of STE03, located 3.2 km from the main pumping station, August 17-25, 2018. The high-frequency noise bands (with red ellipse) from pumping are barely discernable, and the ones at the highest frequencies are no longer present.

To illustrate that the high-frequency noise is most likely connected to pumping, we compared this with a noise spectrum from a quiet period, here January 2019. STE00 is still noisy due to local activities at the pumping station, but the high-frequency noise bands are not present. STE01 has a noise spectrum very similar to STE03 with no obvious anthropogenic signature (figure 6-8).

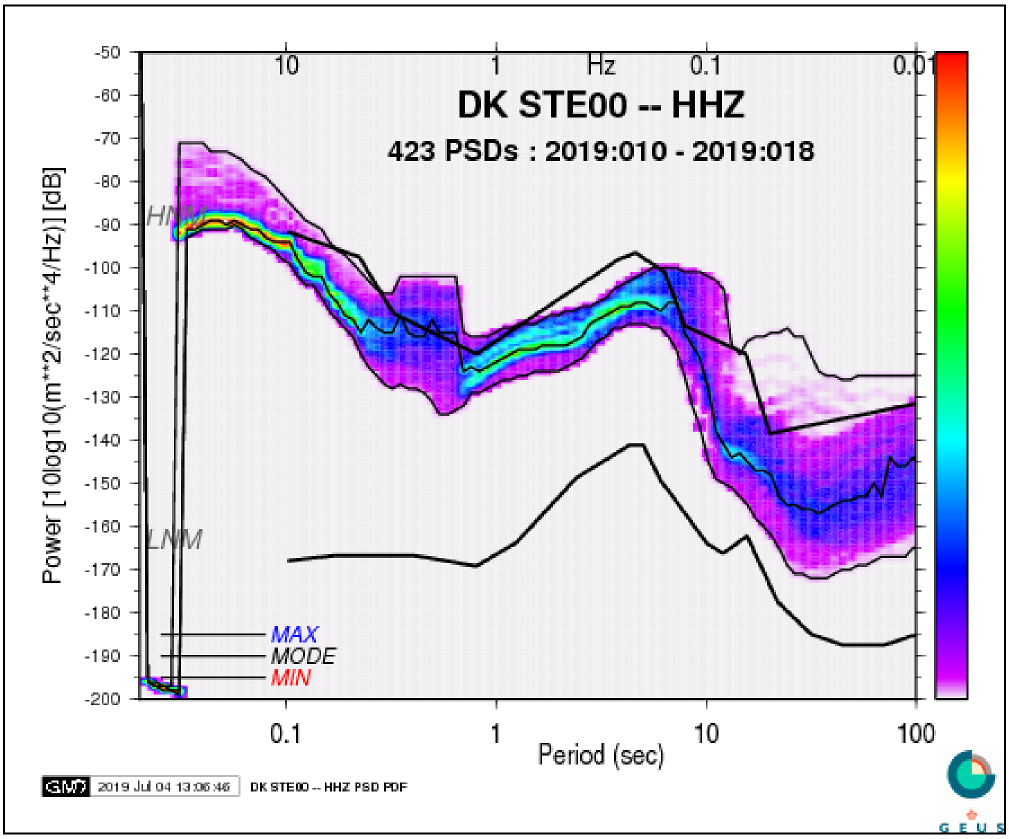

Figure 6. Noise analysis for the vertical component of STE00, located at the main pumping station, January 10-18, 2019. The previously observed bands of intense noise from the pumping in the high-frequency part of the spectrum are gone.

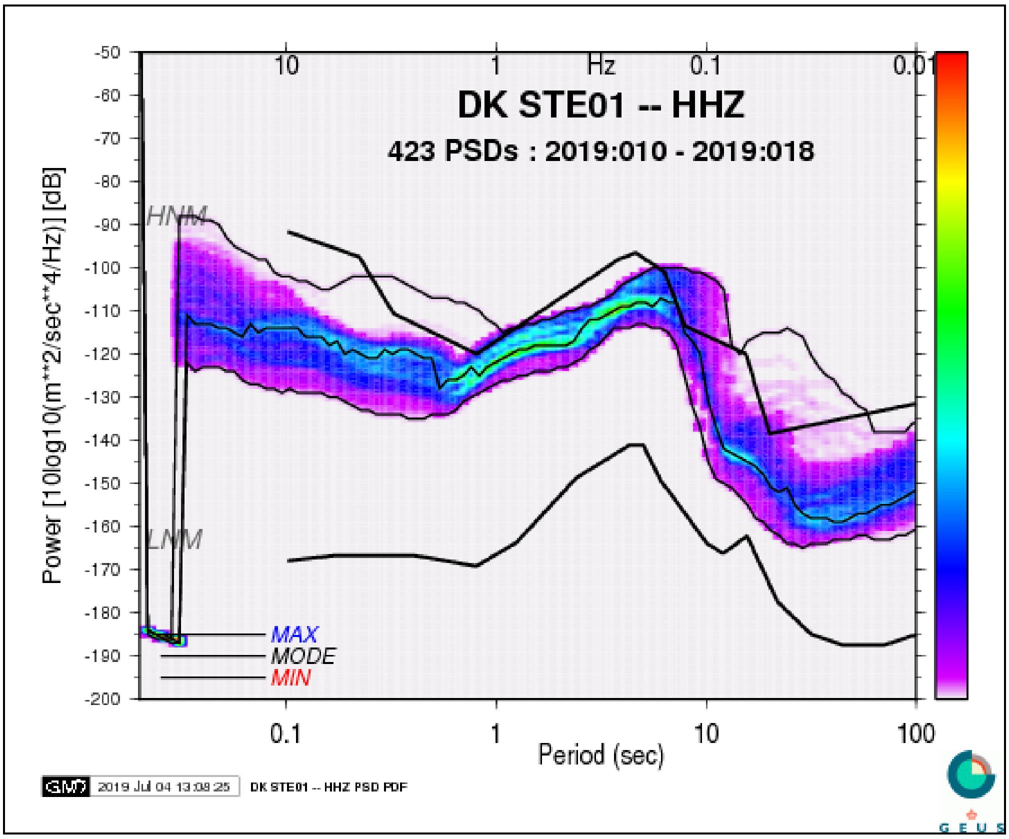

Figure 7. Noise analysis for the vertical component of STE01, located 1.3 km from the main pumping station, January 10-18, 2019. There are no high-frequency noise bands or other clear anthropogenic signals.

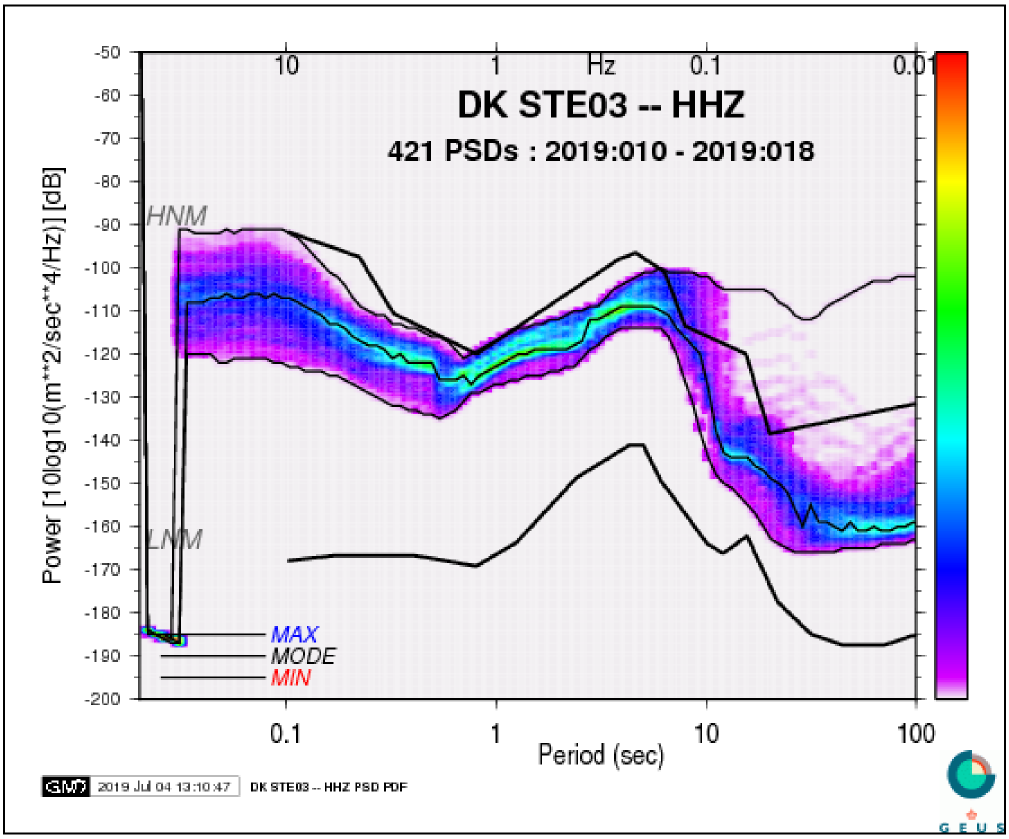

Figure 8. Noise analysis for the vertical component of STE03, located 3.2 km from the main pumping station, January 10-18, 2019. There are no high-frequency noise bands or other clear anthropogenic signals, and it looks very similar to the spectrum for STE01.

The high-frequency noise bands on STE00 (Figure 3) correlate very well with the pumping log provided by Energinet.dk (Energinet.dk is the operator the Stenlille gas storage facility) as illustrated by pumping data from Well ST8 in figure 9 (Energinet.dk, 2019).

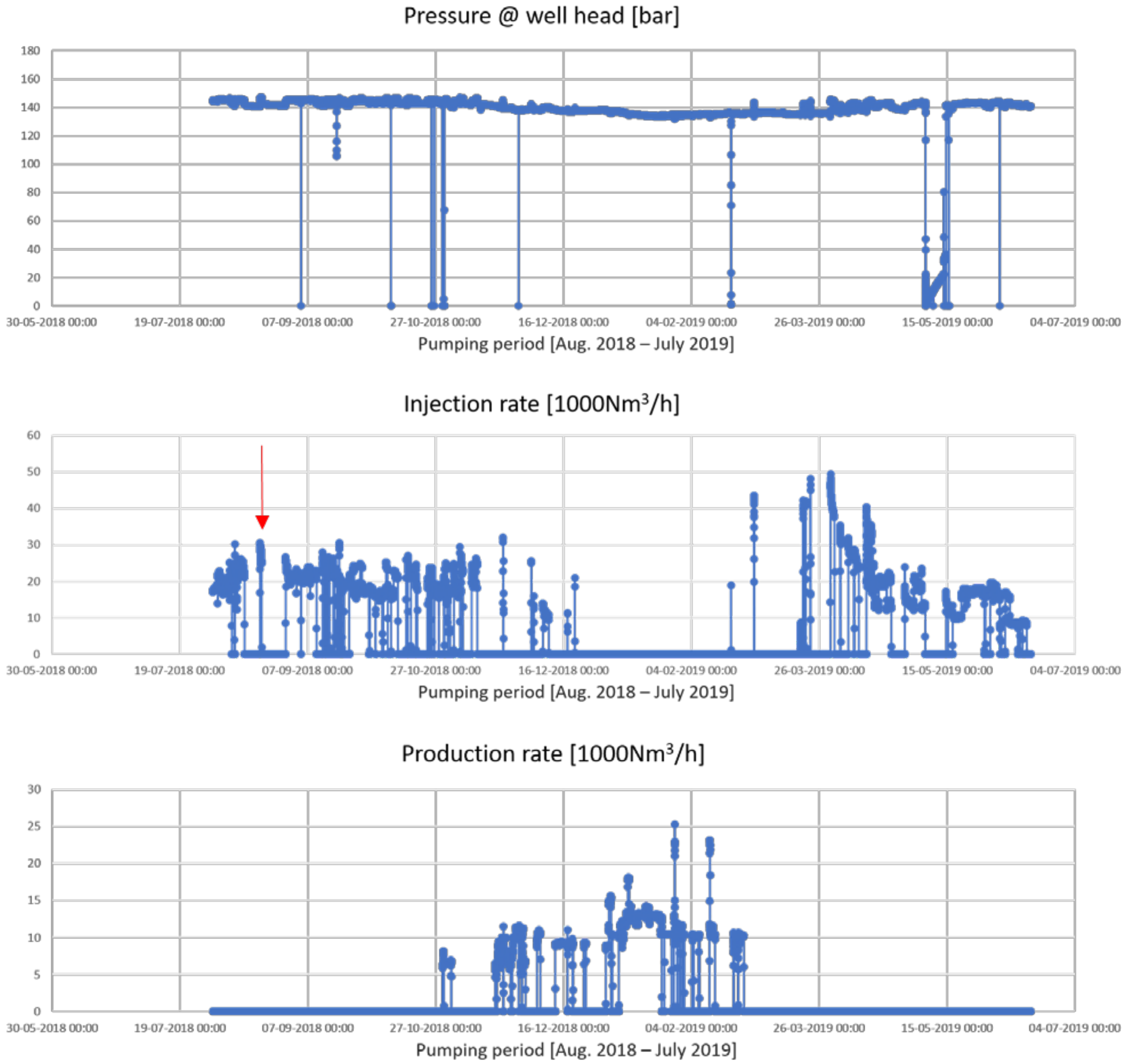

Figure 9. Pumping activity at well ST8 located in the centre of the gas storage. The plots show the pressure at the wellhead, the injected gas in 1000 Nm^3/h and produces gas in 1000 Nm^3/h. The time series covers a year, and show the injection taking place during the summer months and production during the winter months. The noise plot of STE00 (Figure 3) covers the time period julian days 230-238 (18-26/8-2018). During this time injection pumping was ongoing (red arrow in this figure).

3.2 EVENT SCREENING

The preliminary screening for local earthquakes on the data from the Stenlille site has not found any events near the Stenlille Gas Storage Facility. We have carried out targeted screening at periods with significant changes in pressure: April 2019 and a few days in October 2018. A more comprehensive analysis of the data is required.

Concluding remarks

- A microseismic monitoring network has been successfully deployed around the Stenlille Gas storage facility, Denmark. Data acquisition is still in progress, including the added experimental stations at distances from 10 – 100 km, and will continue until August 2020. Data analysis still in progress, and will continue.

- So far, we have learned that the natural background noise level is slightly better than the noise level at the monitoring network near Dybvad, Denmark, however during periods of injection and production, high frequency noise dominates at distances less than 3 km from main pump. To date, we have not seen any microseismicity at the Stenlille

A first analysis of the relevance of both case studies as basis for a broader approach towards post-operational seismic baseline monitoring will be provided in report D.3.2. This report will depict the state of the art of post-operational baseline assessment and the current best practices in this field as input to report D 3.5 (Report on state of the art and new developments for defining the seismic baseline for gas storage and exploitation). It will furthermore outline the planned field activities and data acquisition program till the end of the project.

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