

**Scientific evaluation of Programme area 3
Energy resources (2000-2009)
at the Geological Survey of
Denmark and Greenland
(GEUS)**

Lars Hamberg, Birger Dahl, Lotte Kjørboe,
Holger Lykke-Andersen & Bente Nyland

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY



GEUS

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THE EVALUATION PROCESS

Introduction

The evaluation panel consisted of:

Lotte Kjørboe (Noreco)

Holger Lykke-Andersen (Aarhus Universitet)

Birger Dahl (Bayern Gas)

Bente Nyland (Oljedirektoratet, participated via video link)

Lars Hamberg (DONG Energy, Chairman)

and was given the following task:

The panel shall undertake an evaluation of research and presentation activities within the Programme Area “Energy Resources”, constituted by:

- the period 2000-2009:
 - Hydrocarbon resources in Denmark and North Sea
 - Hydrocarbon resources in and around Greenland
 - Continental shelf mapping, UN Convention on the law on the Sea
 - CO₂ storage
 - Geothermal energy
 - Seismology

based on a thorough examination of selected publications and reports produced by the survey in addition to a visit to GEUS in Copenhagen.

The task of the panel being an evaluation of the research activities of GEUS on the basis of

- publications, reports and other relevant material produced over the period 2000-2009
- interviews with GEUS’ management staff and scientists and visits to laboratories and work facilities at GEUS.

In order to:

- Identification of areas of high quality research
- Identification of areas where the research of GEUS should be strengthened in order to meet GEUS vision and strategies
- Identification of areas which should be strengthened in order to expand GEUS’ ability to provide assistance to third world countries within the energy sector.
- Comments and proposals 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 with this programme area put into perspective of the survey’s status and general mission

Evaluation in practise

Besides comprehensive lists of publications, citations analysis, staff and CV's, evaluation was based on 11 presentations over two days (April 22-23, 2010) given by selected researchers covering topics selected by GEUS within the frame of the over subjects up for evaluation. Presentations were very well carried out and also served as a platform for brief interviews of the presenters and discussions with staff and managers on various issues raised by the evaluation panel. However, an overview of activities within each specific subject under the Energy Resources Programme Area would have been beneficial to the evaluation process.

Not all disciplines and areas of research were presented to the Evaluation Panel. In gross terms these includes the Chalk team, seismic interpretation and geophysical investigations including seismic reservoir characterization, petroleum technology, petrophysics, reservoir modelling and geostatistics, diagenesis, and continent margin uplift and regional tectonics. Absence of direct presentation of these research areas has been partly covered for by the Evaluation Panel by perusal of publications and reports as well as the panels up front knowledge of research work at GEUS. These, specific areas are therefore not discussed in detail in the present report but still form part of the evaluation.

Within the Programme Area "Energy Resources", the topics selected for evaluation are very broad and each may cover many research disciplines, especially relevant for the topics "Hydrocarbon resources in Denmark and the North Sea" and "Hydrocarbon resources in and around Greenland". Time did therefore not allow for a very detailed evaluation of each and every discipline and evaluation focused on the level of research in general and it's applicability to the assessment of hydrocarbon resources.

GEUS' tasks and mission within the Energy Resource Programme

GEUS is responsible for the scientific research of the geology of Denmark and Greenland as well as surrounding continental shelf areas. In order to do this, it is required that GEUS carries out research of high international standard providing state-of-the-art geoscientific knowledge on matters related to the use and protection of geological resources in Denmark and Greenland. Energy resource Programme in particular considers exploration and exploitation of subsurface energy resources in Denmark and Greenland, Continental shelf mapping, CO₂ storage, CCS and seismology.

GEUS' main tasks are geological mapping, data collection and storage, to carry out research projects, to give advice, and to disseminate geoscientific knowledge. It is also the task of GEUS' to provide geological advisory to the Danish Energy Authority, Danish Ministries and the Government of Greenland Authority and carry out required tasks for these Authorities. In reality, the balance of tasks actually carried out has been partly driven by the availability of funding, full or partly, from the Authorities or the industry.

Detailed evaluation of activities

Hydrocarbon resources in Denmark and the North Sea

Research activities

GEUS has an extensive record of research and contract work in the North Sea and Denmark over the last decades. Exploration and exploitation of Denmark and the North Sea has been ongoing since the fifties-sixties and the area is now characterized as a mature petroleum province that is well understood and well documented through more than 50 years of scientific and industry related research. GEUS has made important contributions to this development as demonstrated by the many publications and reports but also by housing several researchers with a strong profile in the petroleum industry. The accumulation of knowledge and high level skills in various disciplines have ensured the demand for GEUS expertise also in the wider North Sea region and neighbouring countries.

GEUS benefits from the copious collections of exploration and exploitation data held in the archives and part of GEUS' mission is to develop new ideas on play types and also to direct industry attention to other areas and stratigraphic levels than the North Sea Central Graben chalk play from which most production has so far derived. The strategic areas of focus within the period 2000-2009 have primarily been on the Chalk Group as this is one of Denmark's most important reservoirs for hydrocarbons, but also clastic reservoirs were assessed, and from 2008 and onwards with special emphasis on deeply buried reservoirs.

Research activities and results as well as publication level were exemplified through four presentations to the Evaluation Panel:

Comparable sedimentology of fossil and recent coastal deposits (by *Peter Johannessen*), draws on two, detailed studies: The first of Rømø barrier island, a cooperation project with Geocenter Denmark, reveals new insight into formation and stratigraphy of modern barrier islands, which have served as analogue for well correlations and sand prediction in Jurassic transgressive deposits of the Danish Central Graben. The second on Skagen Odde, where new sedimentological understanding of a complex and large spit sand accumulation has been used as reservoir model for Norwegian oil fields but also stands as an exciting new explanation for stranded offshore bar reservoirs.

Miocene stratigraphy, sedimentological model and palaeogeography (by *Erik S Rasmussen*), a valuable contribution to the geology of Denmark with wide consequences for the further interpretation of the Miocene in the North Sea region. Research is basically a spin-off from groundwater research, and after approx. 10 years of detailed work where the research team has used innovative techniques from oil exploration, the product is a new, well documented and appealing sedimentological and lithostratigraphy model for the Miocene deltas that will find use in many prospect and reservoir assessments in North Sea, and of similar importance, a refined stratigraphy that has been used to re-evaluate Miocene stratigraphy outside

Denmark. For exploration in the North Sea, the refined stratigraphy seems to be the most significant contribution.

Coal as hydrocarbon source rock (by *Henrik I Pedersen*), demonstrated that the GEUS source rock team and source rock laboratories are in the lead of source rock evaluation, in particular with respect to hydrocarbon charge from terrestrial source rocks. Transforming existing ideas into new innovative techniques of isolating the oil generating parts of kerogen is one example hereof, also applied to Danish North Sea fields, and results look promising for future prediction of type of hydrocarbon sourcing from coals, i.e. in Greenland.

Modelling of hydrocarbon filling of complex traps in chalk (by *Peter Frykman*), an EFP funded project that in an innovative new way combines dynamic reservoir simulation and flow simulation to explain hydrocarbon migration and simultaneous evolution of the reservoir and burial of complex, stratigraphic traps in chalk. Research draws on contributions from geophysics, petrophysics and reservoir modelling, and has had direct implications for understanding chalk reservoirs hosting hydrocarbons.

The mission of GEUS also includes the potential energy resources onshore Denmark and for this, the latest compilation of knowledge presented in the book “The Jurassic of Denmark and Greenland” is a significant contribution for future subsurface work including geothermal and CCS investigations.

The Miocene project, as well as the Rømø and Skagen Odde projects, was born from industry companies and other research institutions request for high level skills in sedimentology and stratigraphy, perhaps as simple as field guiding. Once seeing the potential, GEUS research teams have been very successful in formulating interesting research projects and obtaining funding from external sources. Although long term planning of research may be preferred, the above demonstrates how GEUS expertise and skills ensure opportunities to participate in large research projects.

A large part of the in-depth research and data gathering/interpretation were undertaken through EFP-financed cooperation projects. The EFP program stopped in the middle of the period under evaluation. It is the impression that the former financing through EFP funds ensured continuity in the research carried out in Denmark and Danish North Sea, a continuity that may be less obvious to reach given the current funding situation.

It is notable, that regional subsurface mapping over the Danish areas and Central Graben has not been published since 1995/97. However, new maps may exist electronically as unpublished maps in GEUS’ database.

Research quality

The research in hydrocarbon exploration and exploitation in Denmark and North Sea at GEUS is generally considered to be of high quality and of international standard. The teams are successful in obtaining funding from external sources and attract several Ph.D. - students. Many researchers and teams are well known internationally for studies in sedimentology, bio- and lithostratigraphy, sequence stratigraphy, source rock evaluation, reservoir geology and

continental uplift. In addition, GEUS probably holds one of the most experienced teams on North Sea chalk.

Researchers produce a relatively large number of articles every year, published in highly rated international scientific journals, as well as book chapters and a large number of presentations at international conferences. The publication record in peer reviewed scientific journals has been remarkably constant throughout, typically around an average of 12 p.a., with increased output in the years of the Petroleum Conference proceedings (2005) and Millennium Atlas (2004). Furthermore, a large compilation of important contributions exists in the internationally reviewed book "The Jurassic of Denmark and Greenland". Besides this book, only a few publications were published in GEUS's own series, perhaps reflecting the demand for a high publication impact factor and citation index.

The relatively high numbers of citations of some of the researchers, demonstrate a strong and sustainable international impact of the research. Several publications can be back-tracked to externally funded research studies and demonstrates dissemination of comprehensive research studies. Some of the publications are basic publications on stratigraphy which are of outmost importance for any geological understanding and further exploitation of the subsurface of Denmark.

Researchers work in teams and have demonstrated ability to combine various subsurface data at a high scientific level to improve the understanding of the North Sea reservoirs, source rocks and stratigraphy and a vast amount (>50) of internal reports was produced in the period 2000-2009.

The Evaluation Panel has identified several areas of high quality research in the Danish area:

- Mesozoic and Tertiary stratigraphy (biostratigraphy, regional correlation and regional palaeogeography)
- Sedimentology of coastal and deltaic sediments and chalk
- Terrestrial source rocks, source rock evaluation and modelling
- Reservoir modelling of chalk and clastic reservoirs
- Filling history modelling of complex chalk traps
- Seismic characterization of chalk reservoirs
- Regional tectonic evolution incl. neogene uplift
- Chalk petrophysics and petroleum technology of chalk
- Clay mineralogy
- Presentation techniques, writing publications and guidance in field

Expertise in above listed areas not only originates from research projects but also from a significant amount of projects carried out as consultancy work, primarily for the oil industry in and outside Denmark. It is the impression of the Evaluation Panel that the fairly large engagement in industry projects has sharpened the researchers at GEUS, e.g. to begin to include

alternative views and uncertainties in the work. It is also evident that GEUS now possesses teams that together cover most elements of modern prospect and reservoir assessment.

Recommendations

During presentations and interviews it became clear that some research areas may need to be strengthened in order to meet the requirements expressed in GEUS' goal for the strategic areas and potential advisory to the authorities:

- Diagenesis and petrophysics of deeply buried clastic reservoirs (strategic goal incl.: methodologies and tools to improve prediction of reservoir parameters)
- Use of GIS platforms for data compilations (improve database and accessibility)
- Geostatistics in reservoir modelling (may already have been undertaken by recent employment)
- QC process: It is the impression that GEUS should consider if a formal peer review process could strengthen the quality of the research, advisory and consultancy work
- Deep marine depositional systems (the Paleocene Siri fairway fields decline but continued exploration is ongoing; Exploration and appraisal of deep Jurassic reservoirs (strategic goal), also includes a new deep marine play type)
- Consider use of uncertainty estimates, formulation of alternative models as a natural process in all geological model work
- Use the advantage of having a significant collection of petroleum industry reports and evaluations, e.g. as inspiration for evaluation of deeply buried oil-generating source rocks

Hydrocarbon resources in and around Greenland

Research activities

Three presentations related to exploration activities and general geoscientific studies carried out by GEUS on Greenland were conveyed to the committee. Two dealt with activities on West Greenland whilst one presentation covered East and North Greenland projects. It is evident from the presentations and the available material that main focus has been on West Greenland during the last decade. This is of course natural since exploration activities have been carried out in the area by international oil companies.

The presentation “**West Greenland**” by *Ulrik Gregersen* showed an area which has had been explored for petroleum since 1970 (seismic surveys) with drilling of 5 unsuccessful wells in the mid seventies. The next phase of exploration, during the 90’s, was not particular successful either. A license round led to Open Door policy (e.g. no applicants). However, several onshore core-holes and one deep well were drilled in 1995-1996. The latest exploration well was the dry Qulleq-1 (6354/4-1), by Statoil drilled in 2000. A license round in 2006/2007 granted 7 new licences in the Disko area to 7 oil companies. One of these (Cairn) is scheduled to drill 2-4 wells during 2010.

GEUS have been active and carried out several projects to support exploration and gain interest for area. These activities seem to have increased significantly at the turn of the century. In 2000 to 2003 several large studies were carried out such as:

- Prospectivity evaluation of the West Greenland: 63-68 deg N
- Mapping and prospectivity of the Fylla region
- Basin modelling and thermal maturity evaluation

It is also noteworthy that projects to quantify uplift, erosion and landforms of crucial importance for the petroleum prospectivity have been undertaken since 2003 (leading to 8 papers and 5 reports).

The GEUS studies from the Disko area have been compiled and made available as a GIS database in which

- Oil seep data
- Seismic interpretation
- Provenance analysis
- Biostratigraphy
- Well reports etc.

have been compiled.

During the last few years the exploration interest has reverted further north to the Baffin Bay area and a deadline to apply for 14 blocks is May 1, 2010.

Large GEUS mapping and onshore studies have been carried out in the Baffin Bay area in order to support the industry and increase interest for the region. A large proportion of this material and results are available on a GIS database system similar to the one from the Disko Area.

The most important geological findings seem also to be summarized in an excellent special volume of publications from West Greenland (Dam et al. 2009).

The second presentation from Greenland, “**North East Greenland**” by *Jørgen Bojesen-Koefoed* showed that the interests for this region and associated studies have increased dramatically the last few years. It is not clear what has driven this interest, but Greenland’s position relative to more frontier explorative areas of Europe, the Atlantic margin is quite evident. Issues like Mesozoic deposits, their provenance areas, Cretaceous source rocks, etc in these margin areas will be better understood via knowledge of East Greenland geology. The Worlds demand for hydrocarbon resources and increased general interest of exploration in Arctic areas is also natural driving force for the East and North Greenland geology. One may say the understanding of N&E Greenland is one of the important keys to understand the petroleum geology of the Arctic. It is also obvious that the oil industry will continue the “knowledge gain” in West Greenland and GEUS will support the activities more on a “consultancy” level.

Important impact in this context is the GEUS consortium “Petroleum Geological Studies, Services and Data in East and North East Greenland” that was established in late 2007 and now co-financed by approx.15 oil companies. These projects include field work and shallow core drillings at appropriate locations during the summer and produce analytical results and interpretations during the following winter. Workshops, preliminary results and discussions with the sponsors are important for planning of the next years field work. These projects will continue at least until the first license round has been completed the area. The projects produce studies of

- Uplift and landscaping
- Source rock identification and quality
- Oils seep analysis
- Petroleum system analysis
- Provenance area studies, etc

Some special studies are carried out, at extra costs, for some of the participating companies

The results are conveyed to the industry partners on a GIS format and in separate reports. The GIS systems are updated when data can be added and thus are representing a very practical and convenient tool for the partners. A website with password is also available for the sponsors in order to download results.

Due to the industrial “component” in the project, a time limitation is set for data distribution and likewise the ability to publish result quickly. This is, however, common practice in the oil industry and points on the problem GEUS has with respect to the necessity for external

sources of income which in turn results in limited freedom. There are, however, ways around this by engaging students (M.Sc. and Ph.D's) to carry out their thesis work on agreeable (for the industry) parts of the material. The industry is after all dependent on recruitment of graduates for their future activities.

The third presentation "Biostratigraphy of Greenland. Cretaceous palynology of Greenland" given by *Henrik Nøhr-Hansen* showed continuous project activities since 1979. The presentation documents that all stages of the Cretaceous period are present in Greenland. Greenland is obviously an excellent reference area for Cretaceous. There are only a few Cretaceous periods documented offshore. Greenland strata have been correlated to one Ormen Lange Well in the Norwegian Møre Basin. Both the Møre and Vøring Basins are Cretaceous basins (large accumulation space and fast subsidence during Cretaceous)

Other presentations of importance were *Henrik Petersen's* paper on the source rock laboratory which is a significant contributor, producing data and interpretational results for the Greenland activities. Although not directly of importance for hydrocarbon exploration *Tine B. Larsen* showed that seismology research on Greenland is of supporting impact identifying the depth to Moho and estimating the general thickness of the sedimentary rock layer.

Research quality

Based on the material presented to the committee, it is apparent that GEUS, over the last 10-20 years, have changed as a scientific organization leaving the more academic "one-man-band" research and taken on larger integrated studies. Particular towards the latest part of the last decade the projects has become larger, better organized and "integrated" and thus more comparable with G&G project carried out in the petroleum industry. It is obvious that GEUS has gained scientific strength by organizing the work this way.

During 2000 – 2009, 98 projects average 9-11 pr year (most 15 in 2004 and least, 5 in 2009) were carried out in West Greenland.

East and North Greenland had during the same period 64 projects, in general 5-6 pr year (most 9 in 2007, least 3 in 2003). The interest for the West Greenland has apparently been largest, which is natural due to the licensing policy with several rounds, many active licences, and a high level of exploration activities etc.

There are 60 peer review papers in international journals and proceedings over the same period. West Greenland is covered by 33 of these whilst 18 are related to East and North Greenland. Nine papers are about Greenland in general. This suggests that a considerable proportion of results from the projects are published. It also indicates that projects and research, in general, are of good quality since many papers are in high quality journals and co-authored with several highly merited scientists. In the North and East Greenland "joint industrial consortium" the results available for publications are naturally time-constrained, which are so far limiting the number of publications from this area.

However, GEUS' most important objective is to advice, collect and provide geoscientific data to the authorities in Denmark and Greenland and industry. Consequently, an appropriate

balance between scientific work and publishing must exist. It can be practical to publish more in internal journals and topical reports. Publications could thus be regarded as necessary “spin-off” for scientific quality control. In other words, is the focus on “external” publishing unnecessary high in GEUS? After all it is more time consuming to write a full scientific paper intended for an international journal than writing a report.

Another advantage of publishing is the demand for the scientist to keep updated on relevant literature.

GEUS’ source rock laboratory that contributes strongly to the Greenland activities are currently one of the best, may be the best laboratory of its kind in Europe. This is evident for produced publications, particular with respect to the molecular aspects of organic geochemistry.

Recommendations

The activities on Greenland has obviously shifted focus from West to North-East, leaving the oil industry to explore and gain geological knowledge in the West. North-East Greenland is a new frontier area. GEUS’ strategy seem be production of data and knowledge in order to attract the oil industry, not only for the local area and the Greenland continental shelf, but also to support information to companies exploring offshore Mid and Northern Norway.

The established consortium between GEUS and the oil industry is an excellent initiative and seems to be run efficient with great results. It is difficult to recommend any better approach. Jørgen Bojesen-Koefoed referred to the projects and the way it was organized as a process since the oil companies combined with obtained results promotes and suggests the next season’s field work. It sounds like a creative process.

From an oil industry point of view it is suggested that the results are integrated the best possible way into the planned Cretaceous stratigraphic framework. It is also suggested that stratigraphic frameworks also are established for Jurassic, Triassic and Permian. Source rock studies, provenance characteristics, etc. should be undertaken and integrated with these stratigraphic frameworks. Source rocks and reservoirs of these ages may be of importance in the sub basalt areas at the Norwegian Atlantic Margins. Extensions of GEUS’ East Greenland knowledge into the Norwegian Møre and Vøring basins and integration with Norwegian exploration wells will be of great value for petroleum exploration in that area and for the North Atlantic Margin understanding in general.

A large proportion of the data is delivered on a GIS platform. This activity can probably be improved by connecting this system with a relational database.

Establishment of web access to non proprietary G&G data from Greenland would be welcomed by the industry and academia.

Continental shelf mapping, UN Convention on the Law of the Sea

Background

The UNCLOS Article 76 was ratified by Denmark on November 16, 2004. Denmark has then 10 years to submit a claim to the UN for an extension of the continental shelf beyond the 200nm. In order to evaluate the continental shelf of the Kingdom of Denmark, the Danish Continental Shelf project was set up. The project has been funded by The Ministry of Science, Technology and Innovation the since 2003 and runs for ten years.

Research activities

The Danish Continental Shelf project has five areas of focus; south and north of the Faroe Islands, plus south, northeast and north of Greenland.

A claim of the shelf beyond 200nm can be made on basis of food of slope, sediment thickness and a natural geological prolongation of the shelf. The methods for resolving this are geological and geophysical models based on bathymetric, seismic and gravity measurements.

Activities on the continental shelf mapping and the UN Convention on the Law of the Sea, were presented (by *Thomas Funck*), and GEUS coordinates the technical work for Greenland, and coordinate in cooperation with the Faroese Earth and Energy Directorate the areas around the Faroe Islands.

GEUS is project coordinator and manager for seismic reflection, seismic refraction and data management. The Danish Space Centre is the manager of the gravity and geodesy and the Danish Maritime Safety Administration is manager for the bathymetry.

North of Faroe Islands

A large area could potentially be claimed based on expected continuation of sediment thickness and food of continental in an area also designated by Iceland and Norway.

A geomorphologic interpretation based on reflection seismic and multibeam bathymetry has been completed. New data was acquired interpreted and has been published in cooperation with international partners. The results have been published in internal reports, reviewed international papers and textbooks. The technical work north of the Faroes has successfully been finalized, and Denmark submitted a claim to the UN in 2009.

South of Faroe Islands

Potentially a very large area can be claimed upon a geological natural prolongation of the basalt plateau to the south and possibly enough thickness of the sediment on top of the basalt. Iceland, Ireland and United Kingdom have all designated large parts of the area that Denmark/Faroe Islands potentially can claim.

Seismic refraction profiles were acquired in 2004 in order to investigate the crustal structure in a zone of smaller banks between the Faroe Islands and the Hatton Bank south of the Faroe

Islands. New findings were that the continental crust can be correlated from the Faroe Islands into the zone of the smaller banks and into the Hatton Bank. Segmentation and thinning of the crust between the banks is interpreted as the result of transform zones. The result of the findings has been published in an international paper.

Dredging and drilling of shallow wells have been made in the zone of smaller banks and Hatton Bank in order to determine the relation to the Faroese basalts. The sampling of rocks have been analyzed and dated.

A study of the seabed and the morphology of the sediments based on seismic surveys, multibeam bathymetry and deep-tow side-scan sonar have been made during the period. The study has resulted in an improved understanding of pathways of the Norwegian Sea overflow water. Data acquisition and data interpretation results have been published in internal reports and review international papers with national and international co-authors

South of Greenland

A large area between Greenland and Canada can potentially be claimed. The argument is an expected continuation of the thick sedimentary layers between Greenland and Canada, that Eiriks Ridge both morphological and geological can be regarded as a natural continuation of Greenland, and that the food of slope is located on the deepwater side of the ridge.

GEUS acquired seismic data in the extent spreading axes in the Labrador Sea and on the Eiriks Ridge, a sediment drift just south of Greenland in 2006. The results are published in internal reports.

In 2009, a joint Danish-Canadian cruise (SIGNAL 2009, Seismic Investigations off Greenland, Newfoundland and Labrador) acquired refraction and reflection seismic in order to study the crustal structure in an area including the Eiriks Ridge south of Greenland. The project was a collaboration between the Canadian and Danish National Geological Surveys and University of Dalhousie, Halifax. The crustal structure beneath the Eiriks Ridge was found to be of underplated oceanic origin. The study is reported in internal reports and published in review international paper (in 2010)

Marine seismic multibeam data was acquired in 2008.

North of Greenland

Studies of the Northern Greenland and the area north of North Greenland have been performed to determine food of slope, sediment thickness, and geological origin of the Lomonosov Ridge in order to prepare a claim of a large area north of Greenland.

Marine refraction and reflection seismic and hydrographic surveys in the ice-covered Canada Basin north of Greenland were acquired in corporation with scientist from the Canadian and the US authorities. The ice represents a large risk to instruments. The techniques were refined as experience raised. Short offset hydrophone streamer was used for the seismic reflection seismic and expendable sonobuoys recorded refraction seismic. The first full season of data

was in 2007 and around 300 km was acquired (3000 km sailed). During the 2009 season ca. 600 km was acquired with first one icebreaker and later with a second icebreaker.

Aero magnetic and gravimetric data was acquired during spring in 2009 as a joint Canadian – Danish operation.

Seismic stations were deployed in the northern Greenland in 2004 in order to characterize the crustal structure of northern Greenland prior to establish if Greenland has a natural prolongation to the north along the long narrow Lomonosov Ridge. The assumption is that Lomonosov Ridge is of continental origin. This project is also described under 2.6.

Northeast of Greenland

A large potentially area can be claimed by Denmark/Greenland in the region between Greenland, Jan Mayen and Svalbard. The argument is an expected continuation of the thick sediment layers from Greenland and the East Greenland Ridge both morphological and geological can be regarded as a natural continuation of Greenland, and that the food of slope is located on the deepwater side of the ridge.

In cooperation with University of Bergen, University of Copenhagen and University of Hokkaido, Japan, were reflection and refraction profiles acquired on the East Greenland Ridge, the Greenland Basin and the Boreas Basin basins to the south and north respectively, in 2002. Gravity was integrated into the geophysical modelling of the seismic data.

Findings were that the crustal structure of the Greenland Basin is of oceanic type, the East Greenland Ridge is of overall continental origin and a major faulted basin province above highly extended continental crust was found to the northeast of the East Greenland Ridge. The study has been published in a reviewed international paper with international co-authors. Additional scientific findings are the origin of continental slivers and an improved understanding of the opening of the North Atlantic.

Research quality

In general data coverage in area of interest is low. This is caused by the harsh and remote operational conditions. In corporation with national and international institution GEUS has acquired new data in the areas of interest. Acquisition of data north of Greenland is an extreme challenge. The distances are very large and the ice-covered sea and the low temperatures make the acquisition of new data very challenging and expensive.

New methods of acquisition, adjustment of equipment etc has been deemed necessary because of the remote and harsh environment.

The new data have been analyzed and a wealth of new knowledge has been gained. The data and new findings have been published in internal reports, in reviewed international papers and textbooks. Authorships are most often shared with national and international co-authors.

The seabed studies have resulted in new insight to the depositional systems in the general and in the North Atlantic. The deep crustal studies have also resulted in new knowledge of the regional geology as well as in tectonic systems.

The quality of this section is reflected by the high numbers of reviewed international papers.

Recommendations

- The international cooperation is very important and necessary for the acquisition of new data in these remote and harsh environments.
- It is recommended to publish as early as possible, to put Denmark in the best possible situation when submitting a claim.
- It is recommended to seek to establish a new tectonic model for the Arctic area.
- The programme is an excellent change to acquire data in a remote area with unknown geology. The budget is restricted for an approx. 10-year period and GEUS should consider how to extend the excellent work and stay in front of the research of these remote areas.

CO₂ storage (CCS)

Research activities

GEUS has been involved in research on CO₂ storage since 1995 and have participated in 17 research projects that have received financial support from both national and EU funds, but also international funding (Norwegian Research Council). The role of GEUS is as adviser on risk related to and possible effects of CO₂ storage, planning against other subsurface activities as well as on the economy of storage capacity, injectivity, etc. In addition, GEUS has carried out consulting projects for the industry covering mapping of structures, site characterisation and injection modelling. The assessments of potential sites were based on all available information from deep wells and seismic surveys, mainly from the hydrocarbon and geothermal explorations onshore Denmark.

A presentation was provided on the EU funded experimental site study CO2SINK near Ketzin, Germany (by *Peter Frykman*), a full field pilot study on injection of CO₂ where GEUS provided reservoir modelling expertise as well as contributed to the mapping, sedimentology, reservoir engineering work. All disciplines that draw on experiences inherited from GEUS' many years of involvement in petroleum geology and reservoir modelling including consultancy work for the petroleum industry and geothermal projects.

The canalized sand system in the Ketzin structure was modelled stochastically on industry standard software demonstrating GEUS' ability to make a modern reservoir assessment. And in combination with the leading edge knowledge on the subsurface geology of Denmark, GEUS was chosen to lead onshore investigations of potential sites for CO₂ storage in Denmark for an industry cooperation project.

Research quality

Participation in a vast amount of pioneering projects on CCS has placed GEUS in the leading edge of know how within this field. The Ketzin pilot study in particular may provide information that can prove to be important for future advisory to the Authorities on risk and effects of CO₂ storage. Publications include a large number of well documented reports and many oral presentations at international and national workshops and conferences. In the period 2000-2009 examples of peer review internationally published work include: an early assessment of CO₂ storage in depleted low permeable chalk reservoirs and a second on CO₂ storage in combination with geothermal plants (2003); later on assessment of the Vedsted structure as potential site for storage (2008), and finally, in 2009, GEUS issued a more comprehensive overview on the potential for storage in Denmark.

Recommendations

The early and timely onset of GEUS' assessment of CO₂ storage in Denmark and Europe places GEUS in the front of understanding risk and possibilities, a competitive edge that GEUS is encouraged to take further. It is recommended that GEUS consider if a formal peer

review process could strengthen the quality of the research and consultancy work within CO₂ storage. Exchange of subsurface knowledge with geothermal projects and utilizing the obvious synergies in regional reservoir assessment in Denmark should be pursued.

Geothermal Energy

Geothermal energy has been on the agenda in Denmark since the late 1970'ies. Geothermal plants was established in 1984 (Thisted) and 2006 (Margretheholm, Copenhagen).

Research activities

DGU/GEUS has through all the years acted as geological adviser providing assessments of geothermal potentials for the holders of concessions for exploration and exploitation of geothermal energy in Denmark (DONG Energy and DONG Energy/HGS). At any given stage the assessments were based on all available information from deep wells and seismic surveys mainly from the hydrocarbon explorations onshore Denmark.

In the period 2000-2010 assessments have been provided in a review paper (2004), in a number of consultancy papers, and in a more comprehensive report issued (2009). A presentation was given to the Evaluation Panel covering a detail historical overview, status and future initiatives for geothermal exploration in Denmark (by *Anders Mathiesen*):

Potential reservoirs have been identified in sandstones of Triassic, Early and Middle Jurassic and Early Cretaceous age. Maps have been produced that indicate areas where adequate conditions in terms of structural condition, depth, reservoir thickness and temperature most likely are present.

In the most recent report an attempt has been made to provide conservative estimates of the energy resources (GJ/m^2) and its geographical variation in the various reservoirs. The estimates are calculated based on number of model assumptions for the reservoirs e.g. homogeneity. Temperatures used in the calculations are in the top of the reservoirs and they are based on a regional, linear temperature/depth relationship. The depth to the top of the reservoirs are based on seismic sections on which TWT-depth conversions are performed by application of a best fit to a cross plot of TWT vs. depth in all onshore wells.

In the same report the problems related with estimation of the critical parameter: permeability are described. A cross plot of porosities and permeabilities measured on cores from all reservoirs of interest and from all depths clearly illustrate the point that only very crude estimates of permeability of regional significance can be derived from wire line log-porosities.

The report is an excellent display of the versatility of GEUS' database facilities as an effective means for identification of problems related with specific survey investigations.

The report is finalized by recommending guide lines for a survey strategy applicable in a local area which, based on the regional indicators, has been selected as a potentially suited locality for establishing a geothermal production plant. The strategy is described as a stepwise enterprise starting with a preliminary geological model derived from existing data. Based on the preliminary model a new seismic survey is designed, which leads to refinement of the geological model. In case the estimate of potential reservoir size and structure meets the demands, a program for an exploratory drilling can be set up and pumping test for estimation

of hydraulic properties can be performed. With the new information adjustments of the seismically derived interpretation of the reservoir can be carried out and new estimates of the geothermal potential calculated. Pumping tests for estimation of production capability of the reservoir finalizes the survey process proper, and the geological model can be updated.

Research quality

The research is currently in the beginning phase, but as judged from the material available to the Evaluation Panel, the coming research has a sound foundation in the preparatory work based on existing geo-data and long term geological experience in GEUS. The Evaluation Panel is convinced that the newly launched 4-year project “The Geothermal Energy Potential in Denmark” lead by GEUS and in cooperation with University of Aarhus, SGU and GFZ will significantly improve the understanding of the Danish geothermal reservoirs and their production capacities, and will bring forward enhanced possibilities for establishment of geothermal production plants.

The activity related with the aim of enhanced utilisation of geothermal energy in Denmark very well illustrates the capacity of GEUS as an organisation that in due time prepares itself for coming challenges and, an organisation that is capable of carrying out advisory tasks on a scientific basis and in collaboration with other institutions.

Recommendations

As GEUS’ via its vast expertise functions as geological adviser to the authorities as well as carries out consultancy work for concession holders in assessment of future geothermal projects, it is recommended that GEUS consider if a formal peer review process could strengthen the quality of the research and consultancy work.

Seismology

The seismology group at GEUS is the national body for monitoring and study of earthquakes and other types of earth-tremors recordable in Denmark, Greenland and Faroe Islands. The group consists of three scientists currently assisted by one PhD, one MSc and two BSc students.

Research activities

A very thorough presentation was given on the seismology group and its activities (by *Tine B. Larsen*). The group is responsible for administration and maintenance of networks of seismographs distributed in Denmark and Greenland. The permanent part of the network consists of five stations in Denmark and four in Greenland. Temporary networks are currently established in Greenland as part of ongoing scientific projects.

The permanent seismographs are continuously recording and the records are transferred via permanent telephone connections to the lab at GEUS.

The Danish seismograph network is integrated in an international network for monitoring of earthquakes and furthermore it contributes to the Comprehensive Nuclear Test Ban Treaty issued by UN.

Thus, the recordings contribute to the identification, epicentre-localisation, depth estimate and characterization of earthquakes or other seismological events in the world. The parameters of earthquakes in the Danish region are calculated by the seismology group at GEUS. The information is readily available for the public e.g. on GEUS' homepage.

The seismology group has a long tradition as actively engaged partner in international projects. The two main scientific areas in focus are: studies of lithosphere structures in Denmark and Greenland and studies of glacier dynamics in Greenland.

The first category comprises: 1) a study of the subcrustal lithosphere in an extensive profile across the Sorgenfrei-Tornquist Zone in southern Scandinavia (project TOR) and 2) lithosphere studies in northern Greenland (e.g. project GLATIS). The second category has nucleated in two highly multidisciplinary studies: EGGCITE focussing on revealing the causes for glacier earthquakes and GLISN for monitoring of changes in glacier dynamics.

Research quality

The publication activity is quite high with 9 scientific papers in international peer reviewed journals 2002-2008, 27 conference abstracts 2001-2009, 16 posters w. abstracts 2005-09 and 9 popular articles 2005-2008.

In the period considered the research has its main weight in Greenland. It is innovative and highly original especially in the new field of glacier seismology which seems to hold novel perspectives for acquiring insight into the dynamic behaviour of glaciers. This also appears from the fact that the project consortium consists of ten countries.

The activity of seismology group meets the intensions expressed in GEUS' strategy plan and the publications and presentations made available for the evaluation panel demonstrate research standard in a high international class.

Recommendations

One of the corner stones described in the strategy plan is the application of seismological data for development of refined lithosphere models in the Danish region.

The Evaluation Panel noted that no permanent seismological station is placed on the Faeroe Islands. We envisage that a station here could be a valuable supplement to the scattered network in the North Atlantic Ocean.

Furthermore, it appears to us that an expansion of the permanent net of stations in Denmark could facilitate the possibilities for fulfilment of the aims in the strategy plan also in Denmark.

Overall Evaluation

General observations

GEUS is in general recognized as a strong and focused scientific organization holding a lot of skilled researchers. The research institution covers all disciplines required for a modern assessment and evaluation of the subsurface on a level of international standard.

Researchers demonstrated through presentations and publications that GEUS teams are innovative and have refined existing ideas into modern techniques and work methodologies that have had a direct impact on the geological understanding of Denmark and Greenland.

A number of observations and recommendations are given in the topic specific evaluation above, and in addition to this, the following issues have drawn the attention of the evaluation panel and is commented below:

- Consultancy work: A consistent amount of consultancy work for the industry over the evaluation period.
- Third world country engagements.
- Purpose of publication and citation indexing.
- Additional considerations: GEUS' role as adviser and leader of commercial project at the same time.
- General areas to be strengthened.

Consultancy work

It is the impression of the Evaluation Panel that consultancy work by GEUS, including work in neighbouring countries, as well as third world country projects, have contributed in a positive way to maintain high level of skills and an international standard. But also improved the work methodologies and quality of work in the research teams and made positive feedback and improvements on subsurface matters.

It seems vital and a necessity to maintain engagement in international research including projects funded by the industry in order to keep up a persistent and continuous high level of skills, but also the demands for geological and geophysical analyses in the modern petroleum exploration and exploitation.

It is the impression that the former financing through EFP funds ensured continuity in the research carried out in Denmark and Danish North Sea, a continuity that may be less obvious to reach given the current funding situation.

Recommendations for work in third world countries

GEUS has successfully been engaged in third world development projects, a positive example being long-time training and collaboration with universities and the national oil company in Vietnam. It is not quite clear why these projects became successful (this should be investigated), but it seems obvious that the enthusiasm, professional engagement and many skills in GEUS as the Evaluation Panel has experienced, is a very valuable resource.

GEUS has proven to possess the research capacity and know-how for support in setting up a geological survey, petroleum geology administration and training in petroleum systems and it seems obvious and a natural thing that GEUS should assist third world countries. If decided to continue the mission future cooperation projects could also draw on knowledge within CSS and geothermal energy within the Energy Resource Programme area.

Comments on publications and citations index

Part of the present evaluation concerned publications and included a citation analysis and overview of publications and citations per researcher (by Peter Nytoft). So far, however, it is not yet decided in GEUS how to use citations nor number and frequency of publications although researchers are encouraged to publish.

GEUS as a whole has a common target number for publications to be reached every year, but not specific for any department or subject. Within the last 10 years of the Energy Resource Programme area alone, publications sum up to more than 450 (342 international, 113 GEUS series), or a publication density of about 0.75 per year per senior researcher in the three departments. It is difficult to judge whether this is sufficient or not, but it is the view of the Evaluation Panel that emphasis should not be on numbers alone, rather on quality. And additional to this are the many project reports, or articles in Danish fulfilling the requirement for dissemination to the public, all forms of publication that should count as achievements, i.e. some of the most important stratigraphic reviews appear in GEUS' own journals.

Demands for long publication lists are escalating and affect project funding applications, internal promotions, etc. A position as senior researcher requires a certain number of publications, however, to the Evaluation Panel, this should not be limited to international papers alone for the above reasons.

The time available for writing publications was briefly discussed but no straight answer was given which is understandable since publication options are project specific as well as depending on the individual researcher and team. Some projects carry a confidentiality period clearly delaying any publication.

It is the view of the Evaluation Panel that publications in international peer reviewed journals are important as this is a good way of having research work and quality peer reviewed and measured against quality elsewhere. Secondly, publications internationally may also serve to communicate research results and exchange of ideas. Time for writing publications could perhaps be allocated in each research project proposal.

Benchmarking against other research institutions and geological surveys may be one way of obtaining a measure for number and citations per researcher although previous attempt to do this has been less successful.

Additional considerations

GEUS by its strong position on research and know how in Denmark and Greenland is attractive as partner in industry sponsored research projects, and GEUS partly depends on this type of financing to be able to carry out large research projects. A conflict may however arise in relationship to licensing rounds where 1) GEUS acts as adviser to the Authorities and make recommendations to awards, and at the same time 2), sold data compilations packages and interpretations to the industry, and/or 3) carried out industry sponsored research in the specific area as well as 4) promote the area for the Authorities.

In addition, a conflict may also exist between confidential research for the industry and making results publicly available. GEUS solved this problem by making all data available to everybody at a flat price, e.g. as done in the NE Greenland project. For the same reason consultancy work including prospect assessment primarily has been undertaken in the areas outside Danish North Sea, and evaluations in relationship to licensing rounds in well defined area of the survey with restricted access. It may be of interest to discuss the above issues with e.g. The Norwegian Petroleum Directorate that has solved this differently.

Additional areas to be strengthened

- Keep up the large flux of PhD students as this stimulates work for students and researchers expose students for the world of research and acts as a screening for future candidates for position as researcher.
- Renew and update website to include GIS format overview of data including wells, maps, structural elements, research projects, etc., perhaps merged with parts of the Danish Energy Authorities website information.
- GIS based compilation of updated maps over the subsurface of the North Sea and Denmark (GIS database is part of the new project on Geothermal Energy).
- Keep on providing educational support to Geocenter Denmark as this is an important way for researcher to stay sharp and disseminate research results to a broad audience.
- Consider strengthening the reservoir division if GEUS level of activity within chalk reservoir evaluation is anticipated to increase after 2012.