

Scientific evaluation of programme area 3

Energy resources (2010-2016) at the Geological Survey of Denmark and Greenland (GEUS)

Niels Balling, Sissel Eriksen, Helle H. Midtgaard,
Rolf Mjelde, Lars Nielsen & Chris Parry



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1. THE EVALUATION PROCESS

1.1 Introduction

The evaluation panel consists of:

Professor Lars Nielsen, Dept. of Geoscience and Natural Resources Management, University of Copenhagen, Denmark (Chair)

Associate Professor Niels Balling, Dept. of Earth Science, Aarhus University, Denmark

Director Exploration Sissel Eriksen, Norwegian Petroleum Directorate

Principal Geologist Helle H. Midtgaard, DONG Energy, Denmark

Professor Rolf Mjelde, Dept. of Earth Science, University of Bergen, Norway

Exploration Advisor Chris Parry, Regional and New Ventures Exploration, GER X, Norway

This panel has undertaken an evaluation of research and dissemination activities to identify strengths, gaps and needs for amendments and improvements in relation to GEUS' strategy and mission within the GEUS Programme Area 'Energy Resources'. The evaluation concerns the period 2010-2016.

The panel has made its evaluation on the basis of:

- Publications, reports and other relevant material produced over the period 2010-2016, both years included,
- Presentations given by GEUS scientists, and
- Interviews with GEUS' management staff and scientists, and visits to laboratories and work facilities at GEUS.

Specifically, the panel has sought to:

- Identify areas of high quality research,
- Identify areas where the research of GEUS should be strengthened in order to meet GEUS strategy, and
- Provide comments and suggestions as to strategic changes, amendments, and improvements to GEUS' work within the programme area, in order to improve GEUS' ability to fulfil its main mission within this programme area seen in the perspective of the survey's statutes and general mission.

1.2 The context for research at GEUS

GEUS is a research institution with a focus on "*geological consultancy to public authorities on matters relating to nature, the environment, energy and mineral resources and takes part in carrying out activities for authorities in these areas*", and "*must also carry out mapping, monitoring, data collection, data management and communication about these mat-*

ters.”¹ Furthermore, GEUS “*is a national geological data centre, and ... makes data and knowledge available to authorities, educational institutions, enterprises, individuals, etc.*” These national responsibilities constitute a framework for GEUS’s scientific focus areas and for specific research activities.

In this report, the GEUS Programme Area ‘Energy Resources’ is divided into five topics that - according to the outline – are the focus for GEUS in this programme area:

- Petroleum geology North Sea;
- Petroleum geology Greenland;
- Regional geology and tectonics in the North Atlantic and Arctic Ocean;
- Green energy (geothermal energy, CCS, heat storage), and
- Other topics (seismology, South-East Asia, recent processes, laboratories, shale gas etc.)

Main findings and highlights of the individual focus areas were presented to the evaluation panel through 14 oral presentations each of 15-minute duration given by members of management team, senior scientists, senior advisors and a postdoc on the first day of the evaluation process. Furthermore, a bibliometric analysis was presented.

This round of presentations was followed by 10 short (5-minute long) oral presentations on day two of the evaluation process given by scientists, senior scientists, and PhD students. The oral presentations were followed by ~20-minute long visits in four different laboratories located at GEUS.

All oral presentations were very well organized, clearly presented with high-quality illustrations and contained clearly formulated conclusions as well as outlooks/perspectives/ideas for future activities. Moreover, the presenters responded precisely and clearly to questions asked by the panel members. Based on these oral presentations and the written material supplied by GEUS, the evaluation panel invited six different scientists (two senior scientists, one scientist, one PhD student, and two from the leadership) for additional interviews (20 minutes for each) on day three of the evaluation process.

The oral presentations, the introduction to laboratory facilities, the written material produced by GEUS, and the interviews of selected individual constitute the platform for the evaluation made by the panel.

Below, first a short summary of the main findings is given followed by specific evaluations of the different focus areas of GEUS’ ‘Energy Resources’ programme area. For each of the topics, the written assessment is concerned with research activities and quality as well as specific recommendations. At the end of the evaluation, a list of general recommendations is provided. Together with the specific recommendations for each section, this more general list is considered essential to consider during a process aimed at further strengthening the research profile, the research quality, and the research output of GEUS.

¹ Act no. 536 of 6 June 2007

1.3 Summary

GEUS is a strong geological survey, and GEUS rests on a solid research profile developed over many years. GEUS excels in collection of massive amounts of data from a variety of geoscientific and related fields, maintenance of these large databases, and making these datasets available to society. This is considered a key element for a geological survey of high international standard. Moreover, such large databases constitute a prerequisite for excellent research to be conducted, and, thus, GEUS is considered a potential central partner in a variety of geoscientific research fields. In this context, GEUS has acted and still acts as project leader in a number of large-scale national and international research projects with potentially high impact.

While the evaluation panel recognizes GEUS' strongholds in several disciplines relevant for the 'Energy Resources' programme area, the panel also formulates a list of specific and general recommendations that it considers essential for GEUS to consider. A key recommendation concerns documentation and dissemination of research activities. While GEUS publishes at an excellent or good rate in some research fields, the number of publications is more limited in other areas. Lack of publication of research results is a threat to GEUS, if it becomes a characteristic over longer time intervals, as it will cause erosion of GEUS' research profile. As a consequence, this may lead to less research collaboration with external partners, difficulties in obtaining research funding, and less consultancy jobs for both the private and public sectors in the future. To this end, GEUS is also recommended to develop a careful and ambitious recruitment plan that covers a range of departments. In this context, the panel finds that GEUS has excellent possibilities as a broad selection of both young and senior staff members with different profiles and backgrounds consistently express that GEUS is a good work place, which they also would like to be part of and develop in the future.

2. DETAILED EVALUATION OF ACTIVITIES

2.1 Petroleum geology North Sea

2.1.1 *Research activities and quality*

Three major projects have been carried out within the area of the North Sea Petroleum Geology: **PETSYS** covering the Jurassic Petroleum system in the Central Graben area, **CRETSYS** covers the Cretaceous petroleum system in Central Graben, and **CEN-SYS/UpCENSYS** covers the petroleum system in the Cenozoic in the Danish North Sea basin.

PETSYS

The PETSYS project (2012-2014) was initiated based on encouragement from the Danish Energy Agency and the North Sea Fund supporting the “Government Energy Strategy”. It was established as a multiclient study with 11 participating companies. The project comprises a compilation of all data from deep exploration wells drilled into the Jurassic sequences.

The main outcome is a revised and updated stratigraphic framework and seismic mapping of key stratigraphic intervals for structural analysis of the Danish Central Graben Area. Included is also petro-physical evaluation of all wells, log facies analysis, core descriptions, petrography and diagenesis, and provenance studies. Regional paleo-geographic maps were constructed to illustrate the dynamic depositional history during the Jurassic time period. Based on the mapping and modelling, a synthesis on the petroleum system and play concept is presented. A total of 45,000 man hours were used over 3 years in the project in the period 2011-2014, including 5-6 key persons but in periods involving up to 70 persons in total. The project resulted in a very good database with QC'ed data presented in a consistent and easily accessible way. It is recognized that the biostratigraphic work is of high quality due to contributions from the laboratory with a very experienced group of palynologists. A confidentiality period of 3 years ends summer 2017 and GEUS expects that several papers will be published based on the main findings of the PETSYS project.

The established database supports the GEUS mission of being a geological data centre, and to make the data easily accessible to the public. This ensures that data are utilized for hydrocarbon exploration and exploitation in the Danish North Sea area. The project was available to and used by some companies participating in the 7th Danish licensing round, thus fulfilling the Governmental energy strategy.

Due to the heavy work load in compiling such a large amount of data into a database, the number of publications resulting from the project may not reach the number that would be expected considering the many years of scientific work going into the project. Also, it seems to be a challenge to get enough time to scrutinize the data and identify the relationship between the structural evolution, paleogeography and factors controlling for instance source rock quality, sediment distribution and reservoir quality.

CENSYS/UpCENSYS

CENSYS (2014-2015) and **UpCENSYS** (2016-2017) are multiclient studies with so far 5 companies participating. The purpose is to establish a detailed stratigraphic framework of the Paleogene and Neogene time periods based on seismic data, biostratigraphy, well logs, sedimentology, and sequence stratigraphy. An example of a new biostratigraphic interpretation changing the stratigraphic boundary ~1000 m in one well clearly illustrated the value of reviewing the biostratigraphic data as basis for an updated biostratigraphic framework.

In addition to mapping of the hydrocarbon shows within the new structural-stratigraphic framework other parameters have been interpreted including: Sea level change, climatic change and tectonic influence and impact on siliciclastic depositional systems; source to sink studies; influence from climatic change on microfossil assemblages. Three themes for publications have been identified and should be prepared such that they can be published once the confidentiality period expires (2016 / 2019).

CRETSYS

The CRETSYS project (2015-2017) is a multiclient study with so far 6 companies participating and to be finalized within the next year. As for the PETSYS project, the key objectives are to establish a well constrained seismic-stratigraphic framework for the Cretaceous and Danian time periods as basis for regional understanding of paleogeographical and structural evolution. Detailed information on sedimentology and reservoir characteristics and hydrocarbon migration is included. Based on the findings a synthesis on the Cretaceous prospectivity and hydrocarbon plays will be presented. Results will be integrated with results from the PETSYS and CENSYS studies, thus providing a good basis for unravelling the regional Jurassic – Cenozoic structural and stratigraphic development in the Danish Central Graben area. Further, there is a potential for detailed paleoecological studies and interpretation of the late Ryazanian “basin flushing” event at the Farsund – Valhal formations boundary. As a confidentiality period extends until end of 2020 results cannot be published immediately after finalizing the project. However, papers should be prepared either as part of the project or immediately after to ensure scientists involved are available, and to ensure that publications can be submitted by the end of 2020 at expiration of confidentiality period.

All of the North Sea Petroleum Geology projects have benefitted from support from the Palynology Laboratory and Organic Geochemistry Laboratory services for high quality analysis.

The Core Laboratory has excellent facilities and very experienced staff for reservoir studies. Joint studies are made with GEO (former Danish Geotechnical Institute) and Danish Hydrocarbon Research and Technology Centre (DHRTC), and the Core Laboratory has experience with integration of rock mechanics and special core analysis, especially for chalk reservoirs.

2.1.2 Recommendations

Based on the observed research activities, we recommend the following:

- As part of planning major projects, time should be planned also for publication of results to ensure that staff is not transferred to new projects immediately after delivering the report, alternatively part of the deliverables might be agreed to be as publications.
- Time should be spent to further analyse the data generated in the PETSYS multi-client studies. Also, time should be allocated to integrate the PETSYS, CRETSYS and CENSYS project results in order to make an integrated analysis and investigate the dynamics of basin development and formation of good reservoirs. This might reveal not yet identified geological causal relation and/or feed-back mechanisms, thus improving the scientific significance of the studies.
- In the Department of Stratigraphy studies are made on recent sedimentary processes, and emphasis should be put on linking onshore-offshore studies, as onshore studies provides very detailed models that can be used as analogs for off-shore reservoirs.
- Succession planning of biostratigraphic experts in order to maintain a high activity level and to ensure competences are being developed and kept at a high level in the laboratory.
- In general, succession planning for the prioritized areas and laboratories should be made and it is recognized that there is a good potential with many young and skilled researchers active at GEUS.
- Definition of a new multiclient study covering areas outside the Central Graben area should be considered as this area is highly underexplored in the pre-Paleogene sections.
- The regional multiclient studies in the Central Graben area should be followed up by detailed reservoir studies integrating seismic and quantitative geophysical modelling, reservoir sedimentology and biostratigraphy.
- Ensure competences and expertise are continuously developed in cooperation with both private companies and research institutions in order to ensure that GEUS has the capability of being a technically highly competent advisor to the authorities in matters regarding hydrocarbon exploration and exploitation in Denmark and Greenland.
- It should be considered to expand the Core Laboratory facilities to enable experiments at reservoir conditions for future fields producing from HPHT reservoirs in the Danish North Sea.

2.2 Petroleum geology Greenland

2.2.1 Research activities

Two presentations related to the exploration activities and general geoscientific studies by GEUS on Greenland were communicated to the panel. The first dealt with the activities in Northeast Greenland in support of the first two license rounds in 2013 and 2014. The second related to Baffin Bay/Southwest Greenland, incorporating the results of industry drilling campaign in 2010/2011 and covering activities over the period 2013 to 2015, in support of licence rounds in 2010 and 2012, and for future rounds in 2017 and 2018. Activity has primarily focused on Northeast Greenland in support of a joint GEUS–industry collaboration, which began in 2008 and has resulted in the accumulation of an immense volume of new data and generated funds from industrial participants of DKK 130+ Million. In West Greenland work concentrated on updated interpretations utilizing regional seismic interpretation and mapping, reservoir mapping, uplift studies, biostratigraphy and source rock/maturity modelling.

Northeast Greenland

The background for the Northeast Greenland activity was in anticipation for the first license round in the KANUMAS area, focusing on the Danmarkshavn Basin, in order to be able to assist the authorities and petroleum industry as needed. The area had been highlighted in the United States Geological Survey (USGS) Circum Arctic Resource Appraisal (CARA) published in 2007, as having the potential for large resources to be discovered, but was not without significant uncertainties, geological risks and technological challenges.

The main uncertainties in risking included lack of well data, limited and unsystematic seismic database, and required long-range extrapolation of outcrop analogue data from on-shore Greenland and the subsurface geology from the conjugate margin of Norway.

Key geological uncertainties included: uncertainty of hydrocarbon phase in potential traps, the distribution and correlation of Upper Jurassic source rocks, and post migration loss of oil as a result of Cenozoic uplift.

Additional geological uncertainties related to: the nature and distribution of the reservoirs and seals, and detailed stratigraphic correlation.

A collaboration project between GEUS and industry, entitled “Petroleum Geological Studies, Services and data in East and Northeast Greenland”, was initiated and more than 20 oil companies subscribe.

The platform for this study, which also included three modules: “Seabed Features”, “Uplift Studies”, and “Petroleum Systems” was a compilation of all pre-2007 information and material into a “Geographical Information System” (GIS). Subsequent modules resulted in the collection of new data through field work and drilling fully cored boreholes. These data were used for dedicated studies to address the problem areas identified in the USGS report.

Basic science in a virgin geological territory was undertaken to learn more, refine and modify existing models and concepts, to apply the results and modify existing models and concepts, and to apply the results to assist industry. All data generated remained GEUS prop-

erty, but was covered by five-year confidentiality agreement, which results in the delay of publication on these new data and insights until the period of confidentiality expires.

Ongoing results were communicated very effectively via semi-annual workshops and a website. All income and some GEUS funding was recycled into new optional studies, projects and research and has resulted in a large number of international publications, prepared on data not covered by the confidentiality agreement.

Optional studies included: four fully cored wells investigating the source rock potential of the Upper Jurassic and Upper Cretaceous, and reports on the following subjects: Provenance studies of possible reservoir sandstone units in East and Northeast Greenland, Uplift Phase II, Geology of Store Koldeway, the Triassic of the Wandel Sea, the Jurassic/Cretaceous of the Wandel Sea, and the Tertiary evolution of the Wandel Sea.

The results from these studies were used by industry in their internal evaluations for the first and second license rounds in the Danmarkshavn Basin, which resulted in the successful award of five licences in 2013 and 2014.

West Greenland

On behalf of the Ministry of Mineral Resources of Greenland (MMR), GEUS undertook the following regional evaluations: Baffin Bay (2008 – 2010) for 2010 Licence Round, Baffin Bay Update (2013 – 2015) for 2017 Licence Round and Southwest Greenland (2015 – 2017) for 2018 Licence Round.

The integrated evaluations included seismic interpretations and mapping, investigated the reservoir potential, the effects of uplift/inversion, biostratigraphy, source rock distribution and maturity modelling. The results were initially reported as confidential internal GEUS reports, which has resulted in many internationally peer reviewed publications (some still in press) and many conference presentations.

Additional studies were performed on: Baffin Bay/Davis Strait/Labrador Sea reservoirs, volcanology and uplift (2009 – 2010); the Thule Supergroup Provenance and Reservoir Characteristics (2012 – 2013); Baffin Bay Core Study (2012 – 2014) for Shell-led Baffin Bay Seabed Coring Consortium; Disko-Nuussuaq Study (2015 – 2016) for MMR, and Nuussuaq Source Rock Evaluation (2017) for MMR/GEUS.

2.2.2 Research Quality

Northeast Greenland

The USGS identified hydrocarbon phase to be the major risk, and the Jurassic source rock (quality/quantity) distribution was comprehensively addressed by the successful drilling of the first three fully cored wells. Indications of the presence of a second, previously unknown, petroleum system in the Cretaceous (Cenomanian – Turonian) were identified in the last well in the program.

Drilling of the Jurassic source rock interval proved the section to be two to three times richer and more oil prone than previous outcrop measurements had implied. As a consequence, the accepted models for Jurassic source rock deposition in Northeast Greenland

need revision and the long-held notion of predominantly gas-prone deposits north of Jame-son Land has been discredited and the source rock richness is expected to increase further offshore.

The presence of oil stains in thick, massive reservoir quality Cretaceous-aged sandstones was encountered in the Nanok-1 well, which may form potential objective in the offshore Danmarkshavn Basin. The oil stains originate from a Cretaceous-aged source rock and this well has proven for the first time the unequivocal presence of a Cretaceous-aged source rock in the North Atlantic Ocean.

As of April 2017, a total of 41 publications (peer reviewed, in review, under revision and submitted) have resulted from the initial modules of this project, whose confidentiality has expired. Many more papers will result as the confidentiality period on the optional studies expires.

West Greenland

Mapping the offshore areas – a GEUS core competency, has resulted in: a new regional tectono-stratigraphic framework for the West Greenland margin, where crustal-tectonic studies has resulted in the first unequivocal demonstration of oceanic crust in the Baffin Bay area; a better understanding of the Cretaceous rift phase in Baffin Bay, with the development of a Nuussuaq Basin-wide volcanic stratigraphic correlation, and a better constrained basin evolution of the Labrador-Baffin Bay seaway through seismic/biostratigraphic well ties from Canada to Greenland

Collaboration with industry and other research institutes: new data on biostratigraphy, geochemistry, provenance and structural geology, crucial information on prospectivity and conditions for source rock formation, and improved reservoir prediction and development of new play concepts.

Expertize in biostratigraphy, taxonomy and lithostratigraphy of the region is widely recognized as a result of forging links with universities through research and PhD programs.

2.2.3 Summary of observations

GEUS have developed a well thought out and practical GIS solution for the knowledge retention and sharing of all regional projects, which has been successfully applied to both sides of Greenland.

A quantum leap in the understanding of the Jurassic Petroleum System of Northeast Greenland has demonstrated that the oil potential is two to three times greater than previously thought, and the risk of just finding gas has been comprehensively refuted.

GEUS core competency in operating in harsh remote areas has also identified a previously unrecognized Cretaceous oil-prone Petroleum System through the onshore drilling program, the first unequivocal evidence of the extension of the Cretaceous Global Ocean Anoxic Events into the North Atlantic.

2.2.4 Recommendations

Based on the observed activities around Greenland, we recommend the following:

- GEUS should include key regional mapping surfaces from all 2D seismic data in future-offered data packages, to set the scene for more focused local studies. Moreover, an atlas of the distribution of the various important source rock systems for all areas of Greenland should be considered in an open platform for ease of access to academics and industry alike.
- Investigate and document the distribution of gas hydrates in the onshore and offshore regions of Greenland.
- Northeast Greenland regional petroleum systems analyses should be continued focusing on the Tertiary, as a gas discovery has recently been made in a reservoir close to the Cretaceous/Tertiary boundary in the Western Barents Sea.
- Incorporate all of the results of industry seabed sampling programs into the database, as paradigm shifting results deserve to be widely available to academia and industry alike.

2.3 Regional geology and tectonics in the North Atlantic and Arctic Ocean

During the last 50 years, an extensive amount of geophysical and geological data has been acquired in the North Atlantic, and to some extent in the Arctic, in order to reveal the area's tectono-magmatic evolution and hydrocarbon potential. Elements of particular importance are; the evolution of rift basins in time and space as function of varying stress-fields, the processes leading to continental break-up, magmatic influence from the Icelandic hot-spot, oceanic spreading processes, and post break-up compressional episodes causing local uplift. Numerous projects have addressed these issues, and most processes are relatively well understood locally.

2.3.1 Research activities and quality

In order to understand how these processes interact through time and space in the entire North Atlantic, scientists at GEUS realized the need for gathering existing data and models into an atlas, and took the initiative to NAG-TEC: Northeast Atlantic Tectonostratigraphic Atlas Project.

The project is a phenomenal collaborative achievement involving 83 survey personnel, 9 geological surveys, 7 universities/institutes, and 19 sponsors paying a total of 3.8 million €. The project is a successful result of a GEUS business model; in this case allowing the project to start when 50% of the costs were contracted by sponsors. The project was initiated in 2008 and completed on time in 2014. Part of the project is documented in a Geological Society of London Special Publication consisting of 17 high quality scientific publications, 11 of these with GEUS author or co-authorship. This quantity already exceeds the number of publications foreseen in the 'Resultatkontrakt 2016-2019', which expects 10 in total. The decision to present the results in a special publication is one of the factors that lead to the high number of papers, as it put pressure on the individuals responsible for writing. Another important factor is the decision to define publications as a delivery from the start of the project. This also helped in achieving the funding, as several sponsors need research outcome as criteria for providing funds. The GEUS leadership deserves credit for providing funds allowing resulting scientific publications to be open access.

Another impressive GEUS project is the Continental Shelf Project of the Kingdom of Denmark, carried out from 2002 to 2014. The 330 million DKK project had as main objective to define relevant Danish areas in relation to UNCLOS article 76, collect necessary data and prepare submissions to the Commission on the Limits of the Continental Shelf (CLCS). The surveys defined five partial submissions; north of the Faroe Islands, south of the Faroe Islands, south of Greenland, northeast of Greenland and north of Greenland. The surveys consisted of a selection of multi-beam bathymetry, seismic reflection, seismic wide-angle, aeromagnetic and dredging, and were partly performed in cooperation with institutions from Norway, Iceland, Ireland, UK, Canada, Sweden and Russia.

The project is so far documented by an impressive total of 14 publications of high scientific quality, and the submission for the area north of the Faroe Islands was fully endorsed by the CLCS in 2014. The 4 remaining submissions will be processed by the CLCS in the next 5 to 10 years. It is important that GEUS continues to publish results from the project, both in order to enrich the scientific community and to strengthen the support for the submissions.

It is expected that other nations will refine their geological models for the areas of interest in this period, and it is thus important that GEUS updates their database and maintain necessary scientific expertise within the project. This could be particularly important for the area north of Greenland, which falls into the area defined within the Norwegian research program, GoNorth; a potential collaborator for GEUS.

The acquisition of seismic data in ice-covered areas is very difficult and requires the design of special equipment and handling procedures. GEUS has, in cooperation with Aarhus University, designed an efficient container-based seismic acquisition system that can be applied even for crustal studies. The system is an important door-opener for international scientific cooperation. It is important that GEUS sustains its ability to experiment on, construct and maintain technical expertise on large scientific infrastructure of this kind. Furthermore, it is important that GEUS maintains its capability to engage in large geophysical surveys using Ocean Bottom Seismometers, combined with potential field investigations.

2.3.2 Recommendations

Based on the observed research activities and an assessment of their quality, we recommend the following:

- GEUS should consider whether the extremely successful manner the NAG-TEC project was conducted, could be used as a model for other projects.
- The panel strongly supports the NAG-TEC 2 initiative. The NE Atlantic is probably the only location on Earth with sufficient high data and model density to allow the study of all phases from orogenic collapse to oceanic crustal accretion. Moreover, GEUS should consider an initiative (“NAG-SED”), which could outline the characteristics and development history of the sedimentary cover in the area.
- It is important that GEUS continues to publish the results from the Continental Shelf Project, updates the data relevant for the project, and maintains the necessary scientific expertise on the areas of interest. North of Greenland, GEUS could consider cooperating with GoNorth.
- It is important that GEUS maintains its technical expertise on large scientific infrastructure, such as the containerized seismic acquisition system as well as on the new Dan-Seis seismometers.

2.4 Green Energy: Geothermal Energy, CCS, heat storage

2.4.1 Research activities and quality

The Danish subsurface has a multitude of applications in relation to the transformation of Danish energy consumption to a future of predominantly sustainable green energy supply. With a political goal of covering Denmark's electricity and heat supply by renewable energy by 2035 and ultimately, reaching a society free from fossil fuels by 2050, there is significant demand for research and development in a variety of fields. Within the areas of geoscience, this applies to information about subsurface geological conditions and development and use of new methodologies in relation to subsurface energy applications.

The panel notes that GEUS is very much aware of this development as reflected in GEUS focus areas, number of important projects as well as in the number of scientists working in this area of green energy. Projects and research teams in relation to green energy include a wide range of disciplines and cover the areas of deep and shallow geothermal energy utilization, subsurface storage of thermal energy as well as storage of CO₂ in subsurface reservoirs (CCS).

Within the evaluation period of 2010-2016, the area of green energy has had four large research projects, each with a total funding of more than 5 million DKK, 11 projects with between 1 and 5 million DKK as well as a large number smaller projects. The staff currently involved in green energy research constitutes about 15 scientists with their primary research activities within this area and an equal number of persons with important, but secondary research activities.

Since research on deep geothermal energy started in the late 1970ties, GEUS has provided geological advice to and assessment of local geothermal potential for the holders of geothermal concessions, and GEUS has had the leading and coordinating role in a number of larger projects aiming at mapping and characterizing potential geothermal reservoirs across the country.

Despite existence of favourable geological conditions in large parts of the country, and a well-developed system of district heating in Danish cities, generally easily connected to geothermal production, a relatively few number of three geothermal plants are in operation (Thisted from 1984, Copenhagen/Amager from 2005, and Sønderborg from 2013).

This small number seems to reflect political reasons rather than lack of suitable geothermal reservoirs. In contrast to the conditions of other important green energy technologies, geothermal energy in Denmark, until very recently, has not had any economic compensation or support schemes for stimulating utilization. The possibility of producing sufficient amounts of warm water from reservoirs, covering the depth interval of 1200-2600 m and temperatures of 45-75 °C, is demonstrated by the above geothermal plants.

Among the large research projects within the area of deep geothermal energy was the project "The geothermal energy potential in Denmark – reservoir properties, temperature dis-

tribution and models for utilisation”. Project partners included Dept. of Geoscience at Aarhus University, Geological Survey of Sweden, and GFZ Potsdam. Integrated with results of other projects, including a comprehensive reinterpretation of onshore seismic reflection lines, this project has resulted in a new mapping of basin sedimentary sequences and provided regional information on depth and thickness of sandstone reservoirs. These reservoirs may be suitable, not only for geothermal energy, but also as reservoirs for heat storage and storage of CO₂. Information on distribution of reservoirs, thickness, reservoir properties and temperature is compiled into a comprehensive open to clients user-friendly web-based database at GEUS (<http://dybgeotermi.geus.dk>). This is a significant and an impressive contribution from those projects.

Recently, GEUS, together with national university-, industrial- and district heating distribution partners as well as international partners, has succeeded in obtaining significant funding from Innovation Fund Denmark in the project GEOTHERM (Geothermal energy from sedimentary reservoirs – Removing obstacles for large scale utilization). This project is designed to identify and address obstacles for geothermal utilization. This applies to geological, technological as well as economic. Challenges include the ensuring of long term stability of fluid circulation systems. The important issue of potential geochemical reactions between injected cold brine and reservoir rock will be addressed.

It is noted that, within the evaluation period, GEUS has had several medium size projects on CCS (funding between 1 and 5 million DKK) including EU financed projects.

Research focused on shallow geothermal energy and shallow heat storage (depth generally less than 300-500 m) is relatively new at GEUS. Starting in 2011, GEUS had the leading and main role in the project “Energy systems based on closed loop boreholes” (EUDP² project, 2011-2014). This is followed by a project, also supported by EUDP, focusing on shallow heat storage (“Evaluation of the potential for geological heat storage in Denmark, 2016-2019). Both projects are carried out in collaboration with university and industrial partners. Here, GEUS is using its basic knowledge and expertise on near surface geology and groundwater, and is integrating this knowledge with existing and new information on near surface temperature distribution and thermal properties of materials. A sensitivity study on the closed loop borehole systems has demonstrated the importance of thermal conductivity of the geological materials into which the boreholes are drilled.

The panel recognizes the ability of GEUS to include external partners, also industrial and international partners, into large projects to cover competences needed.

Strong research teams exist at GEUS in relation to deep geothermal energy including different disciplines and represented by all departments having energy research. Focus areas has included characterization of reservoir units based on core and log analysis with laboratory porosity and permeability determinations, diagenesis analysis as well as general sedimentological and depositional environmental studies. The panel supports recent initiatives of introducing new state-of-the-art geochemical and diagenesis modelling (application of the software system Touchstone).

² Det Energiteknologiske Udviklings- og Demonstrationsprogram – a public Danish fund supporting innovation and new technology in the area of Energy.

The new expertise being built and research results provided within the areas of shallow geothermal energy and subsurface energy storage – shallow as well as well as deep - are important. The demand of knowledge in these areas clearly will increase in line with the increasing amounts of energy being produced from renewable energy systems and with production generally not in phase with demands.

Within the period of evaluation, in the area of green energy, a significant number of more than 50 GEUS reports were produced, and, considering the number of scientific staff involved and topics worked on, a less impressive number of 10 peer-reviewed publications.

2.4.2 Recommendations

For the Green Energy area it is recommended that:

- GEUS expands its knowledge and expertise in green energy as the need for geological research and advisory services in relation to green energy systems and environmentally sustainable technologies will increase.
- GEUS puts more emphasis on reservoir physics (e.g. obtained from quantitative seismic interpretation), which in turn may be integrated with general sedimentological and diagenesis studies.
- GEUS seeks more and closer collaboration with partners in the EU and abroad to obtain EU funding (e.g. horizon 2020) for larger international, collaborative projects.
- GEUS documents its research in more peer reviewed publications.
- Moreover, the panel recommends that GEUS maintains the competences regarding CCS for potential future activity.

2.5 Other topics: Seismology, Laboratory facilities, South-East Asia, Shale Gas

2.5.1 Research activity and quality

Seismology

Seismic activity has been systematically recorded in Denmark since 1926, and since 2005 this service has been hosted by GEUS. Maintenance of the seismological database and the automatic interpretation and cataloguing of seismic arrivals is done at a high level ensuring availability of seismological data for the future. The seismology activities include localization of earthquake epicentres in the Danish area based on, primarily, the seismograph network installed onshore Denmark and in southern Sweden. Surprisingly, apparently, the localization of earthquakes is based on a simple, one-dimensional model of the sediments and crystalline crust. This simple approach for localization is considered problematic, since the thickness of the sedimentary cover as well as the depth to the crust-mantle boundary (Moho) varies significantly in the area. Thus, missing account for three-dimensional variation may lead to systematic errors and inconsistencies in localization of earthquake epicentres. Three-dimensional models of changes in seismic velocity related to changes in sedimentary cover and thickness of the crystalline crust can be established from existing data and maps. It should therefore be possible to improve the localization of earthquakes significantly by developing and employing a three-dimensional model of the crystalline crust and sedimentary cover.

GEUS is partner in a large and ambitious international infrastructure (GLISN³), which constitutes of a network of seismological stations placed along the Greenland coastline and on the inland ice sheet. The main focus of this excellent infrastructure is to monitor dynamic changes in glacier behaviour and provide a better understanding of active tectonics in the region. However, the open database provided by this network of stations will expectedly find application for several other basic research projects as well as applied research. There should, for example, be good opportunities to integrate findings based on the recordings from this seismological network with other GEUS activities in Greenland and the North Atlantic.

Data generated from monitoring of Danish earthquakes has resulted in 10 peer-reviewed publications since 2010, and, similarly, the earthquake recordings from Greenland have resulted in 10 peer-reviewed publications in the same time interval.

South-East Asia

GEUS' research activities in Vietnam started in 1994 as development aid energy projects. The research was performed in collaboration with Petro Vietnam, VPI⁴, Vietnamese univer-

³ Greenland Ice Sheet Monitoring Network

⁴ Petro Vietnam's research branch)

sities and the University of Copenhagen. The cooperation has so far resulted in the training of more than 20 Vietnamese Ph.D.s and master students.

The development aid projects were terminated in 2012, but the activity in SE Asia continued as industrially funded research projects on Vietnamese, Cambodian and regional SE Asian geology.

The research focused on regional basin analyses, drilling of analogue settings, petroleum system analyses, regional tectonic studies, uplift and denudation analyses, as well as dating and geochemical studies of igneous rocks within the Song Hong Basin, the Gulf of Thailand and the Phu Khanh Basin.

GEUS has ambitions to continue the work in the South China Sea, as well as expanding the ongoing activities in Cambodia and Myanmar, where a university/oil company/ministry network has been established.

The activity in SE Asia has been very productive scientifically, with a total production of 32 peer-reviewed papers, some with high citation rate. The panel encourages GEUS to engage in development aid projects when the opportunity comes, both since they have proved to be able to transfer the activity into strong science, in addition to the obvious aid component and 'geology for peace' bonus. When the funding related to aid stops, the panel supports that the activity continues, as long as industrial funding prevails.

Laboratories

GEUS has several laboratory facilities, which here are divided into the following laboratories: Core analysis; Organic Chemistry and Petrology; Biostratigraphy; Photogrammetry.

The **Core Laboratory** facility is well equipped and busy. The laboratory facility provides special core analysis for the industry, contributes to several R&D projects, and offers a wide range of analysis. In particular, the laboratory provides analysis relevant for characterization of reservoir, flow properties and rock mechanics. Flooding experiments were described especially to the panel. The Core Laboratory focuses on sandstone and chalk reservoirs in the North Sea. It also performs R&D studies on CO₂-flooding of reservoirs to enhance recovery, and interesting results on injection of CO₂ were presented. Staff of the Core Laboratory facility have performed research and development studies on CCS and geothermal energy. Different institutions and industry have financed several studies in the period 2007-2013.

It is the panel's impression that the Core Laboratory facilities of GEUS are highly relevant and attractive in-house as well as for external partners.

The laboratory facility for **Organic Chemistry and Petrology** is well equipped and busy. The laboratory provides analysis to the industry and participates in collaborative projects. It contributes both to basic and applied research within more than 30 different countries. In brief, it is a state-of-the-art laboratory facility and constitutes a great expertise. The Organic Chemistry and Petrology Laboratory has a succession planning challenge in the coming years. We encourage careful succession planning with new recruitment, if this laboratory is to continue to contribute with valuable research results and income to GEUS.

The **Biostratigraphy Laboratory** facility is also well equipped and busy. The visit showed a strong awareness and focus on health, safety and environment (HSE), which is considered crucial as the work involves handling of dangerous acids.

The laboratory provides palynological, micropaleontological and geobotanical analysis. The clients are a range of local authorities and larger oil- and energy-companies. The panel identified the lack of training and employment of new palynologists in academia in Denmark. The GEUS expertise may therefore be considered as being unique. Moreover, it is important to maintain this expertise as it provides a competence that is rare in industry today. Specifically, the palynological studies provide crucial information/interpretations used e.g. in the integrated work in the CENSYS project.

The **Photogrammetry Laboratory** facility has a large database of aerial photographs and has access to high-end processing software through a link to an external partner. This laboratory facility has a great potential to contribute also to quantitative analysis of reservoir analogous sequences when combined with ground truthing and sedimentological data and models. For example, the Greenlandic study focused on structural geology at Kilen benefits greatly from the photogrammetry facility method as 3D modelling is now possible over large areas in more time- and resource-efficient way as compared to traditional field work. Moreover, the photogrammetry facility has a large future potential to gather large datasets and should be used in connection with traditional fieldwork studies.

Over all, it is the impressions of the panel that the laboratories are busy and that they contribute substantially to the science and income of GEUS as they seem to be applicable to a wide range of the focus areas of GEUS. The quality and standards of the laboratories is very high and the extensive flow of external jobs confirms that the laboratories are attractive also for external partners.

Shale gas studies

GEUS has completed several projects in the period 2011-2017, both with industry, the University of Copenhagen, and USGS. GEUS has drilled four shallow cores and recorded 2D seismics on Bornholm, made seismic modelling and identified a seismic signature of the Alum shale. A resource assessment of the Alum shale, which is the major gas shale reservoir, was performed in cooperation with USGS.

GEUS has also taken the responsibility to inform and educate the public on matters of shale gas. The resources are controversial and there may not be any future activities for exploration and exploitation of gas from these reservoirs.

2.5.2 Recommendations

Based on the observations made in the diverse "Other"-group of activities, the panel recommends the following:

- The seismological research activities of the geophysics group should be further integrated with other GEUS activities. For example, activity in the North Sea may be monitored by installation of seismometers over producing fields. Also, seismological monitoring could be used to assess possible induced seismicity related to establishment of

geothermal plants. Different groups at GEUS can help provide data for and establish a three-dimensional velocity model of the crystalline crust and sedimentary layers based on existing data for improved earthquake location.

- The panel recommends that GEUS is active in development aid projects when the opportunity arises, and continues the activity as long as industrial funding prevails. Such activities may also be viewed as strategically important for building strong, future international networks and gain experience.
- The panel recommends that the challenge related to allocating resources for publication of laboratory results is recognised and that GEUS decides whether they want to continue the strong competence in the different laboratory disciplines. In this context, careful succession planning is also considered vital.
- The laboratory facilities may constitute a competitive edge and bring income for GEUS also in the future. Further, we recommend that testing and development of new, innovative methods for strengthening of laboratory methodologies are conducted.
- The panel recommends that GEUS maintains the competence concerning shale gas to be able to continue to advise the authorities and inform the public.

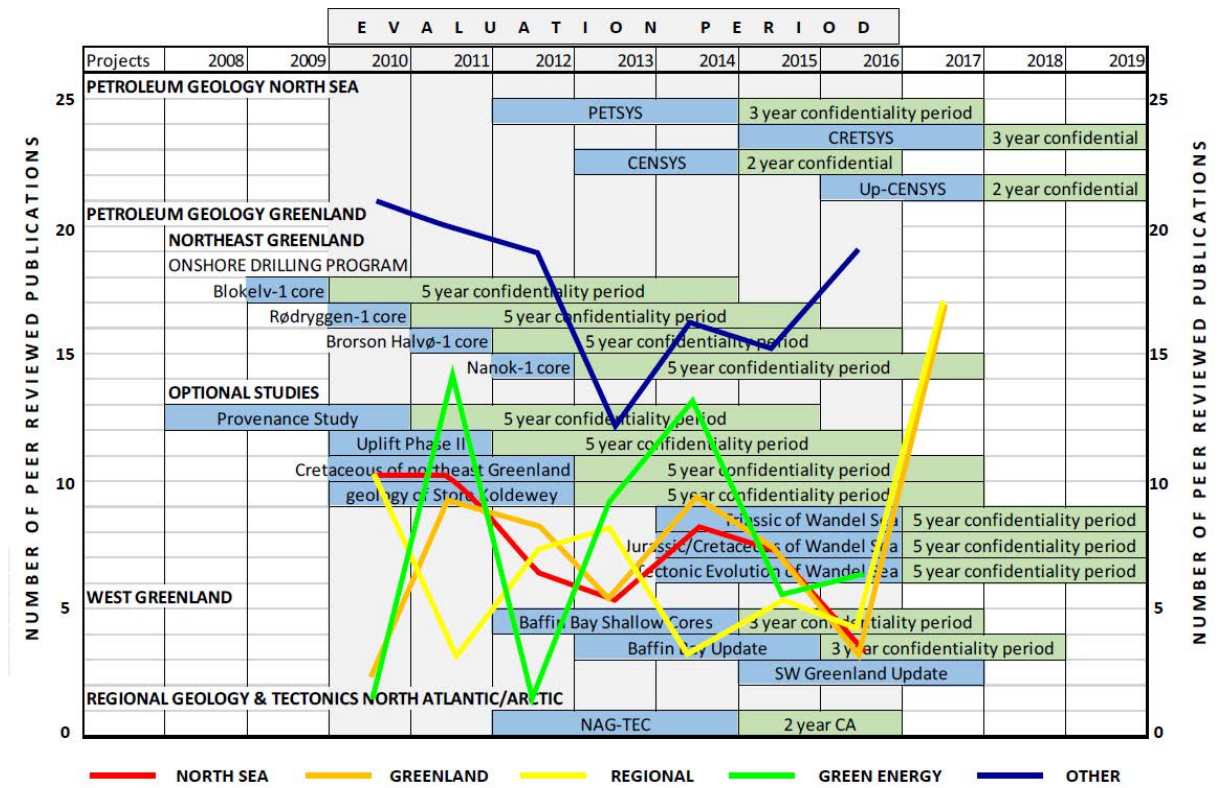
2.6 General recommendations

Supplementary to the specific recommendations given in the sections above, the panel recommends GEUS to consider the following more general recommendations:

- GEUS' management and scientific leadership should consider the funding and publication pressure of the individual researchers. In particular, they should judge if it is realistic for all scientists to both formulate and submit proposals for funding at the current frequency and level, and at the same time publish sufficient amounts of research results to develop and maintain a strong research profile of the individual researchers.
- GEUS should consider to what extent individual researchers should be given new opportunities to create a solid base for further developing their scientific track record (e.g. publication record, conference participation, conduct change of scientific environment, sabbatical leave etc.) and thereby be able to improve their chances for attracting large, prestigious research grants from international and national research councils. In this context, programmes of some month's duration where scientific staff are free from administrative and consultancy tasks may be beneficial to launch.
- If projects only have focus on consultancy output and do not allow ample time for publication of scientific articles (cf. Appendix), new map material etc., then the research activities cannot be properly documented, and the individual disciplines risk lack of research strength in the future. Moreover, the solid research base that GEUS is resting on may gradually erode in some fields in the future, if strong focus on documentation of research through peer-reviewed publications is disregarded. In this context, it is noted that some project applications have been successful in also allocating funding for time for writing of scientific articles for dissemination of the results of the research project. GEUS is encouraged to investigate if such positive elements can be implemented more generally in future research project applications in different fields.
- A list of national and international grants aimed at strengthening early career scientist exists. GEUS has several excellent and talented young researchers in-house. Support from GEUS, e.g. in the form of co-financing, aimed at supporting such young scientist has the potential to increase the success rate for applications submitted to research funding programmes by these young scientists.
- Requirements for qualification to the different scientific levels exist and are publicly available. However, career paths for how to progress from postdoc to researcher and then onwards to senior researcher should be made even more transparent. Such transparency combined with careful succession planning in a number of GEUS' core activity centres are considered essential for maintaining high quality, further development of the scientific activities and, at the same time, maintaining a high working morale.
- An ambitious recruitment plan at professor level could provide additional leverage for strengthening the research profile of GEUS and forming additional research groups with strong international impact. To this end, GEUS should also consider to develop plans for adjunct professors together with, for example, the Geocenter universities.

- GEUS should consider strengthening of their expertise in reservoir geophysics either internally or by collaboration with external partner. Expertise in reservoir geophysics is considered essential not only in relation to hydrocarbon studies, but also in geothermal studies and in relation to groundwater.
- GEUS covers a breadth of disciplines and has material available to establish analogous models of both deep and shallow reservoirs from outcrop and surface sediments studies. Such approaches would also be beneficial to a broad range of the studies that GEUS undertake.
- The DHRTC located at the Technical University of Denmark is a significant funding body, which supports research activities that are essential for GEUS. GEUS should work keeping a position, where GEUS is a preferred and central partner for other institutions that apply for research projects at DHRTC. Moreover, GEUS should aim at coordinating large, ambitious proposals to DHRTC.
- GEUS has demonstrated excellence in coordinating large, complex projects with several and diverse international partners. GEUS should build on and further strengthen its strong organization to take lead on even more large-scale international projects. GEUS is encouraged to strengthen share of knowledge regarding construction of successful international, cross-disciplinary teams between its departments and individual project leaders in a systematic manner.
- GEUS has great expertise in building and maintaining large databases consisting of many different data types. These databases are expected to grow significantly over the coming years and at the same time increase in complexity. New methodologies for mining such complex databases and providing quality control of such data should be developed, for example in collaboration with external partners. Documentation of systems for efficient ways of storing, quality checking and retrieving data may in itself make GEUS a preferred international partner for large, ambitious projects for new data collection.
- Oil production is expected to decrease in the future due to changes in energy policy. GEUS should make a detailed mapping of what oil is used for apart from energy production. Such a mapping is considered essential for estimating the full impact and consequences of decreased oil production. Moreover, oil and gas is expected to be a vital energy source several years ahead, and GEUS should keep a high level of expertise in this field. Thus, GEUS should focus on both hydrocarbon and renewable energy research, and it is important that GEUS maintains a very strong competence on geological and geophysical characterization of petroleum systems.

3. APPENDIX



Publication history including projection of 17 publications expected to come out of the Greenlandic NAG-TEC study. Note increase in publication activity for some study regions when the confidentiality period has ended.