DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/41**

Capture, Storage and Use of CO_2 (CCUS)

Seismology in relation to safe storage of CO_2 (Part of Work package 7 in the CCUS project)

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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO_2 capture technologies, (2) the potentials for both temporary and permanent storage of CO_2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO_2 usage potentials, including business case for converting CO_2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plant in Denmark.

The present report forms part of Work package 7 and focuses on natural and anthropogenic seismicity in relation to safe storage of CO_2.

Content

Dansk resume

Danmark ligger i et område med meget lav risiko fra jordskælv. Hvert år registrerer GEUS mange små jordskælv, som sjældent er større end 3 på Richterskalaen (*M* 3). Det største registrerede jordskælv i Danmark målte *M* 4.7 og havde sit epicenter i Kattegat i 1985. Større jordskælv har formodentlig ramt Danmark i historisk tid, men jordskælv større end ca. *M* 5.3 +/- 0.1 forventes ikke.

Aktiviteter i undergrunden kan føre til små jordskælv på grund af det ændrede tryk forårsaget af f.eks. udvinding af olie og gas, nedpumpning af vand til geotermi eller nedpumpning af gas med henblik på lagring. I forbindelse med injektion i undergrunden skelnes der mellem to typer menneskeskabte jordskælv: inducerede jordskælv og reaktiveringsjordskælv. Inducerede jordskælv er små rystelser, som opstår i nærheden af borehullet. Disse rystelser overstiger kun i sjældne tilfælde en størrelse på *M* 2. Reaktiveringsjordskælv kan i nogle tilfælde udløses når trykfronten rammer en forkastning. Hvis væske siver fra et reservoir ind i forkastningen og nedsætter friktionen, kan det også føre til reaktiveringsjordskælv. Det største kendte af denne type jordskælv målte *M* 5.7 og fandt sted i Oklahoma, USA i forbindelse med udvinding af skifergas. Der er ikke observeret større jordskælv i forbindelse med CO_2-lagringsprojekter på verdensplan. Derimod er de inducerede mikrojordskælv helt almindelige. Størrelsesmæssigt ligger de typisk mellem *M* -2 og *M* -0.5 på Richterskalaen, som er logaritmisk. Jordskælv skal være meget større, typisk mindst *M* +2, før de kan mærkes af lokalbefolkningen, og endnu større før der er risiko for skader. Ved hyppigt gentagne mikrojordskælv er der dog eksempler på at de bliver følt af befolkningen og er til gene. Overvågning af mikrojordskælv i forbindelse med et CO_2 deponeringsprojekt kan være meget nyttig i forhold til at fange eventuelle uregelmæssigheder på et tidligt stadium. Hvis antallet af mikrojordskælv pludselig stiger, eller deres størrelse pludselig vokser, kan det være tegn på, at trykket i undergrunden er for højt. Problemet kan hurtigt afhjælpes ved at reducere nedpumpningen eller eventuelt holde en pause. Når mængden og størrelsen på mikrojordskælvene igen falder til et lavt niveau, kan aktiviteterne langsomt starte op igen. Mikroseismisk overvågning af aktiviteterne i Stenlille Gaslager gennem næsten to år detekterede ingen jordskælv i selve reservoiret. Overvågningen blev gennemført med et lokalt overfladenetværk af seismografer og følsomheden var ned til en størrelse på *M* 0. Mere detaljeret overvågning af mikroseismicitet kræver brug af målinger i borehuller.

Summary

Denmark is located in a low-seismicity region. Although many earthquakes are detected every year, they rarely exceed a magnitude (*M*) of 3. The largest instrumentally recorded earthquake in Denmark measured *M* 4.7. In historical times at least one larger earthquake may have hit Denmark, but earthquakes lager than *M* 5.3 +/- 0.1 are not expected. Subsurface activities can lead to induced and/or triggered earthquakes. These are known particularly from hydrocarbon production, but also geothermal projects and CCUS around the world. While induced earthquakes occurring in the vicinity of a well seldom exceed *M* 2, triggered earthquakes up to *M* 5.7 have been observed in connection with shale gas fracturing in Oklahoma, USA. Triggered earthquakes happen when a fault is reactivated by either a propagating pressure front or leaking liquids. CO_2 is stored in porous rocks where the flow is through a matrix as opposed to shale gas production where hard rocks are fractured. The risk of larger earthquakes in connection with CCS is much smaller, something that is supported by observations from CCS-projects worldwide. The CCS induced earthquakes are typically between *M* -2 and *M* -0.5, several orders of magnitude smaller than anything that can be felt by the local population, and most likely posing no risk to the reservoir seal. Monitoring microseismicity is a useful mitigation and prevention tool. An increase in the number of microearthquakes or an increase in observed earthquake magnitude can be a sign that the injection is shifting from matrix flow to fracture flow. Changes in microseismicity is a first sign, and if observed, a temporary change in injection pressure can bring the seismicity down again. This can be regulated through a pre-defined Traffic Light System. Microseismic monitoring at the Stenlille Gas Storage Facility in Denmark for almost two years did not detect a single event within the reservoir using surface instruments with a sensitivity down to *M* 0. For microseismic monitoring, downhole instruments are more effective, but can be supplemented by a local surface monitoring network.

Introduction

According to Annex I of the Directive on the geological storage of carbon dioxide (EU, 2009), seismicity is one of the required data sets to be included in the evaluation. In the following we will deal with a) natural seismicity in Denmark – including natural seismic hazard in Denmark, b) induced and triggered seismicity in relation to stimulation projects worldwide, c) induced and triggered seismicity in CCS projects worldwide, and d) evaluation of the relevance for Denmark of the international experiences with stimulation projects. Furthermore e) state-of-the-art methods for monitoring microseismicity in and around a reservoir will be reviewed with emphasis on those relevant for Danish conditions, and f) mitigation based on microseismicity will be covered.

Induced and triggered seismicity can occur in connection with subsurface activities across a wide range of fields such as hydrocarbon production, gas storage, waste disposal and geothermal energy production. Induced earthquakes are micro-events occurring near injection wells, whereas triggered earthquakes are small to moderate events caused by stress changes on nearby faults (e.g. Ellsworth 2013). The occurrence of larger earthquakes in connection with operations must be prevented to avoid harm and expensive damage. Even smaller earthquakes can lead to public concern and resentment, as seen for example near the gas production fields in Groningen, the Netherlands (e.g., van Thienen-Visser and Breunese, 2015) where the local population is bothered by trembling from small earthquakes. Applying a microseismic monitoring and mitigation strategy can ensure early detection of undesired changes and the timely launch of preventive measures.

Natural seismicity in Denmark

Denmark is located far away from plate boundaries where most earthquakes occur. However, every year many small earthquakes are recorded in Denmark by GEUS as part of the seismological monitoring program. Most of these earthquakes are too small to be felt by anyone, but occasionally conditions allow the shaking to be felt by the local population within some tens of kilometers from the epicenter (e.g., Lehmann, 1956; Gregersen et al, 1998; Dahl-Jensen et al; 2013). The seismicity in Denmark is low compared to many other parts of the world, but historical records contain reports on earthquakes with larger impact, e.g. in 1759 where damage in the city of Aalborg was reported (e.g. Wood, 1988). As the driving forces for tectonic earthquakes operate on timescales of millions of years, it is important to supplement the short instrumentally recorded time series of less than 100 years by historical records in the evaluation of the natural seismic hazard. The primary cause of earthquakes in Denmark is stress build-up from the Mid Atlantic Ridge pushing the Eurasian plate from NW (Gregersen, 2002). Most of the earthquakes occur under Kattegat or Skagerrak, and in the Northern part of the North Sea. On land the most active localities are central Zealand and NW Jutland.

In 1930 the first Danish earthquake was recorded instrumentally (e.g. Lehmann, 1956). From there on the earthquake epicenters, depths and magnitudes are known. As the instrumentation through the years has become more advanced and sensitive, smaller earthquakes can be detected and located. The epicenter determination precision has also improved, especially since the change to digital data around year 2000.

Danish earthquakes occurring prior to 1930 are known only from historical accounts without any instrumentally recorded data to support the observations. Without instrumental data it is impossible to determine an accurate epicenter and magnitude. Instead of a calculated magnitude, older earthquakes are assigned values on the 12-step European Macroseismic Scale based on the Mercalli intensity Scale (Grünthal, 1998). The intensities can thereafter be used to estimate the location of the epicenter and the magnitude, but with large uncertainties. The steps on the scale define the earthquake intensity based on how the shaking was felt by eye witnesses and which effects the shaking had on nature and buildings.

It is important to emphasize that an earthquake’s intensity on the Macroseismic Scale is not the same as the earthquake magnitude. The magnitude is one number for each earthquake, calculated from the recorded amplitude and period of the shaking and related to the amount of energy released by the earthquake, whereas the earthquake intensity varies with the distance to the epicenter, and depends furthermore on earthquake depth and local geological conditions. First-hand reports on shaking and damage are also collected in the local communities for instrumentally recorded earthquakes and the resulting intensity maps provide a valuable link to historical earthquakes. By comparing reports from earthquakes affecting the same area, it is in some cases possible to assign an approximate epicenter and magnitude to a historical earthquake. When historical earthquakes are listed in tables, the maximum observed intensity is included.

Instrumentally recorded earthquakes

GEUS estimates that all onshore earthquakes in Denmark occurring since 1960 and having a magnitude of at least *M* 3.0 have been recorded instrumentally (Voss et al., 2015). During the last approximately 15 years, upgraded instrumentation and methods have improved the detection level and lowered the magnitude of completion to include all earthquakes with a magnitude of at least *M* 2.5. Many smaller earthquakes are also detected, and occasionally earthquakes with magnitudes less than *M* 1.0 are recorded. Detection of micro-earthquakes requires a denser, local seismograph network to supplement the national network.

The uncertainty on the calculated epicenters vary from earthquake to earthquake and depends on several parameters: Most important for the calculation are the number of seismographs with a clear signal, the quality of the phase readings, and the geographical distribution of the recordings relative to the epicenter. The better the azimuthal coverage from seismographs surrounding the epicenter, the smaller uncertainty. Proximity of seismographs to the event will typically yield a higher signal-to-noise ratio – depending on local noise conditions - thus reducing the uncertainty on the position. The quality of the velocity model also contributes to the total uncertainty.

Usually larger earthquakes are registered on more seismographs than the small ones, and their epicenters can be calculated with a smaller uncertainty. The uncertainty is in general larger on older earthquakes due to the instrumentation. The lateral uncertainty on the Danish earthquakes vary between a few km and 50 km. The uncertainty on the determined depth of the earthquakes is typically 10-20 km.

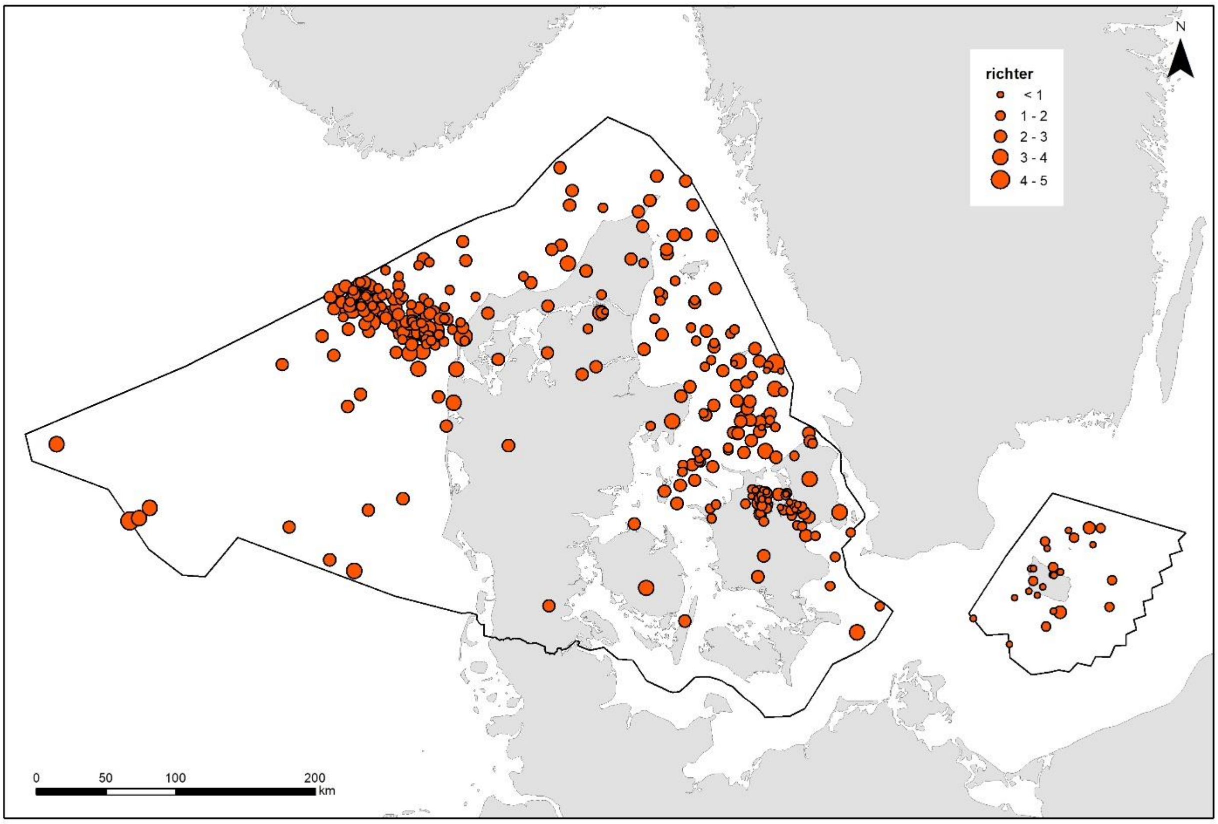

Figure 1: Earthquakes and potential earthquakes from 1930-10-01 to 2020-06-30, each registered on at least three seismographs.

The map in Fig. 1 contains all seismic events in Denmark from 1930-10-01 to 2020-06-30 registered on at least three seismographs. Known explosions are excluded. The database most likely still contains some explosions, particularly on the seabed. The seabed below the Danish territorial waters is littered with unexploded mines from World War II. As the mines pose a potential threat to fishery and other marine activities, the Danish Navy searches for the mines and destroy them by detonation, where they are found. The Navy regularly informs GEUS of these activities, but not consistently. In many cases a seismologist can discern an earthquake from an explosion just by inspecting the seismograms. In case of doubt the event is left in the database. The database is continuously updated and improved, whenever new information or new data become available. For studies in a specific locality the event lists extracted from the earthquake database can benefit from further in-depth analysis.

The strongest felt earthquakes in Denmark are listed in Table 1.

Year	Mth	Day	Latitude Deg	Longitude Deg	Depth km	ML	Max int.	Location	reference
1759	12	22	Unknown	Unknown	Unknown	Unknown, Estimated 5.4-5.6	VII	N Kattegat	(Wood 1988)
1841	04	03	Unknown	Unknown	Unknown	Unknown, estimated 4.5	VII	Offshore Thy	(Forchhammer 1841, 1869; Ambraseys 1985; Wood 1988)
1904	10	23	Unknown	Unknown	Unknown	Unknown, estimate 5.4	V	Olso Fjord	Harboe 1915; Lehmann 1956; Gregersen *et al.* 1998; Bungum *et al.* 2009)
1913	07	29	Unknown	Unknown	unknown	Unknown	V	West Jutland?	Harboe 1915; Lehmann 1956)
1929	05	23	57.18	6.61			III	North Sea	(Gregersen *et al.* 1998)
1930	10	31	55.50	12.70		4.5	IV	Copenhagen	“
1941	11	28					IV	Jutland	“
1954	06	04	55.40	12.60			III	Falsterbo	“
1954	10	18	56.82	8.26	44	4.6	III	Krik Vig	“
1969	04	05	57.13	7.04	33	4.3	V (VI?)	North Sea	“
1973	10	30	59.00	17.00	17		III	Skagerrak	“
1985	06	10	55.6	4.70	22.7	3.5	IV (offshore)	North Sea	“

1985	06	15	56.61	12.23	9	4.7	V (in SW Sweden)	Kattegat	“
1986	04	01	56.50	12.11	2.1	4.2	IV	Kattegat	“
1989	01	20	57.90	8.39	21.8	4.3	III	Skagerrak	“
1993	07	07	55.55	4.50	15	4.3	IV (off-shore)	North Sea	“
1995	10	04	56.75	12.16	26.4	4.1	IV (in Sweden)	Kattegat	“
1995	11	30	55.64	12.26	25	2.5	IV	Tåstrup	“
1996	12	17	55.574	12.879	13.4	2.7	IV	Skåne	(Voss et al., 2017)
1997	12	04	56.911	7.690	8.5	3.4	IV	North Sea	“
1998	07	08	57.203	8.423	15	3.4	IV	Ferring	“
2001	06	02	56.801	7.803	59.3	3.5	V	North Sea	“
2001	10	21	56.733	7.661	29.1	3.4	IV	North Sea	“
2001	11	06	55.677	11.701	19.7	2.8	VI	Holbæk	(Larsen *et al.* 2008)
2003	07	10	56.745	9.283	11.4	2.7	IV	Jutland	
2004	02	23	55.516	12.184	36.3	2.9	VI	Bay of Køge	
2004	09	21	54.82	19.96	10	5.2	V	Baltic Sea	
2008	12	16	55.5	13.6	9	4.8	VI	Skåne	(Voss *et al.* 2009)
2010	02	19	56.874	7.581	38.7	4.3	VI	North Sea	(Dahl-Jensen *et al.* 2013)
2012	08	06	56.600	11.948	22.1	4.1	VI	Kattegat	“
2014	08	15	54.924	15.013	21.6	2.6	-	Bornholm	
2017	03	02	56.130	12.311	28.3	2.7	II	Kattegat	GEUS
2018	09	16	56.421	8.189	42.6	3.6	-	Holstebro	GEUS

Table 1: The strongest felt earthquakes in Denmark. Modified from Voss et al (2015).

Pre-instrumental earthquakes

Earthquakes in Denmark prior to 1930 are known only from historical accounts. There are no instrumental recordings of these events, and it is therefore impossible to calculate an epicenter and a magnitude. In some cases, it is possible to assign an approximate epicenter and magnitude by comparing historical observations of earthquakes to recent well-described, instrumentally recorded events.

Historical accounts of earthquakes contain valuable information; however, it is necessary to read the reports with great care. Descriptions of earthquakes are sometimes mixed up with other natural phenomenon such as storm and thunder. On many old barometers the lowest pressures below “storm” are marked as ”earthquake”. The limited understanding of geophysical processes back in time often leave the neutral descriptions of the shaking contaminated by unreal interpretations and conclusions.

When encountering a credible description of shaking it is also necessary to seek information about the shaking beyond the Danish borders. In some cases, earthquakes elsewhere in Europe were felt in parts of Denmark. The most spectacular example was the devastating 1755 Lisbon earthquake that was clearly felt over much of Europe, including in Denmark (e.g. Voss et al., 2015). The strongest felt local earthquakes are listed in Table 2 below.

Earthquake hazard

To calculate the earthquake hazard it is necessary to include information on all known earthquakes to extend the time series as far back in time as possible. Several of the strongest felt earthquakes occurred before 1930 as seen in Table 1. A Swedish and a Norwegian earthquake have been included in the list as they were felt in Denmark and contribute to the picture of our regional seismicity.

The Gutenberg-Richter relationship (e.g., Gutenberg and Richter, 1956) is applied to extrapolate known seismicity to expected future seismicity. It describes the relationship between the number of earthquakes and their magnitude:

$\mathrm{Log}_{10}\mathrm{N} = \mathrm{a}-\mathrm{b}M$

where N is the number of events having a magnitude $\geq M$, and a and b are constants.

The b-value governing the relationship between the number of earthquakes and their magnitude is determined from the known seismicity, and it is an important parameter for extrapolating a time series for the number of larger earthquakes expected in a given region. A b-value of 1 is equivalent to a 10-fold increase in the number of earthquakes as the magnitude decreases by 1, e.g. if the time series contain 1000 earthquakes of magnitude 2, and 100 earthquakes of magnitude 3, then the equation would predict that 10 earthquakes of magnitude 4 could occur. This extrapolation is highly uncertain especially in low seismicity areas such as Denmark, as it is challenging to collect a sufficiently solid statistical material. Reducing the magnitude of completion is the only way to improve the data set, as it is not feasible to wait for decades or hundreds of years for more of the larger earthquakes. If we are able to register all earthquakes of magnitude 2, or even better all earthquakes of magnitude 1, the b-value can be determined more accurately. The b-value for Denmark was determined to 0.96 +/- 0.1 by Voss et al, 2015.

The probabilistic seismic hazard analysis carried out for Denmark (Voss et al, 2015) is based on the method initially developed by Cornell, 1968. The analysis is based on a number of assumptions and limitations. The analysis is only valid for onshore areas, and hazard due to liquefaction is not included. Standard values describing attenuation from normal faults in hard-rock conditions are taken from the global reference model by Spudich et al. 1997 as the ground motion prediction equations have not been determined specifically for Denmark. The estimated maximum magnitude of a natural earthquake in Denmark is *M* 5.3 +/- 0.1. This is based on the largest known earthquakes in the region, including historical earthquakes as well as regional information from Southern Norway, Southern Sweden and Kaliningrad (Voss et al., 2015).

The common way to quantify the earthquake hazard, is to calculate the probability of non-exceedance of peak ground acceleration values for a given return period. In plain words, the values on the map are peak ground accelerations [$\mathrm{cm/s^2}$] carrying a 90% probability not to be exceeded during a 50-year period. This measure can be calculated for time periods of other lengths.

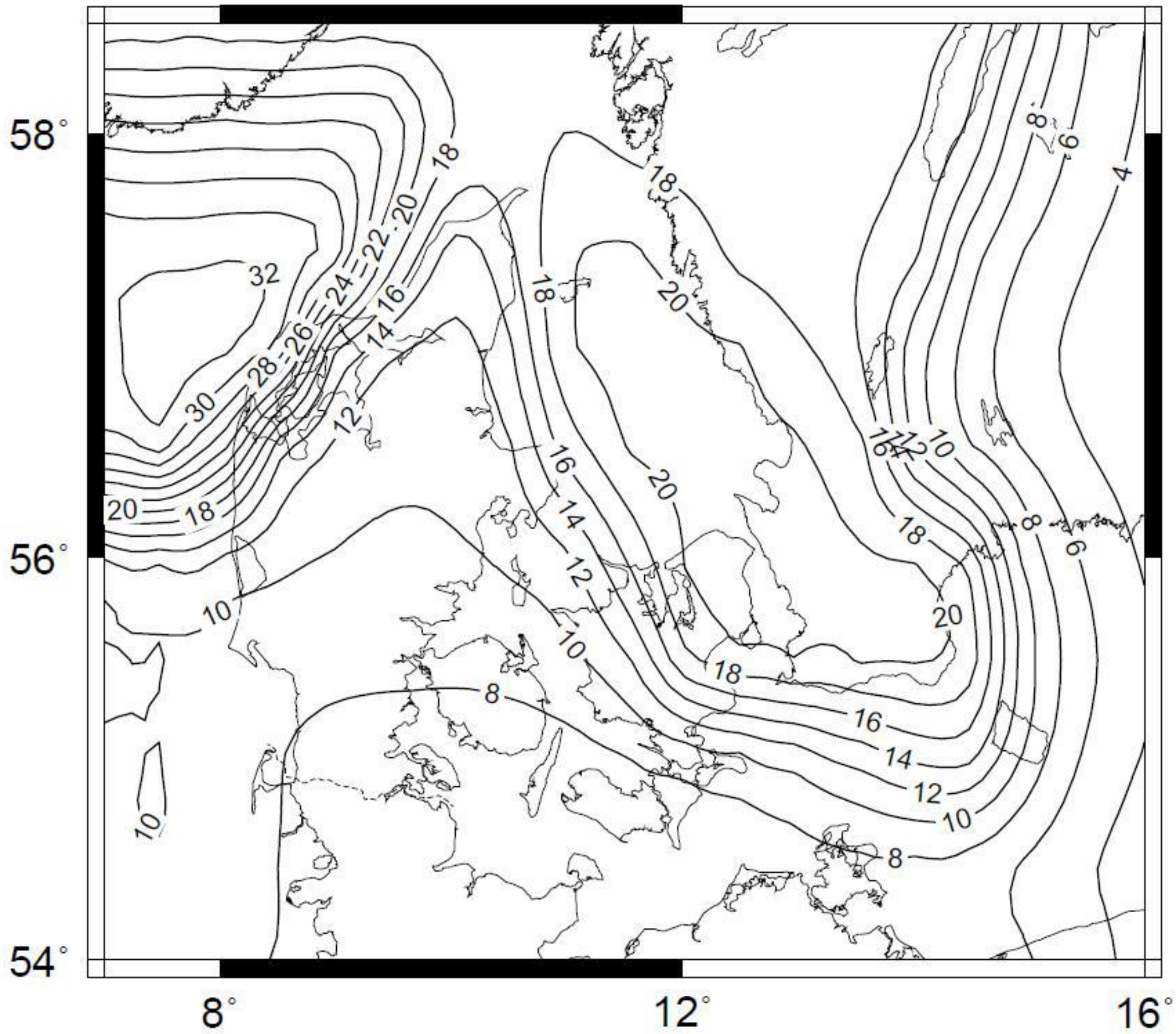

Figure 2: *The estimated hazard given by the peak ground accelerations [cm/s^2] for a return period of 475 years, which correspond to a 90% non-exceedance probability in 50 years. From Voss et al., 2015.*

The seismic hazard in Denmark is low on a global scale, however, large earthquakes sometimes occur unexpectedly even in areas with low seismicity.

Induced and triggered seismicity in relation to stimulation/production projects in other parts of the world

High pressure stimulation projects can cause earthquakes due to pressure changes and/or lubrication of faults. As the number of CCS projects is still limited on a global scale, it is relevant to draw on the experiences from other stimulation projects. The general stress reaction from the subsurface is expected to be similar under similar geological conditions.

Anthropogenic earthquakes are different from natural earthquakes and can be divided into two sub-classes: induced earthquakes and triggered earthquakes (e.g., Bommer et al., 2015). Earthquakes near a well during stimulation are called induced seismicity when natural causes can be ruled out. These events are typically micro-earthquakes with magnitudes less than *M* 2.0, and in some projects micro-earthquakes with magnitudes down to -2.0 have been detected (e.g. Goertz-Allmann et al, 2014, Kaven et al., 2014). Especially under hard rock conditions induced earthquakes can be larger as seen e.g. in the deep geothermal project in Basel where induced earthquakes of *M* 2.7 and *M* 3.4 occurred as a consequence of the water injection (Deichmann and Giardini, 2009).

Triggered earthquakes are caused by stress changes on a favorably oriented fault and can be stimulated by a propagating pressure front and/or leakage from the well or reservoir. This type of events is closer to natural earthquakes as it involves slip on a fault, and in these cases, it can be hard to discern if an event is natural or anthropogenic. The events can be quite large, and it has been seen than injection can re-activate a fault with no previously recorded activity (e.g., Keranen et al., 2014).

Oklahoma, USA, experienced a 40-fold increase in seismicity during the period 2008-2013 (Keranen et al., 2014), most likely caused by high-rate wastewater injection in connection with unconventional oil and gas production. Well-located earthquakes and earthquake swarms can illuminate known faults and map out new ones as seen in Oklahoma. The triggered earthquakes are suggested to be caused by the propagating pressure front encountering critically stressed faults on its way. The resulting seismicity was traced up to 35 km from the wells (Keranen et al., 2014). The largest injection related earthquakes occurred in November 2011 in Oklahoma approximately 180 km from the nearest known active fault and measured *M* 5.0, *M* 5.7, and *M* 5.0. Analysis of the aftershocks illuminated the active faults and found that the tip of the initial rupture plane was within 200 m of an active injection well (Keranen et al., 2013). The study also suggests that the stress changes caused by the first earthquake in the sequence, triggered the following earthquakes, something that is collaborated by a later study by Norbeck and Horne (2016). In 2016 another earthquake sequence struck Fairview, Oklahoma 12-20 km from high-rate injection wells, with the largest event measuring *M* 5.1 (e.g., Yeck et al, 2016). It is important to point out that the large earthquakes occurred in low porosity, hard rocks, very different from the geology under consideration in Denmark.

The large onshore gas fields exploited in Groeningen in the northern part of The Netherlands has generated numerous low-magnitude, shallow earthquakes (e.g. van Eck et al, 2006). Most of the events are small with *M*<3.0, but a few events have been larger, nonetheless still *M*<4.0

(Spetzler and Dost, 2017). The earthquakes are primarily located in the reservoir and the lower part of the overburden (e.g., Smith et al, 2020), posing no risk to the reservoir seal. As the events are very shallow, the shaking has caused minor building damage and nuisance for the local population, leading to a reduction of the gas exploitation Thienen-Visser and Breunese, 2015.

Induced and triggered seismicity in CCS projects worldwide

CCS is an emerging technology and the experiences with large-scale injection of CO_2 are limited. While induced and triggered seismicity are well-known and documented from the oil and gas, in particular from shale gas fracturing e.g. (Ellsworth, 2013), as well as from geothermal energy projects e.g. (Deichmann and Giardini, 2009), there are still uncertainties related to how the subsurface will respond to large-scale CO_2injection. The larger events known from shale gas and hard rock geothermal projects are not foreseen and not known from existing CCS projects, as CO_2 is injected into porous rocks, resulting in lower pressure increases. Certain elements are expected to be the same across injection projects. The injection will generate a propagating pressure front, and the increased pore pressure can result in an exceedance of fracture pressure in the material. Whether fracturing will happen or not depends on material- and injection parameters. Important controlling factors are well-head pressure, porosity, permeability, viscosity and matrix strength.

The In Salah CO_2 storage project in Algeria is well studied. At industrial scale, CO_2 is injected horizontally into an approximately 20 m thick Carboniferous reservoir at 1.9 km depth (e.g. Goertz-Allmann et al, 2014). Microseismicity is measured using a 1D array of geophones installed in a borehole. More than 1500 microseismic events were detected over a three-year period by Oye et al., 2013, and Goertz-Allmann et al, 2014 were able to increase the detections on the same data set to more than 5000 events using a master event cross-correlation method. Most magnitudes are below M 1, and thus far below anything than can be felt by the local population.

According to Goertz-Allmann et al., 2014 the In Salah microseismic events fall into four clusters, three of which correlate directly with injection rates and well-head pressures. The last cluster is located at shallower depths and the events have different characteristics, resembling natural seismicity. As the cluster is located at the end of a pre-existing fault zone, triggered seismicity from fault re-activation is suspected. A possible trigger mechanism is the general uplift and deformation of the region (Goertz-Allmann et al., 2014), and ground motion monitoring seem to support the fault re-activation hypothesis (e.g., Rinaldi and Rutqvist, 2013).

At the French CCS project in Lacq-Rousse, more than 600 microearthquakes were detected and located within the reservoir between 2011 and 2014 (Payre et al., 2014). The events range in magnitude between M 2.3 and M -0.5. The study concluded that the induced seismicity did not pose any risk to the reservoir integrity.

Microseismic monitoring at the Decatur, Illinois, USA CCS-project found induced seismicity ranging in magnitude from M -1.52 to M 1.07. The microseismic events were primarily located in the basement below the reservoir and posed no risk to the integrity of the seal (Kaven et al., 2014). Pre-injection baseline monitoring was carried out for a year and a half preceding the injection to establish the natural background seismicity. Eight microseismic events with magnitudes around M -2.0 were detected in addition to drilling noise and regional events (Smith and Jaques, 2016).

In another study from Weyburn, Canada, Verdon (2016) analyse data from microseismic monitoring to assess the likelihood of inducing larger events. Verdon et al., 2011 had previously shown through modelling that events in the overburden can be caused by stress transfer. The 2016 study uses Gutenberg-Richter b-values in combination with time series of events and injection/production logs to conclude, that the activities at Weyburn are unlike to induce larger events. The microseismic events range in magnitude from *M* -3 to *M* -0.5.

Evaluation of the relevance for Denmark of the international experiences with stimulation projects

Larger induced and triggered earthquakes are known from high-rate injections into hard rocks as seen e.g. in Oklahoma and Basel. This is fundamentally different from a CO_2 sequestering project in Denmark. In a Danish context it is more relevant to draw on experiences with more porous rocks where matrix flow, not fracturing is the intention.

The Dutch experiences with gas exploitation from the sandstone reservoirs in Groningen are more applicable, with the reservation that the subsurface may react differently to injection than to production. Production from Groningen has been ongoing since 1960 (e.g. van Eck et al., 2006) and many induced earthquakes have been recorded, however most of them with $M<3$ and none of them with $M>4$ (Spetzler and Dost, 2017). Damages have been limited to cracks in masonry.

In a laboratory experiment Samuelson & Spiers (2012) tested if fault frictional strength and slip stability would be affected by injection of CO_2 using sandstones and caprocks from the Netherlands sector of the North Sea. The injection was carried out under a variety of conditions, and the study concluded that the reservoir faults would behave aseismically in all cases.

CO_2 sequestering projects in porous rocks, as carried out in The Decatur project, USA; In Salah, Algeria and Laq-Rousse, France are all highly relevant for Danish conditions. Algeria stands out in the sense that the country, in contrast to Denmark, has large, active fault zones, occasionally generating large, natural earthquakes. It is therefore not surprising that the In Salah-project seemed to reactivate a fault zone (Goertz-Allmann et al., 2014). Something similar was not seen at Decatur and Lacq-Rousse. It is therefore expected that CO_2 injection in Denmark will lead to induced microseismicity, but larger triggered earthquakes are less likely.

Review of State-of-the-art methods for monitoring microseismicity in and around a reservoir with emphasis on those relevant for Danish conditions.

The background seismicity at a potential storage site should be established prior to drilling and injection through a baseline monitoring program. Measuring microseismicity at undisturbed conditions is the most effective tool for later identifying changes in seismicity that may need attention. In some cases it is not possible to measure a microseismic baseline ahead of all other activities, and in those cases it may be necessary to deal with drilling noise (e.g., Smith and Jaques, 2016) or even operational activities (Larsen et al., 2019).

To establish a microseismic baseline, a local network of seismographs is deployed in and around the potential storage site for a few years or even longer (Schoenball et al., 2015, Wilson et al., 2015). During operations statistical methods are used to compare the microseismic activity to the level of background seismicity established pre-operational. If an increase in seismic activity is detected, the higher level is assumed to result from operational activities (Ellsworth, 2013, Grigoli et al., 2017). Ideally the baseline monitoring network should have the same sensitivity to microseismic events as the monitoring network during operations (Dahl-Jensen et al., 2020a). This will reduce the risk of underestimating the level of natural seismicity.

In reality measuring microseismicity at operational sensitivity, ahead of all activities, can be a challenge as downhole instruments are more appropriate than surface instruments for detecting microseismic events with magnitudes well below *M* 0. An array of three-component geophones in one or more wells is commonly used. This was done at In Salah (Oye et al., 2013; Goertz-Allmann et al., 2014) at Weyburn (Verdon et al., 2011), Decatur (e.g. Kaven et al., 2015; Will et al., 2016; Ringrose et al., 2017), and at Lacq-Rousse (e.g. Payre et al., 2014). Kaven et al., 2015 obtained good results at Decatur using primarily surface seismographs combined with a few borehole instruments. However, this network did not recorded events smaller than magnitude *M* -0.5.

Vertical geophone arrays in deep boreholes constitute a proven technology for monitoring microseismicity. However, it is also a technology ridden by problems. Most of the In Salah events are recorded on just one functioning geophone (Goertz-Allmann et al., 2014).

Grandi et al. (2017) test the use of Distributed Acoustic Sensing (DAS) in the depleted Goldeneye gas field in the North Sea, UK sector. DAS is an emerging technology for measuring microseismicity. The fiber optic cables provide high-resolution spatial recordings of events along the entire length of the cable, not just at a few distinct depths where geophones are placed. There are, however, still challenges associated with DAS as the cable is only able to register waves propagating along the length of the cable, not perpendicular. This can be overcome by curling the cable for better detecting events within the reservoir.

GEUS has conducted microseismic monitoring for Total around the Dybvad drilling site, and around the Stenlille Gas Storage site during the H2020 project SECURe. At Dybvad GEUS established a pre-operational baseline in the Gassum Formation using 6 surface seismographs for a period of 21 months from 2014 to 2015. The seismographs were placed at distances between 1 km and 5 km from the test well location. The recorded noise level on the individual seismographs was significantly higher than the noise level on the instruments in the national seismograph network due to local geological conditions. The baseline network did not detect any local events within 10 km of the test drilling site. The closest event was a small earthquake with a Magnitude of *M* 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 (Denmark or border region), 48 regional events and 212 distant events.

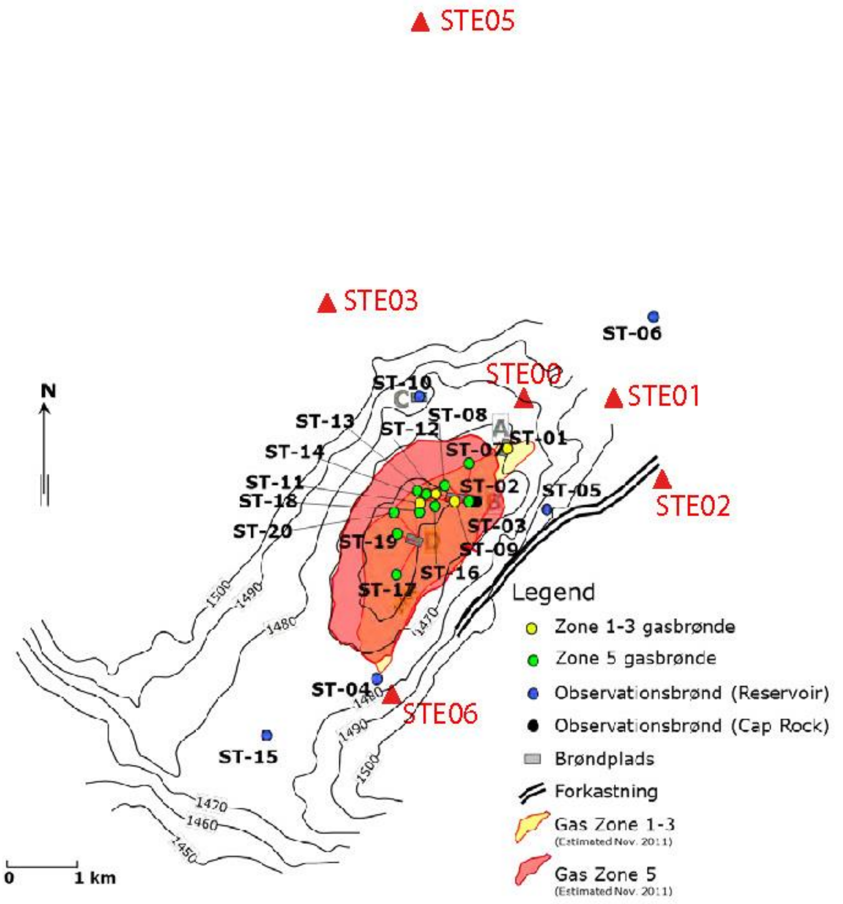

Figure 3: Laier/ Dahl-Jensen

During the period August to September 2018 GEUS established a microseismic monitoring network on the Gassum Formation around the Stenlille gas storage facility (Figure 3). The network consists of 6 seismographs placed within 5 km of the main pumping facility. The noise level on the seismographs is fairly good and 32 locatable events were detected by the network during the period 2018-10-01 to 2020-03-31. The local events range in magnitude from *M* -0.2 to *M* 2.5 and none of them are within the Stenlille Gas Storage Area (Dahl-Jensen et al., 2020b).

Mitigation based on seismicity

Microseismic activity near a production site can act as a state-of-health indicator for the subsurface, where a rising level of microseismic activity can be a sign of stress perturbations or pore pressure changes (Ellsworth, 2013). Comparing microseismic activity during operation to the background seismicity measured during a baseline study is a commonly used prevention and mitigation tool, also known as the Traffic Light System, TLS, e.g. (Cherry et al., 2014; De Pater and Baisch, 2011; Koppelman et al., 2012). A TLS consists of three levels: green, yellow, and red. At the green level the microseismicity is at a pre-defined acceptable level. At the yellow level either the number of events or the magnitude of the largest events exceed a level where caution should be taken, typically by reducing the injection pressure, or even making a temporary halt until the microseismicity is back at an acceptable level. If the red level is reached, all activities should stop immediately and not be resumed until microseismicity is back at the green level. The red level for seismicity should be defined well below any danger level and below the magnitude level that might be felt by the local population.

At In Salah injection was temporarily suspended when the daily number of microseismic events exceeded 20 – 40 (Oye et al., 2013). This halt caused the number of events to fall significantly. Goertz-Allmann et al., 2014 use microseismicity to distinguish between periods of matrix injection and periods of fracture flow injection, the latter being characterized by a sudden increase in microseismic activity. Real-time monitoring of microseismicity can be used to monitor and guide injection, raising a flag when the reservoir fracture pressure is exceeded. This tool can also help mitigate the risk of inducing felt seismicity bothering the local population, and ultimately reduce the risk of compromising seal integrity. Analysis of shear wave splitting in the microseismicity can reveal formation fracturing through the occurrence of seismic anisotropy (e.g., Goertz-Allmann et al., 2014, Verdon et al., 2011).

It is important to point out that seismic monitoring cannot serve as the sole monitoring technology. It should be part of a larger monitoring plan encompassing other geophysical, geological and geochemical technologies as outlined in (European_Communities, 2009).

Suggestions for supplementary investigations

Drawing on the international experiences and on GEUS' knowledge of the Danish seismicity and the Danish earthquake database, three tasks need attention in the next stage of a CCUS project:

- In-depth analysis of all seismic events in the GEUS earthquake database near the locations of interest. The purpose is to eliminate explosions that may potentially still be in the database
- Relocation of all earthquakes near the locations of interest using a local velocity model and cutting-edge methods. The purpose is to reduce the uncertainty on the epicentres and depths.
- Establishing a microseismic baseline in the area of interest. The purpose is to have an undisturbed baseline for comparison with operational activities.

Establishing a baseline can be done simultaneously with the suggested earthquake analysis.

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