

**Scientific evaluation of Programme area 4
Raw Materials (2004 - 2010)
at the Geological survey of
Denmark and Greenland
(GEUS)**

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Summary and list of recommendations

Digital bedrock geological maps at the scale 1:500 000 and the base data sets behind these compilations are now available for the entire part of Greenland not covered by ice. Similar digital maps suitable for use at the scale 1:250 000 are also available in the northern and north-eastern parts of the country. The completion of all this work is a major achievement for GEUS. The completion of a seamless database with a common legend in the south-western part of Greenland, the systematic geological mapping of the Danish land area and the completion of a digital seabed sediment map at the scale 1:500 000 are also all major achievements.

The quality and frequency of publications in especially the Greenland part of the Raw Materials programme is highly impressive. The publications in highly respected, international geoscientific journals with peer review provide a solid guarantee that high quality research has been completed at GEUS, especially in the field of igneous petrology. There is a clear potential for more peer review publications within economic geology, as long as the very well qualified staff is given more time to write such papers. The evaluation panel experienced some difficulties to identify areas of high quality research in the Danish part of the programme due to the restricted number of peer-reviewed papers. Once again, we judge that there is a clear potential. However, better planning to accommodate the completion of such publications in geoscientific journals is necessary.

Society needs an overall, consolidated assessment of the Danish raw materials resources. A long-term strategy accessing sustainable exploration of the Danish raw materials resources is needed. This will both be a valuable tool for the regulators, but also ensure a stable supply of raw materials. GEUS would be the natural body to collect data and provide information for administrators and industry. We are aware that it will be a major challenge to establish such a strategy in view of the present administrative set-up. A political decision would be required. GEUS may facilitate such a decision by considering how such a strategy could be structured and include this in the upcoming strategy.

The panel urges development of new areas of research such as environmental health, which has a direct bearing on public health, and element mapping related to economic geology research in support of the Programme's mineral exploration activities. Current and future instruments in the GEUS laboratory pool are well-suited to this purpose. Programme area 4 is an appropriate place to develop these new areas of research.

The evaluation panel has identified several activities and procedures that need to be strengthened or improved, both under individual activity areas and as broader strategic adjustments. These recommendations are presented in the main body of text. However, in order to bring these recommendations into the reader's focus, we have decided to repeat all these recommendations below in this summary. The recommendations are presented here without any specific order of priority:

Bedrock geological mapping and regional geological research in Greenland

- Digitalization of the remaining older bedrock geological maps at the scale 1:100 000 should be completed.
- The bedrock databases need to be continuously under scrutiny so that their quality and accessibility are held at the highest possible level. If base information is only in analogue form (e.g. field notebooks from the 1970's and 1980's), it is recommended that a key reference to archive material at GEUS is included in the respective database. The problem of the release of data to the public on GEUS' web site prior to publication in a printed GEUS document or international geoscientific journal needs to be addressed, so as to avoid misuse of these data by external customers.
- Airborne geophysical data is needed over the whole of Greenland not covered by ice, most urgently in the south-eastern part of Greenland. GEUS should look into alternative financing models for geophysical mapping, for example, joint financing by Greenland Bureau of Mineral Resources and Petroleum, industry and GEUS for limited target areas.
- Geological mapping and integrated regional geological research form a sound basis for mineral resource assessment. However, the digital maps at the scale 1:500 000 are not considered to be of sufficiently high resolution to provide the necessary foundation for this assessment. We recommend that geological mapping in a particular region in the future involves, firstly, a detailed in-house evaluation of geophysical and remote-sensing data and older geological data, followed by selection of key areas for more detailed field mapping at 1:100 000 or 1:250 000 combined with focused geological research activities. The selection of key areas in, for example, south-eastern Greenland should make full predictive use of the recently completed detailed work in the south-western part of the country and close cooperation with representatives from the mineral exploration industry. Time needs to be planned for even more highly focused work on specific mineral deposits by one or more specialist economic geologists, possibly at a later stage.
- The documentation of ongoing or completed work in GEUS' bulletin and report series is important and should be continued. With the exception of the confidential reports, all these documents need to be placed on the GEUS web site to make them easily available to the public. Time also needs to be planned, during or in the later stage of a project, for the completion of publications to be submitted to international geoscientific journals. In this way, GEUS will maintain its highly respected scientific reputation.
- In the context of the bedrock mapping and regional geological research activities, there is a need for specialists in metamorphic petrology and geophysics at GEUS. We would welcome one or more geophysicists who also hold a tight understanding of geological processes, especially in structural geology and tectonics.

Mineral resource assessments in Greenland

- More emphasis on promotion of impact of GEUS activities for society, industrial investments, work possibilities and tax revenue. This could be quantified to show how limited governmental funding can make a huge difference and quick pay back to society in form of industrial investments, work opportunities and tax revenue.

- The economic geology group should be increased to obtain a critical mass. In this respect a strategic discussions should define what competence is lacking and a recruitment plan should be set up.
- GEUS should take a coordinating role in helping to establish a Greenland long-term mineral strategy that involves the Greenland Bureau of Mineral Resources and Petroleum, other relevant Greenland authorities, other government agencies (national and regional), research institutions, and the private sector. The strategy should include provisions for prioritizing near- and long-term mineral exploration objectives, necessary scientific baseline information (data and interpretations), and aligning with sustainable resource development objectives.
- There is currently a window of opportunity in EU funding for raw materials research. So far GEUS has been fairly invisible in this discussion. Given the fantastic potential, not the least for so called, critical commodities, in Greenland, GEUS should be involved of EU project development, for instance in the potential for a European Innovation Partnership on Raw materials.
- A serious issue that most staff expressed a frustration not having time to publish their work. While the evaluation panel fully realizes that this is a funding issue at the same time it is in GEUS mission to conduct highest level science and the only way to substantiate this is publishing in peer reviewed scientific journals.

Raw materials and geological mapping in Denmark

- The extremely comprehensive borehole data and the JUPITER data base should be used to create a 3-D map of on-shore top Quaternary. This will benefit not only groundwater mapping but also a much better understanding of the Quaternary of Denmark.
- In view of the large construction projects under way and the very significant raw materials interests, the robust activity regarding off-shore raw materials should be continued.
- The sustainable use and society's need for a stable long-term supply of raw materials makes a National raw materials strategy for Denmark a pressing concern. GEUS should facilitate this development.
- As part of this long-term strategy, it is recommended to create a unified sea-land geological map, enabling a much more complete understanding of the raw materials resource.
- We recommend assessing the consulting activities in connection with raw materials exploitation both to avoid conflict of interest but also to evaluate if the efficiency of operation can be increased.
- In order to better facility industry needs, we support GEUS's efforts to make the MARTA database accessible to the users, and further propose to establish a stakeholder forum.
- A more rigorous mechanism for review of reports and quality control of GEUS projects.
- Address the serious imbalance in peer-reviewed scientific publications between Denmark and Greenland.

Applied Mineralogy and Laboratory Development

- Build upon the strengths of the established, demonstrated international reputations of the LA-ICP-MS and CCSEM laboratories by:

1. Assuring continued, adequate staffing for both scientific and technical positions to maintain effective operations and “cutting edge” scientific productivity.
 2. Considering investments in a new CCSEM and subsequently in a multi-collector LA-ICP-MS.
- Examine new areas for application of the current (and any future, new) instruments to new areas of research such as environmental health which has a direct bearing on public health, and element mapping related to economic geology research in support of the Programme’s mineral exploration activities. Programme area 4 is an appropriate place to develop this new area of research.

International projects

- The panel recommends that a concerted effort should be taken by Programme area 4 to continue and expand international work, by actively seeking new sponsors and collaboration partners.

Communication/outreach

- Impacts of GEUS research: The Programme should develop good and balanced set measuring tools or metrics for its research activities that is not limited to peer-reviewed publications. These metrics could include, for example, post-delivery dissemination plans following delivery of the product, an active plan to demonstrate and communicate project relevance to appropriate audiences, etc.
- The Programme should identify and develop strategy for specific target audiences: Primary audiences are likely to be (1) Ministry; (2) Greenland Bureau of Mineral Resources and Petroleum; (3) other government authorities in Denmark and Greenland. Secondary audiences, dependent upon the activities, may include the private sector and the general public. The expectations and needs of the audiences should be identified and appropriate communications mechanisms and formats discussed.
- The Programme should develop a more through-going communications strategy for ongoing research and research/objectives in development. Some short, one-page summaries of these communications points can be developed, if not already available, for discussions with potential sponsors and collaborators.
- Build upon the very informative web page for the Department of Petrology and Economic Geology, continuing to provide new information in a variety of formats for different audiences.
- Formalize one or more advisory panels of representative stakeholders who should regularly meet GEUS directors and departmental heads to provide feedback to each other on activities.
- Quantify and communicate how important GEUS is for society.

Evaluation process

Objectives, tasks and time schedule

According to the Danish Statutory Order from the Ministry of Climate and Energy of October 7, 2008 on research evaluation at the Geological Survey of Denmark and Greenland (GEUS), the GEUS Board has decided that the next research evaluation shall cover the “Raw Materials” programme area. The evaluation panel shall undertake an evaluation of research and presentation activities within this programme area for the period 2004-2010, constituted by the following main themes:

- Mineral resources of Greenland
- Mineral resources of Denmark
- Geological mapping of Greenland
- Geological mapping of Denmark

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

The tasks of the panel are to evaluate the research activities of GEUS on the basis of:

- Publications, reports and other relevant material produced over the period 2004–2010;
- Interviews with GEUS’ management staff and scientists, and visits to laboratories and work facilities at GEUS.

In order to:

- Identify areas of high quality research;
- Identify areas where the research of GEUS should be strengthened in order to meet GEUS vision and strategies;
- Identify areas which should be strengthened in order for GEUS to expand GEUS’ ability to provide assistance to third world countries with the broad area of raw materials;
- Provide 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 within this programme area seen in the perspective of the survey’s statutes and general mission.

The evaluation panel is supposed to report their observations and conclusions in writing. The experts shall not disclose to any third party information gained in their capacity of being a member of the evaluation panel.

It is planned that the evaluation panel pays a visit to GEUS for evaluation (3-4 days), including preparation of the final draft report, in the period May–June, 2011. The presentation of the findings in the final report shall be presented to the GEUS Board in September 2011. Based on the findings, an implementation plan will be developed by the programme area staff and presented to the GEUS Board in the autumn 2011. The Board decisions are planned to be implemented in 2012.

GEUS' tasks and mission within the Raw Materials programme

GEUS responsibilities within the Raw Materials programme are described in Act 536 of June 6, 2007 as: “GEUS provides 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”. According to the presentation materials provided to the evaluation panel, this includes extensive advice to the following authorities in Greenland and Denmark:

- Bureau of Minerals and Petroleum (strategies, promotion, resource estimates, advice on exploration and exploitation of minerals);
- Nature Agency and Environmental Protection Agency of the Danish Ministry of Environment (On- and offshore raw materials, resource estimates, construction work, wind power plants etc.).

It is further stated in Act 536 of June 6, 2007, “GEUS may take on tasks from public authorities and private individuals in Denmark and abroad against full or partial payment”. According to the presentation materials provided, this includes advice and consulting for private companies, especially mining and oil companies, contractors etc. under four main activities:

- Distribution of data and results;
- Sponsored research projects;
- Data acquisition and QC for clients;
- Consulting.

Act 536 of June 6, 2007 also states the following: “GEUS is responsible for the scientific exploration and geological conditions in Denmark and Greenland and adjacent shelf areas. GEUS must conduct research to the highest international level into matters of importance for the exploitation and protection of Denmark’s and Greenland’s geological natural values. GEUS must also carry out mapping, monitoring, data collection, data management and communication about these matters”. According to the presentations, this task includes comprehensive dedicated research and build up of knowledge, especially within the Department of Petrology and Economic Geology (previously separated into the Departments of Geological Mapping and Economic Geology), but also in the Department of Groundwater and Quaternary mapping (includes the previous Department of Quaternary Geology) and the Department of Marine Geology and Glaciology, with strong collaboration internally in GEUS and with many national and international partners.

Within the Raw Materials programme, the strategies were approved by the board of GEUS and described further in 4-year contracts with the Ministry (2004-2007 and 2008-2011), the latter provided to the evaluation panel prior to the site visit. The major strategic goals defined in the contract were as follows:

2004-2007:

- Supracrustals and their resources, Greenland
- Magmatic environments and their resources, Greenland
- Applied Mineralogy
- Marine Geology (primarily in programme area 5)
- Quaternary mapping (primarily in programme area 5)

2008-2011

- Mineral resources in the Archaean block south of 64° N, south-western Greenland
- Geological and metallogenetic maps – Greenland
- Applied mineralogy
- Coast and seabed (primarily in programme area 5)
- Geological mapping and change of landscapes (primarily in programme area 5)

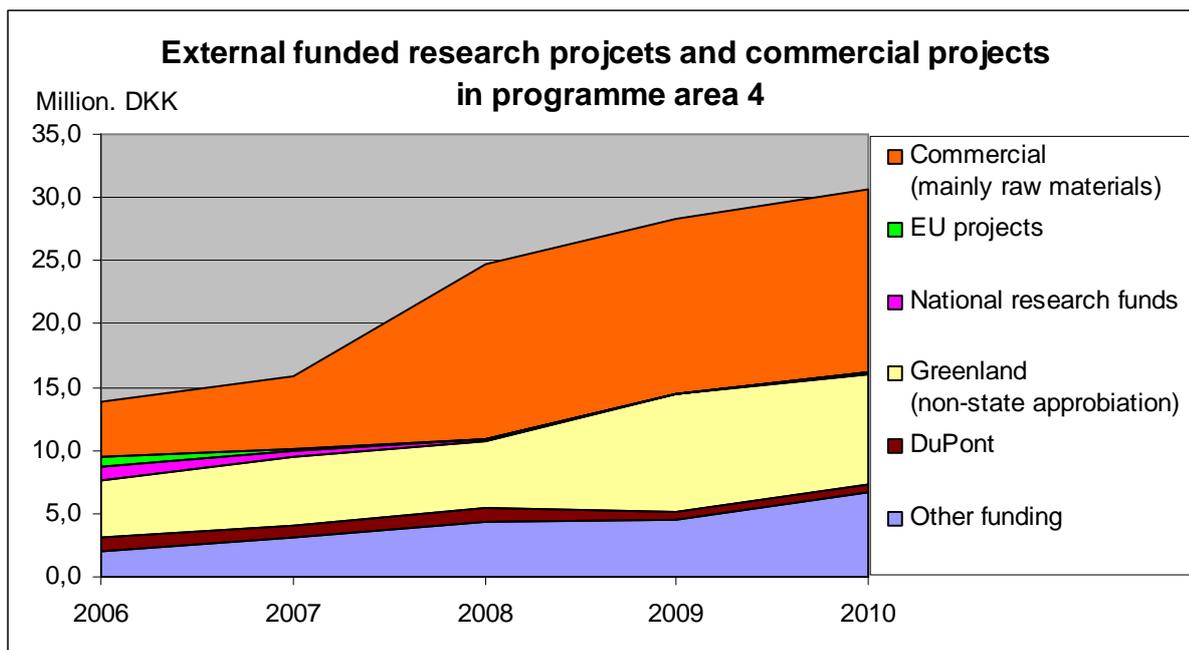
Table 1 – The personnel and budget to complete these activities are summarized for each year in the following table:

Year	Personnel (budgeted)	Personnel (account)	Expenditure (budgeted) Million DKK	Expenditure (account) Million DKK	External income Million DKK
2004	48	52	36.2	40.0	16.7
2005	47	50	41.0	43.1	15.0
2006	48	48	44.3	42.6	13.8
2007	53	54	45.3	44.5	15.9
2008	56	54	47.4	46.6	24.8
2009	48	55	43.3	55.0	28.3
2010	53	55	47.0	54.4	30.7

The evaluation panel was informed that approximately 80% of the funding in the Raw Materials programme was allocated to activities in Greenland. Furthermore, the vast majority of the remaining funding in Denmark was related to sea-based activities.

Upon request, the external income was presented to the evaluation panel and divided according to different funding sources. The breakdown for 2010 is shown in figure 1. The evaluation panel note especially the very limited input from EU.

Figure 1 – External funded research projects and commercial projects in programme area 4.



Evaluation procedure

The evaluation panel consisted of the following persons:

- **Jesper Sand Damtoft**, R&D, Quality and Technical Sales Support Director, Cementir Holding, Italy/Denmark;
- **Elizabeth Eide**, Senior programme officer, National Research Council, Washington DC, USA;
- **Michael Stephens**, Professor, Senior state geologist, Geological Survey of Sweden, Sweden;
- **Pär Weihed**, Professor, Director Centre for Advanced Mining and Metallurgy, Luleå University of Technology, Sweden.

The evaluation panel carried out their work according to the original planning and the detailed programme shown below:

Monday, June 6

- 9.00 Welcome, Introduction to GEUS and the Evaluation Project. Presentation of results contracts, the involved departments and the sub-programme areas (Flemming Getreuer Christiansen – deputy director)
- 10.00 Discussion on the role of the evaluation panel members, on the mission programme, the outcome of the mission, and the timescale for the evaluation.
- 11.00 Leif Thorning and Christian Knudsen: Overview presentation of the programme area 4.
- 11.40 Stig Schack Pedersen: Terrestrial raw materials and mapping in Denmark
- 12.05 Jørgen Overgaard Leth: Sea bottom raw materials and mapping in Denmark
- 12.20 Lunch
- 13.20 Nynke Keulen & Thomas Kokfelt: Research activities in SW Greenland (2004–2010)

- 13.50 Jochen Kolb & Bo Møller Steensgaard: Research activities in SE Greenland (2004–2010)
- 14.20 Troels F.D. Nielsen: Kimberlite
- 15.20 Christian Knudsen: Zircon – Provenance
- 15.50 Per Kalvig: Foreign countries
- 16.10 Discussions with selected staff members

Tuesday, June 7

- 9.00 Laboratory visit
- 10.00 Individual interviews
- 13.00 Individual interviews
- 15.00 Preparation of mission report

Wednesday, June 8

- 9.00 Discussion with selected researchers if demanded
Continued preparation of draft mission report
- 13.30 Preparation of final draft mission report
Preparation of debriefing conclusions
- 16.30 Debriefing

Thursday, June 9

- 9.00 Preparation of final mission report
- 14.00 End of mission

The following staff members were interviewed: Flemming Getreuer Christiansen, Karen Edelvang, Henrik Granat, Karen Hanghøj, Nynke Keulen, Thomas Find Kokfelt, Jochen Kolb, Christian Knudsen, Bo Møller Stensgaard, Max Nykjaer Strunck and Leif Thorning. Besides the presentations, visit to laboratories and staff interviews, the evaluation panel also had access to all pertinent publications (in provided publications list) for on-site review. A summary of recommendations was presented to director Johnny Fredericia and departmental heads Karen Edelvang and Karen Hanghøj between 16.30 and 18.30 on Wednesday, June 8. The evaluation panel wishes to extend particular thanks to Jens Stockmarr who coordinated our visit to Copenhagen and ensured that the evaluation work was conducted under the most acceptable and agreeable circumstances possible.

Detailed evaluation of activities

Bedrock geological mapping and regional geological research in Greenland

Activities

Knowledge of the character and spatial distribution of rock units at the ground surface, their structural and metamorphic relationships and the tectonic evolution for their development are essential prerequisites for any assessment of the mineral resource potential of a region. The focus of bedrock mapping and other field activities by GEUS in Greenland between 2004 and 2010, coupled to the question of mineral resources, has been in the central-western and south-western parts of the country. Stream sediment and fresh water geochemical work as well as reconnaissance geological mapping was also carried out in south-eastern Greenland, in the context of a new project that initiated 2009. The description of the ongoing and planned work provided the evaluation panel with some fruitful insight into forthcoming work on the Precambrian bedrock in Greenland under the auspices of the new organization at GEUS.

Excellent oral presentations by Nynke Keulen, Jochen Kolb and Christian Knudsen followed by interviews with Nynke Keulen, Jochen Kolb, Christian Knudsen, Bo Møller Stensgaard and Leif Thorning assisted considerably the evaluation of bedrock geological mapping and regional geological research in Greenland for the period 2004–2010. Knudsen provided an overview of the geological mapping and research work in the context of the Raw Materials programme, while some of the results of the recently completed work in south-western Greenland were addressed by Keulen. Kolb presented the ongoing work in the recently established project in south-eastern Greenland.

During 2004 and 2010, GEUS has produced five new bedrock geological maps at the scale 1:100 000, including descriptions of two of these maps, and one new bedrock geological map at the scale 1:500 000 in the western part of Greenland. Furthermore, a revised compilation and printing of two older bedrock maps at the scale 1:500 000 in the south-western part of the country was completed. Production of digital versions of the remaining older bedrock maps at the scale 1:500 000 and more than twenty older bedrock maps at the scale 1:100 000 were also completed in this time period. The development of a 3D mapping system using oblique photographs, the production of new 1:100 000 topography in north-eastern and central-western Greenland and progress with the digital capture of field data at specific observation points have all been completed. Special mapping at different scales, the construction of cross-sections and geological research on the East Greenland Caledonides and on plateau basalt and intrusions complete the founding geological activities in Greenland during the time period 2004–2010.

Nearly 100 peer-reviewed papers in international geoscientific journals that address the geology and geophysics of Greenland have been published between 2004 and 2010. These publications occur in highly respected journals, including Contributions to Mineralogy and

Petrology, Economic Geology, Lithos, Journal of the Geological Society, Precambrian geology etc. The papers published 2009 in special volume 112 of Lithos, which accompanied the 9th international kimberlite conference, and the papers on the East Greenland Caledonides published 2008 in Memoir 202 of the Geological Society of America, with Higgins, Gilotti and Smith as editors, merit special attention. All this scientific documentation is accompanied by approximately 60 peer-reviewed, commonly shorter papers in GEUS' bulletin series as well as by many unedited scientific reports (both open and confidential), popular scientific and promotion articles, and published abstracts to conferences. The book by Henriksen on the geological history of Greenland published in both Danish and English during 2005 and 2008, respectively, merits special attention.

Evaluation

Digital bedrock geological maps at the scale 1:500 000 and the base data sets behind these compilations are now available for the entire part of Greenland not covered by ice. Similar digital maps suitable for use at the scale 1:250 000 are also available in the northern and north-eastern parts of the country. GEUS deserves warm congratulations on the achievement of this major task. Maps at the scale 1:100 000 are now present in mainly the western part of Greenland and the systematic conversion of older 1:100 000 geological maps into digital equivalents is a correct development and needs to continue. The completion of a seamless database in the south-western part of the country with a common legend, placed on GEUS' web site, is also a major achievement.

There is currently a low level of knowledge of the bedrock geology in the whole of south-eastern Greenland and, as a consequence, this region remains one of the poorly understood Precambrian bedrock domains on planet Earth. The evaluation panel wishes to emphasize that the current bedrock database for this region is insufficient for a solid evaluation of the mineral resource potential of the region. A more detailed bedrock mapping campaign with follow-up, in-house studies to understand the geology and the tectonic evolution is required. The evaluation panel noted with some disappointment that quality airborne geophysical data were not available at the initiation of the new project in south-eastern Greenland.

The quality and frequency of publications in the Greenland part of programme area 4 is highly impressive. The publications in highly respected geoscientific journals with peer review provide a solid guarantee that high-quality research has been completed at GEUS, especially in the field of igneous petrology. However, the evaluation work revealed that there are serious problems for geoscientists at GEUS to find the time to write articles for international scientific journals with peer-review procedure in the context of the available project time. Since, according to Act 236 of June 6, 2007, "GEUS must conduct research to the highest international level into matters of importance for the exploitation and protection of Denmark and Greenland's geological natural values", it is not acceptable that such work is carried out in the author's free time without any financial reimbursement. If GEUS aims to hold its hard-earned, high international standard in the geoscientific world and, thereby, attract business or research partners, these publications are of key importance. For this reason, the work behind their generation merits stronger appreciation in the planning procedure for projects.

Notwithstanding these considerations, the evaluation panel also notes the occurrence of some peer-reviewed papers that address the regional geological relationships in other countries in the world which, as far as the panel is aware, do not involve GEUS contracted activities. There is possibly a need for closer oversight and communication concerning the work with publications, so as to optimize the time needed in the publishing of material related to projects under contract at GEUS. The focus at a geological survey should always be on the specific societal needs and commonly in a long-term perspective.

Recommendations

In accordance with the two contracts between GEUS and the Ministry of Climate and Energy, GEUS' work in programme area 4 "Raw materials" during the period 2004–2007 has focused on the central-western and south-western parts of the country. The evaluation panel very much welcomes the closer integration of bedrock geological mapping, regional geological research and mineral resource assessment for which the new organization, operative from 2009 onwards, provides a basis. We take the opportunity here to provide some recommendations for forthcoming activities in the field of bedrock geological mapping and regional geological research:

- Digitalization of the remaining older bedrock geological maps at the scale 1:100 000 should be completed.
- The bedrock databases need to be continuously under scrutiny so that their quality and accessibility are held at the highest possible level. If base information is only in analogue form (e.g. field notebooks from the 1970's and 1980's), it is recommended that a key reference to archive material at GEUS is included in the respective database. The problem of the release of data to the public on GEUS' web site prior to publication in a printed GEUS document or international geoscientific journal needs to be addressed, so as to avoid misuse of these data by external customers.
- Airborne geophysical data is needed over the whole of Greenland not covered by ice, most urgently in the south-eastern part of Greenland. GEUS should look into alternative financing models for geophysical mapping, for example, joint financing by Greenland Bureau of Mineral Resources and Petroleum, industry and GEUS for limited target areas.
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- The documentation of ongoing or completed work in GEUS' bulletin and report series is important and should be continued. With the exception of the confidential reports, all

these documents need to be placed on the GEUS web site to make them easily available to the public. Time also needs to be planned, during or in the later stage of a project, for the completion of publications to be submitted to international geoscientific journals. In this way, GEUS will maintain its highly respected scientific reputation.

- In the context of the bedrock mapping and regional geological research activities, there is a need for specialists in metamorphic petrology and geophysics at GEUS. We would welcome one or more geophysicists who also hold a tight understanding of geological processes, especially in structural geology and tectonics.

Mineral resource assessments in Greenland

Activities

Leif Thorning, Jochen Kolb and Troels F.D. Nielsen presented the mineral resource assessment activities to the evaluation panel. Thorning gave an overview presentation of the activities related to mineral resources conducted within the Department of Economic Geology until mid 2009 and then within the Department of Petrology and Economic Geology. One slide presented performance indicators within the value chain and this will be referred to below in recommendations.

The mineral resource assessment programme has had a very ambitious goal and deliverables were clearly set up by the start of the contract period. Discussions with staff members clearly indicated that this was seen as a clear and transparent process. Activities have been focused on:

- Finalizing the highly successful work on Greenland kimberlites (described in detail by Nielsen)
- Supracrustal rock types in the Nuuk region,
- Homogenized geology, hydrothermal mineralisations, integration of data and geochronology in SW Greenland
- Geological evolution of SE Greenland

The activities have included coordinated research covering many aspects of, and relevant for, mineral resource assessment, carried out in selected areas and not with the ambition to cover the entire programme area. There has been a focus on critical metals, and what is referred to in the presentation by Thorning as “fashionable commodities”. A detailed “gant” style chart was presented for the core activities within individual projects broken down into 1) Kimberlites, 2) Nuuk, 3) SW Greenland, 4) SE Greenland 5) “Raids”, 6) East-Greenland Tertiary, 7) Display on Web, 8) Commodity workshop, and 9) Airborne geophysics and remote sensing.

Some deposit scale studies are reported (i.e. the Nalunaq gold deposit) and projects referred to as “raids”, which are industry funded shorter projects (from a few months up to two years). These projects focus on specific sites (deposit studies) or specific commodities (i.e. REEs). Results are confidential for a brief time and then released. The “raids” provide important addition to more long-term research projects. Activities on method development were reported and one example of hyper spectral mapping of the Malmbjerg molybdenite deposit was presented. Quality control and geophysical investigations were mentioned as important, but there was a lack of funding for completing geophysical surveys in SE Greenland (see recommendations above).

Outreach and involvement in international development projects are also important activities. The fact sheets and the publications “Geology and Ore” are compiled on a regular basis and are downloadable on the web page as pdf-documents. According to GEUS staff, stakeholders have very well received these reports. Data on mineral occurrences is also available from the

GEUS web page. Data is provided free of charge and a minor handling fee is charged for delivering physical data.

The presentation by Kolb provided a useful insight into the south-eastern Greenland project started in 2009. This presentation also showed that the subprojects set up also involves many external collaborating organisations, primarily universities, but also research institutes. This project seems to fully utilise the new organisation structure of GEUS and involves both more regional “mapping” type research activities and more focussed studies of different styles of mineralizing systems. A large-scale correlation with Trans-Hudson and Fennoscandia was mentioned as a possible future research objective. This could potentially constitute a multinationally funded correlation project.

Nielsen gave a presentation of the Kimberlite investigations conducted between 1996 and 2009 (i.e. only the latter part is within the evaluation period). This project is an example of what could be described as a strategic project based on GEUS in house competence. It is the opinion of the evaluation panel that this type of strategic projects should be possible to conduct as it not only provides important information that could be utilized by industry to develop economically viable projects, but also is a showcase for where both fundamental and applied research of high quality is conducted in an integrated manner. The discovery of the Tikiussaq carbonatite should serve as an example since, now, five years after the discovery, a concession is in place that could lead to commercial extraction. The Kimberlite project also created a lot of media attention to Greenlandic mineral resources, and can be regarded as a project of highest quality research.

Evaluation

The activities seemed to be very well organized with well-defined deadlines and deliverables. It is unknown to the evaluation panel if milestones and deadlines were fully met or to what degree or if there were delays related to these activities. In the core programme of resource assessment the presentation by Thorning reported major “discoveries” carried out by GEUS on Greenland through the years (i.e. also before the evaluation period). The list contains 23 mineral occurrences that have been discovered within the mineral resource programme. This is extremely impressive and it is the opinion of the evaluation panel that this is not fully utilized to promote GEUS. To put this into perspective, if just one mine would be opened based on GEUS data, it would create an investment in excess of 1 billion DKK and it would create work opportunities in the regional and tax revenue to the government (see recommendations below).

During the evaluation period 2004-2010 a major reorganisation was made in mid 2009, when the former Departments of Petrology (essentially the mapping activities and related research) and Economic Geology merged. In this evaluation, we chose to keep an evaluation structure that conforms to the older organisational structure, mainly since the bulk of activities have been organised in this way. It was clear from discussions with staff that this merger was regarded by most people as positive and provides more incentive for further collaboration between the former mapping and economic geology groups. The evaluation panel shares this

view and sees the benefits of the new organisational structure, which hopefully will lead to more interaction between petrology and economic geology. Although we regard this merger as a positive change with a lot of potential, we also see the need for further defining the role of mapping activities within Greenland. Some recommendations are presented in the previous section.

The economic geology research in Greenland has been a core activity of GEUS and the former Greenlandic geological survey before the merger of the Danish and Greenlandic surveys. The evaluation panel strongly recommends a continued focus on economic geology in GEUS. This is based on several facts:

- Greenland is one of the best exposed Precambrian areas on earth and as such can function as a natural laboratory for ore deposit studies in general.
- The mineral potential is regarded as excellent and the work done by GEUS has clearly shown this potential and also clearly shown the extreme importance of conducting economic geology research in this region (see above under activities).
- The current focus on raw materials globally, with for instance the EU Raw materials Initiative and the report on critical commodities to the EU economy and similar reports from the US authorities, clearly shows that there is currently a large focus on raw material
- Several commodity prices are at all time high levels, many of which have a high potential for economic extraction in Greenland.

The mineral potential in Greenland is indicated by the increased activities from exploration companies. This is illustrated in figure 2. Successful exploration needs good geological basic information including an understanding of ore deposit types, predictive and metallogenetic studies and basic information from mapping projects. Again the importance of high quality economic geology research conducted by GEUS can be illustrated with the investment in exploration in Greenland, which in 2008 was around 500 million DKK (see figure 3).

Figure 2 – Number of exploration permits and licenses in Greenland during the last decade.

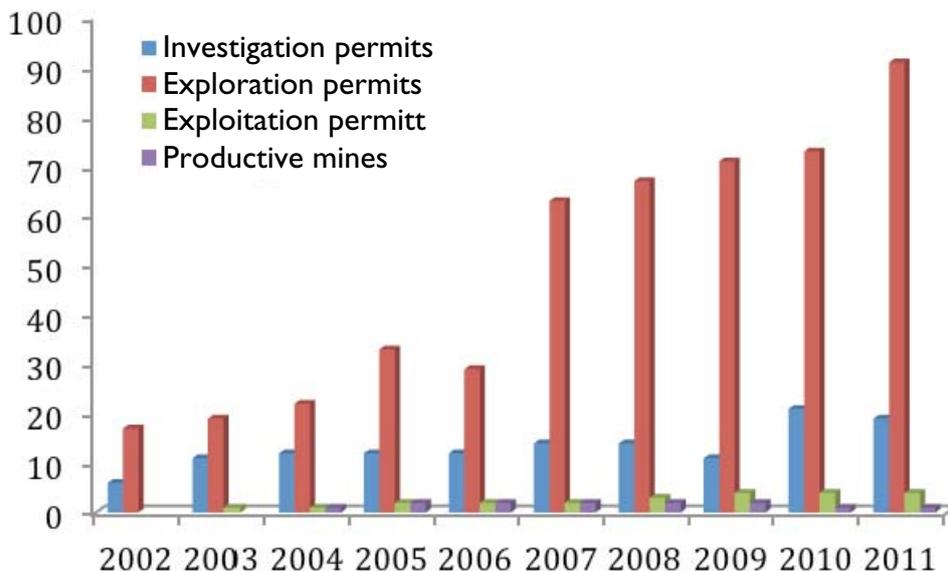
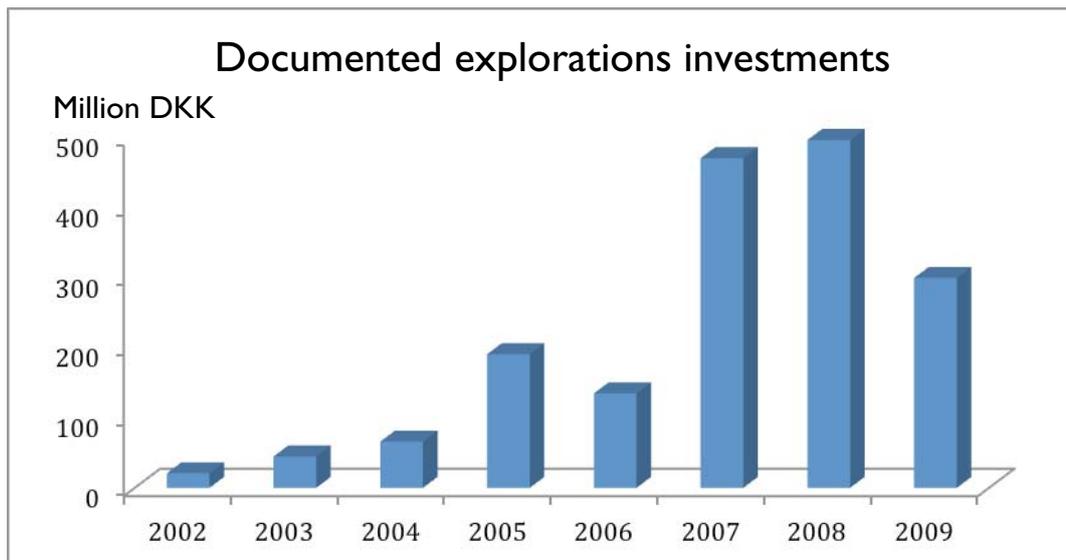


Figure 3 – Exploration investments in Greenland during the last decade.



The evaluation panel had the opportunity to discuss various matters with several of the economic geology staff members and also the Head of the former economic geology department. The staff was, in general, very positive to the activities, research focus and recent formal collaboration with the staff from the petrology department. There was a general opinion that there was not enough time for writing up the research and activities in the form of peer review scientific papers. This view was shared by most staff interviewed (see also recommendations in the previous section) and points to a certain discrepancy between the mission statement, which emphasizes highest scientific level publications, and the time available for staff to fulfil the mission and tasks given to GEUS.

The project generation phase seemed to be a rather ad hoc process based on discussions with RMP a.o. in preparation for the contract between GEUS and the Danish Climate and Energy ministry. This contract is a 4 year contract, broken down into project activities (see above). The evaluation panel thinks that it could be beneficial for the GEUS activities if this was coupled to a mineral strategy for Greenland that would include a long term commitment to define research in a regional scale (metallogenic studies), detailed scale (deposit studies), commodity focus (i.e. critical metals). If this is possible, it will, in the view of the panel, facilitate a better planning of long-term activities and also include time for scientific writing up of projects.

It is also recommended that customers and clients should become more involved in the prioritizing of activities. It was not clear to the panel how much this is currently done. Not only would this warrant a relevant focus, but also make sure that relevant stakeholders are involved in the policy making, which in the long run would aim to strengthen GEUS ability to carry out activities based on funding from various sources, both public and external.

Given that economic geology will be a prioritized activity of GEUS in the future, which the panel strongly recommends, there is a concern in the panel for the current status of critical mass in this group. Some people are close to retirement and others work with task not directly

relevant for Greenlandic economic geology. Although the staff is very active the combined results, due to the work load and under criticality, is that surprisingly few peer review papers (see below) devoted to economic geology in Greenland have been published the last few years. During discussions with the current Head of department for petrology and economic geology, it was indicated the GEUS plan to recruit more senior staff within economic geology. The evaluation panel strongly supports this action. In this context it could also be good to have an internal discussion on what type of competence could be relevant for the economic geology research (i.e. what fields of expertise within economic geology is needed). There is also potentially an untapped in house resource in utilizing the petrology department even further in detailed investigations and regional metallogenetic studies since tectonic, petrological, structural, geochemical and isotope geochemical competence is also needed in the economic geology research.

The evaluation of the “Applied mineralogy” or GEUS laboratories is treated in a separate chapter, but it is the view of the panel that the laboratories could be used more in the economic geology research. For instance, the very high quality research and high competence in LA-ICP MS techniques could be further utilised for element mapping in mineralized systems.

There was very little mentioned on EU-funding and EU activities related to raw materials. According to information on external funding there is currently no external funding to programme area 4 from EU sources. There is currently a window of opportunity in EU funding for raw materials research. So far, GEUS has been fairly invisible in this context. Given the fantastic potential, not the least for so called, critical commodities, in Greenland, GEUS could be a partner in FP-projects related to economic geology.

The evaluation panel did not check citations for individual scientists. The GEUS publication list is impressive and without doubt is the best evidence of the high quality of GEUS research, which is definitely in the top among geological surveys worldwide. It was clearly stated in interviews that GEUS staff strives for highest scientific quality research, and thus has a focus on peer review publications in top ranked scientific journals. The number of peer review publications related to economic geology research in Greenland could be raised especially compared with the world class publication record in, for example, igneous petrology. We appreciate that this reflects the conclusions drawn above concerning critical mass and workload, but it may also warrant an internal discussion on prioritization of staff time. However, there are many non-peer review reports included in the list of publications provided to the evaluation panel. There seems also to be a good attendance in international conferences. To the panel this indicates that there is potential for more peer review publication within economic geology assuming that the very well qualified staff is given more time to write scientific papers.

Recommendations

The evaluation panel very much welcomes the closer integration of bedrock geological mapping, regional geological research and mineral resource assessment where we think many

new exciting projects could be developed. Based on interviews and presentations we would like to make the following recommendations within the field of economic geology:

- More emphasis on promotion of impact of GEUS activities for society, industrial investments, work possibilities and tax revenue. This could be quantified to show how limited governmental funding can make a huge difference and quick pay back to society in form of industrial investments, work opportunities and tax revenue.
- The economic geology group should be increased to obtain a critical mass. In this respect a strategic discussion should define what competence is lacking and a recruitment plan should be set up.
- GEUS should take a coordinating role in helping to establish a Greenland long-term mineral strategy that involves the Greenland Bureau of Mineral Resources and Petroleum, other relevant Greenland authorities, other government agencies (national and regional), research institutions, and the private sector. The strategy should include provisions for prioritizing near- and long-term mineral exploration objectives, necessary scientific baseline information (data and interpretations), and aligning with sustainable resource development objectives.
- There is currently a window of opportunity in EU funding for raw materials research. So far GEUS has been fairly invisible in this discussion. Given the fantastic potential, not the least for so called, critical commodities, in Greenland, GEUS should be involved of EU project development, for instance in the potential for a European Innovation Partnership on Raw materials.
- A serious issue that most staff expressed a frustration not having time to publish their work. While the evaluation panel fully realizes that this is a funding issue at the same time it is in GEUS mission to conduct highest level science and the only way to substantiate this is publishing in peer reviewed scientific journals.

Raw materials and geological mapping in Denmark

Activities

This section is based on the information provided, study of www.geus.dk, informative presentations by Stig Schack Pedersen (terrestrial raw materials and mapping) and Jørgen O. Leth (marine raw materials and mapping) as well as a comprehensive interview with the head of the Marine Geology and Glaciology Department, Karen Edelvang.

The activities in Programme Area 4 mainly deal with mapping of the uppermost Quaternary deposits both at land and sea.

General overview

By far the largest volumes of raw materials extracted in Denmark are used either as aggregates or as raw materials for construction materials such as cement, concrete and bricks (chalk, sand, brick clay, expanding clays). Other materials are used as industrial minerals for e.g. agriculture, paper production, isolation, cat litter etc. (limestone, quartz sand, diatomite, bentonite, granite etc.).

Danish raw materials are mainly produced on-shore (>70%) and to a lesser amount at off-shore (<30%). Denmark is generally self-sufficient of construction raw materials. Exceptions include import of granite for aggregate or dimension stone and certain raw materials for production of white cement (kaolin) and insulation materials (basalt). The raw materials extracted are consumed in Denmark, but there is a significant export of manufactured products, such as cement, limestone filler and insulation materials.

The production of raw materials has declined very significantly as consequence of the general reduction of construction activities; from a peak production of 42 million m³ in 2007 to only 23 million m³ in 2010. The construction activities are expected to increase at a moderate rate in the coming years. In addition to this, a number of very large infrastructure projects will demand access to large amounts of raw materials. Most notable is the construction of the Femern Link which in the peak activity years 2015-18 will demand very large amounts of aggregate and cement. Investigations related to the geological setting and raw materials supply for these large projects constitute a part of GEUS' off-shore activities.

It is an increasing demand that extraction of raw materials are carried out in a sustainable manner taking care of other nature and societal interest. On-shore, these conflicts often deals with conflicting interests between raw materials excavation and groundwater protection. Off-shore, protection of natural habitats is of major importance.

Legal and administrative framework

Raw materials extraction on land is administered by the new regions and municipalities. The administrative reorganisation of Denmark in 2007 transferred a number of these tasks from the former counties to the enlarged municipalities. Overall controlling on land is the

responsibility of the Nature Agency and it is GEUS's roles to provide the scientific background for the regulation activities.

Administration of off-shore raw materials extraction is the direct responsibility of the Nature Agency. It is the role of GEUS to advise the Agency. This advice is based on GEUS' own marine geological investigations and investigations carried out by the raw materials industry. According to the Raw Materials Act of 2007 (with changes in 2009), applicants for exploration licenses are required to carry out a minimum programme for exploration and environmental assessment. This shall include documentation of the resource (quality, volume, availability) and an assessment of the environmental impact. The results have to be reported to GEUS which then consolidate the results into the general geological knowledge used to advise the Nature Agency.

Geological mapping and resource assessment

Geological mapping on land proceeds at a limited rate with around one 1:50,000 sheet each year. 15% of the Danish land area remains to be mapped. Advice regarding specific civil works and resource exploration has been carried out. The comprehensive JUPITER database, comprising bore hole sample descriptions from all land based borings (water, resource assessment, construction activities) has continuously been expanded and now comprises data from 240,000 bore holes collected since 1927.

At sea, GEUS role in marine raw materials mapping comprise:

- Research projects
 - Quaternary development
 - Environmental history and mapping
- Governmental advisory projects
 - Raw materials resources
 - Nature conservation (habitat mapping)
- Commercial activities
 - Investigations in relation to construction works (bridges, wind farms, cables, reclamation and replenishment)
 - Consulting services to aggregate extraction companies

A very comprehensive mapping has been carried out, resulting in the creation of a 1:500,000 digital seabed map of the entire Danish off-shore area. General shallow seismic surveys have been carried out associated with limited sampling. A comprehensive raw materials data base, MARTA (similar to JUPITER on land) has been completed but not yet released.

The budget of the Denmark activities comprise around 20% of the total Project Area 4 budget, equivalent to a turnover of less than 10 million DKK per annum and around 10 FTE. Because of the large amount of external financing and consultancy at the off-shore activities, the external financing is significantly higher than the average for the Programme Area.

Departments

The departments participating in Programme Area 4 have been reorganised in the period. Presently, two departments are involved:

- Groundwater and Quaternary Mapping Department
- Marine Geology and Glaciology Department

The Groundwater and Quaternary Mapping Department (manager: Richard Thomsen) was created after the abolishment of the Danish counties, when the ground water department of Aarhus County was transferred to GEUS. The bulk of the department is physically located in Aarhus but the researches involved in Programme Area 4 in for most parts situated in Copenhagen. The main activity of the department is ground water mapping.

The Marine Geology and Glaciology Department (manager: Karen Edelvang) comprise a wide variety of activities:

- Glaciology
- Marine geology
- Natural forest research
- Paleolimnology
- Laboratories
 - Sedimentary laboratory
 - Bore hole sample laboratory
 - Marine geology instruments

Around 12 researchers and technicians from the Marine Geology group as well as the staff of the sedimentary laboratory and borehole sample laboratory participate in the Programme Area 4 activities.

Evaluation

General assessment, on-shore activities

The present rate of general mapping is limited but seems satisfactory to serve society's needs. There are no indications that GEUS is not able to lift its advisory obligation to the authorities.

The borehole archive presents an impressive collection of data which is unique in the World. The JUPITER database is easily accessible on GEUS web page and a significant opportunity lies in using these data to produce a 3-D map of the Danish uppermost Quaternary. The main benefit of this would be related to groundwater assessment (Programme Area 2) but would enable better understanding of the Quaternary and hence the on-shore raw materials potential.

General assessment, off-shore activities

The significance of the off-shore activities to society can hardly be overestimated. Better exploitation of the off-shore resources will be needed to ensure a sustainable long-term supply of construction raw materials in Denmark. The very large construction activities under way

related to infrastructure projects and renewable energy are dependent of a solid understanding of the off-shore geology.

It is the impression of the evaluation panel that the research quality in this field is excellent and very relevant to the society's need. This is substantiated by feedback from industry. A robust presence in this area should be maintained.

The MARTA data base will be a valuable tool not only for research but also for assessment of raw materials potential by industry. We are aware that there are issues with general access to these data, some of which is generated by industry as part of the investigation obligations. We recommend that a solution is found in cooperation with the main stakeholders so that these data will become available with due care regarding the confidentiality requirements of the individual companies. We are aware that such a process is underway.

Some of the activities are carried out at part of Programme Area 5, notably area 5.1: Coastal Zone and Sea Bottom. This is outside the scope of the present evaluation.

National raw materials strategy

The recent administrative reorganisation abolishing the Counties and distributing their tasks to the new Regions and enlarged Municipalities appears to have created gaps and lack of coordination in Danish raw materials exploration.

At the same time, it is clear that society need an overall, consolidated assessment of the Danish raw materials resources. A long-term strategy for access to and sustainable exploration of the Danish raw materials resources is needed. This will both be a valuable tool for the regulators, but also ensure a stable supply of raw materials. GEUS would be the natural body to collect data and provide information for administrators and industry.

We are aware that it will be a major challenge to establish such a strategy in view of the present administrative set-up. A political decision would be required. GEUS may facilitate such a decision by considering how such a strategy could be structured and include this in the upcoming strategy.

One of the requirements of a future national raw materials strategy would be to better integrate the knowledge of the on-shore and off-shore raw materials investigations. We were explained that an important tool for this would be to create a map combining the available land and sea data. Such a map is not available today, e.g. because of different nomenclature and classifications. This presents a significant potential for GEUS.

Consultancy

The raw materials act of 2007 (with changes in 2009) has had significant impact in GEUS activities. All exclusive rights for raw materials exploitation in specific areas are now licensed to industry. Applicants for exploration rights are required to carry out an exploration programme and to report the results back to GEUS. At the same time GEUS is carrying out exploration programmes as consultants for industry in competition with commercial advisors.

This has resulted in some misgivings from industry, which worry that exploration data submitted as part of the reporting obligation are handled by the same persons which act as consultants for their competitors. Also questions about economical transparency could be asked. On the other hand, industry welcomes that the activities of GEUS increase competition amongst the small community of consultants.

In order to address these issues, GEUS has put into operation a system according to which data are reported to the Geological Data Centre at GEUS, which oversees proper governance of the consulting tasks in respect of data confidentiality. Economic arms-length handling of the consulting activities from the general survey activities are ensured using the very efficient time-task management system of GEUS, making cost tracking easily made. The National Audit Office ensures the rules are respected.

Consulting activities are important for GEUS are important as means of acquiring additional data and creating a critical mass of scientists and equipment. Nevertheless, a proper balance between GEUS advisory obligations to the State and the commercial activities should continuously be assessed and maintained.

Two questions can be asked:

- How to ensure full economic transparency and barriers between consultancy and advice to authorities?
- Can the consulting activities be made more cost-effective, improving the quality of service to the customers and increasing contribution?

Good practice could be to avoid conflicts of interests by separating the consulting activities from government advice in some way. This has to be done without compromising the integrity of the present organization. This needs further consideration. However, efficiency of the consultancy and economic transparency could be increased by:

- Making a separate “profit centre” for the consulting activities; with a balance sheet comprising hours bought internally, general costs, cost for equipment rental and income.
- Aligning the salary rules, specifically the rules related to overtime, with the rules of the Greenland activities. This could result in a more efficient use of human resources, freeing staff for other activities.

The panel recognizes a need for a more rigorous mechanism for review of reports and quality control of GEUS projects.

Publications

A large amount of information is generated especially in the off-shore field. This is, to a large extent, reported as part of GEUS advice and consulting services and therefore not in peer reviewed papers. This is not surprising due to the requirements of the private or public customers. We are aware that the researchers are pushing for more time to publish. The salary rules alignments mentioned above could help in this aspect.

Internal organisation

The Denmark activities of Programme Area 4 have very little relationship to the activities in Greenland. On the other hand, many activities seem closer related to Programme Area 2 (ground water) and Programme Area 5 (coast and sea bed). It could be considered to rearrange the programme areas to enable a more efficient matrix organization.

Recommendations

Based on the assessments, we recommend:

- The extremely comprehensive borehole data and the JUPITER data base should be used to create a 3-D map of on-shore top Quaternary. This will benefit not only groundwater mapping but also a much better understanding of the Quaternary of Denmark.
- In view of the large construction projects under way and the very significant raw materials interests, the robust activity regarding off-shore raw materials should be continued.
- The sustainable use and society's need for a stable long-term supply of raw materials makes a National raw materials strategy for Denmark a pressing concern. GEUS should facilitate this development.
- As part of this long-term strategy, it is recommended to create a unified sea-land geological map, enabling a much more complete understanding of the raw materials resource.
- We recommend to assess the consulting activities in connection with raw materials exploitation both to avoid conflict of interest but also to evaluate if the efficiency of operation can be increased.
- In order to better facility industry needs, we support GEUS's efforts to make the MARTA database accessible to the users, and further propose to establish a stakeholder forum.
- A more rigorous mechanism for review of reports and quality control of GEUS projects.
- Address the serious imbalance in peer-reviewed scientific publications between Denmark and Greenland.

Applied Mineralogy and Laboratory Development

Laboratory Descriptions and Activities

Descriptions

Laboratory data from samples collected in the field are a foundation to scientifically sound interpretation and validation of mineral occurrences, mineral- and rock-forming processes at all scales, and boundaries and divisions of mapped rock units. GEUS' Economic Geology Programme (Area 4) oversees six laboratories including facilities for:

- rock sample preparation;
- microscopy;
- scanning electron microscopy (SEM);
- inductively coupled plasma mass spectrometry (ICP-MS);
- laser ablation ICP-MS (LA-ICP-MS); and
- photogrammetry and three-dimensional stereovisualization and digital analysis of outcrops at all scales.

The review committee also visited the borehole sample laboratory which is overseen by the Department of Marine Geology and Glaciology.

Descriptions of the laboratory facilities and the main activities they support (below) are based in visits to the laboratories and discussion with GEUS staff responsible for the laboratory operations. Supplemental descriptive information was also derived from the laboratory web pages and project descriptions under the GEUS Department for Petrology and Economic Geology main web page.

Sample preparation: facilities include rock crushing, splitting, separation and mounting of mineral grains.

Microscopy: two petrographic microscopes for optical analysis of rocks in thin section or as mineral mounts. The facilities include the capability for generating digital images and image processing.

CCSEM [*laboratory visit and discussion with Nynke Keulen [primary lab contact], Christian Knudsen, and Thomas Find Kokfelt*]: The 17-year old instrument has three detectors for different types of analyses of polished thin sections or grain mounts including mineral morphology (e.g. topography, shape, and shape); mineral identification and chemical contrast; identification of mineral growth stages and major and minor element mapping of minerals. GEUS staff has worked to develop a new analytical capacity during the past 10 years for automatic particle analysis; the technique, called computer-controlled SEM or CCSEM, is performed on grain mounts from samples such as beach sands, stream sediments, soil samples, and sandstones and enables automated characterization of a large number of unknown sample grains. The resulting data can then be compared to an existing library of sample analyses to determine provenance for the grains.

ICP-MS: A 12-year old quadruple ICP-MS instrument is used to analyze a range of trace elements in inorganic rock and mineral samples. Elements analyzed include most metals, rare earth elements, and other elements such as Rb, Sr, U, Th, and Pb. Jørgen Kystol is the responsible contact for this laboratory.

LA-ICP- MS [*visit and discussion with Thomas Find Kokfelt [primary lab contact] and Christian Knudsen*]: A single collector mass spectrometer uses an ultraviolet laser to analyze trace elements at high precision from single grain samples. The instrument was first installed 5 years ago and analytical capacity was developed rapidly to produce precise U-Pb ages for single spots in zircons. The laser can be focused to a spot size of 30 microns, allowing for very detailed elemental mapping and age profiles across mineral grains. Improvements to the software (initiated by the GEUS staff), optimizing the sample chamber size, and developing an effective analytical protocol to alternate analysis of unknown samples and standards have reduced the time to collect U-Pb data for one spot on a zircon grain to about 30 seconds. Implementation of these improvements allowed analysis of 45,000 zircons in 2010 for a specific project (a commercial client group [see also below]).

Photogrammetry [*visit and discussion with Max Nykjaer Strunck [primary lab contact] and Christian Knudsen*]: The laboratory has developed the capacity to generate digital topographic maps from the combination of air and ground photos in areas lacking topographic data coverage and to create 3D images of rock exposures. The laboratory facilities include three photogrammetric workstations; equipment for computer 3D visualization and stereoprojection of photographs; software for aerotriangulation, digital terrain model genesis, orthophotoproduction, and vector compilation; and two calibrated cameras for field photography of large rock exposures (cliff faces, large outcrops). In addition, the laboratory has an extensive archive, available for loan, of paper copies of air photos that cover Greenland in several scales.

Borehole sample laboratory [*visit and discussion with Henrik Granat [primary lab contact]*]: The Danish groundwater supply law of 1926 requires that any individual, public works, or private company drilling a borehole for water wells, raw materials, environmental investigations, or geotechnical purposes send representative samples to GEUS for description and archiving in a national database. The lithologic description and the interpretation of the samples are entered into a GEUS environmental database, JUPITER, which is freely accessible to the public. Both legacy analogue data from the time the law was first enacted and current data are entered into the database which now contains about 240,000 borehole sample descriptions. The possibility to use this database in generation of 3D subsurface hydrogeological models is discussed further in the previous chapter on Denmark raw materials and mapping.

Although all of the laboratories appear to have a consistent level of activity, whether for sample preparations or routine geochemical analyses, two of the laboratories, the CCSEM and LA-ICP-MS, have undergone targeted development in the past 10 and 5 years, respectively. The CCSEM developments were applied to an existing (then-7-year old) instrument, while the LA-ICP-MS developments occurred from the time the instrument was first installed at GEUS

~5 years ago. The projects, which inspired and partially financed the developments were for clients in the private sector, and have been broadly labelled as projects in “applied mineralogy.” These laboratory developments and the resulting products—a combination of peer-reviewed journal articles and long-standing commercial client support (including co-authorship on several articles)—are representative of high-quality research conducted by staff Programme area 4.

CCSEM Activities

Beginning about 10 years ago, GEUS established a long-term research collaboration with DuPont (E.I. du Pont de Nemours and Company), primarily to pursue the company’s interest in high-purity titanium for use in their enormous global production of pigment. The minerals rutile and ilmenite are of specific interest for the company because of the high proportion of titanium oxide in these minerals and well-established processing techniques for its extraction. Ilmenite and rutile are most easily accessed in large quantities as heavy mineral fractions in beach and river sands. The CCSEM was developed at GEUS in order to optimize the ability to obtain chemical data on mineral grains and modal analysis of large quantities of the heavy mineral fractions of sediment samples from different parts of the world. These analyses could be compared to an in-house (GEUS) sample library to assist in interpreting mineral provenance for the mineral samples and thereby aid in DuPont’s exploration for high-purity ilmenite and rutile detrital deposits.

The technique’s success in identifying mineral provenance for ilmenite in beach sands has been demonstrated for DuPont by GEUS for sands in the Miocene of Denmark (*Knudsen et al., 2005*) and in SW India (*Bernstein et al., 2005, 2008*), and has been proposed as a fast, reliable tool for diamond prospecting in SW Greenland (not a DuPont project) by Keulen et al. (*2008a, 2009*). *Keulen et al. (2007, 2008b)* have also described applications for CCSEM in examination and interpretation of fault gouge and fault rock. It is notable that the GEUS staff also developed a unique sample preparation technique for the mineral mounts that enables repeatable and rapid analyses of a maximum number of grains from any given mineral fraction.

The review committee was informed that the income from the long-term project with DuPont has supported the maintenance of the CCSEM laboratory, including instrumentation and staff support. GEUS researchers have produced several confidential reports for industry describing the CCSEM methodology (*Keulen and McLimans, 2009*) and applying the method to characterize heavy mineral concentrates from West Greenland (*Keulen, 2009*).

Approximately 70% of the operation time for the laboratory is currently used for commercial projects, although this varies at any point during the year. The service contracts for the commercial jobs include support for the laboratory’s basic operation for the purpose of the analyses but no set percentage of the income from commercial projects is earmarked for general laboratory maintenance or development.

LA-ICP-MS Activities

The LA-ICP-MS was installed in 2005 and rapidly became an internationally recognized facility for U-Pb geochronological analysis of zircon and in-site trace element analysis (e.g. *Frei et al., 2006; Nasdala et al., 2008; Frei and Gerdes, 2009*). In an international comparison of 17 LA-ICP-MS laboratories, the GEUS instrument was independently rated among the top three. The rapid analytical capacity, especially for zircons, naturally led to a significant number of applications of the method to collaborations between GEUS and other researchers, including zircon provenance studies in NW Svalbard (*Pettersen et al., 2010*), Ghana (*Kalsbeek et al., 2008*), and Greece (*Meinhold and Frei, 2008; Mikes et al., 2009; Meinhold et al., 2010a,b*). The instrument was also used to collect trace element data and U-Pb ages from minerals in kimberlite of West Greenland to help examine the origin, age, and provenance of these kimberlites and their diamond occurrences (*Hutchinson and Frei, 2009*) and to examine fundamental questions related to experimental petrology (*van Kan Parker et al., 2010*).

The capacity of the LA-ICP-MS to analyze enormous quantities of zircons was employed in several explicit provenance studies of sandstones in West, East, and North-East Greenland for industry and results are described in confidential reports for the petroleum industry (e.g., *Thrane et al., 2010; Rehnström et al., 2010*). The review committee was informed that these large datasets were part of a multi-client arrangement that generated ca. DKK 5 million through sales of the datasets and interpretive reports to ~7 petroleum companies. The large number of zircons analyzed in 2010 (45,000) were directed toward this multi-client study and absorbed ca. 90% of the active laboratory time that year in order to complete the commercial project.

The panel was also informed of some new endeavours to use the LA-ICP-MS to analyze organic samples (fish scales and mussel shells) and corundum for an existing project on rubies.

Evaluation: Instrument development and scientific productivity

In all cases, the review committee found the responsible scientific and technical staff affiliated with the laboratories to be highly competent, innovative, and engaged in maintaining the daily laboratory operations, in advancing new analytical innovations particularly with the CCSEM, LA-ICP-MS, and photogrammetry laboratories, and in increasing the variety of projects in which the laboratories are engaged. Their record of peer reviewed publications and GEUS reports is impressive and shows an ability to address basic scientific problems and applied questions that respond to industry requests. These results are all indicators of high-quality research. Furthermore, the descriptions of the laboratory facilities within the Department of Petrology and Economic Geology website are clear, appropriately descriptive, and demonstrate a personal scientific interest and responsibility on the part of the primary laboratory contacts. These basic issues of personnel engagement make the laboratories attractive to potential research collaborators and clients.

Access to high quality laboratory analytical facilities in which researchers are also engaged in instrument development is deemed very positive for GEUS. The capacity to prepare samples and perform a range of chemical and geochronological analyses on site at GEUS has had two direct impacts:

1. Raising the profile of GEUS and GEUS scientists internationally as a respected provider of geologic information;
2. Increasing the network of national and international collaborators and number and variety of projects and clients.

The laboratory facilities and services are used almost exclusively by GEUS for preparation and analysis of rock samples collected in the course of GEUS project work. In the past year or more, the weight of analyses appears to have been directed toward completion of contractually obligated commercial projects. The panel realizes that the operational time dedicated to one or another project for any laboratory instrument will vary from day to day and over the course of months for natural reasons, including project deadlines. However, the evaluation panel noted some frustration on the part of staff otherwise enthusiastic to use CCSEM and LA-ICP-MS for analyses of non-commercial projects. The general impression was that commercial projects, particularly in the last year or two, were prioritized over non-commercial projects during the normal weekday hours. The panel sees valid points for all sides of this issue: (1) laboratories are expensive to operate and maintain, and a reliable source of income to cover (at a minimum) service costs is essential; (2) instrument development or purchase of new instruments is a very expensive direct expense, but is necessary, in periods, to maintain a scientific advantage; and (3) the ability to acquire basic data to support geologic mapping and mineral exploration projects and to respond to general scientific questions are integral to maintaining high-quality staff and the reputation of the institution. These points call for a balanced approach to laboratory operations and several recommendations are provided to try to help the laboratory managers and GEUS staff to optimize laboratory time to satisfy the various demands on the facilities.

Recommendations

Overall, the panel evaluates the laboratories reviewed as being of very high quality and encourages GEUS to continue to support and develop laboratory capacity within Programme area 4.

- Build upon the strengths of the established, demonstrated international reputations of the LA-ICP-MS and CCSEM laboratories by:
 1. Assuring continued, adequate staffing for both scientific and technical positions to maintain effective operations and “cutting edge” scientific productivity.
 2. Considering investments in a new CCSEM and subsequently in a multi-collector LA-ICP-MS.

The current CCSEM may have several additional years of productive use ahead. However, it is an old instrument that has demonstrated a very consistent level of productivity and income and a delay in data production, should the instrument require any major instrument repairs, would be detrimental. A multi-collector LA-ICP-MS would expand the existing capacity of the laboratory by allowing analyses of a large range of metals, in addition to the current range of elements measured with the existing

ICP-MS instruments. An additional instrument would also serve the purpose of hedging against the eventual retirement of the older (12-year old) ICP-MS. The possible expansion of these activities within mineral exploration is also described in context in the section on “Mineral resource assessments for Greenland.”

- Examine new areas for application of the current (and any future, new) instruments to new areas of research such as environmental health which has a direct bearing on public health, and element mapping related to economic geology research in support of the Programme’s mineral exploration activities. Programme area 4 is an appropriate place to develop this new area of research.

International projects

Activities

The international activities for Programme area 4 have centred on capacity-building, research, and commercial projects in ~25 countries. Although some of the projects were of short duration (one visit for purposes of discussion, reconnaissance, etc.), others are of several years duration and have relied upon the core scientific competencies of GEUS staff in geology, geophysics, mapping, databases, and mineral resource assessments. Highlights from some of these longer-term projects were shared with the panel by Per Kalvig and Christian Knudsen. Additional information about the international activities was gleaned from the webpage where the projects are clearly and succinctly described.

Work combining geology and human health has been conducted in Uganda and the Philippines. In Uganda, GEUS has worked with Ugandan women on mercury impact assessments and awareness associated with their use of mercury-containing soaps to bleach the skin. In the Philippines, mercury is often used by small-scale gold miners for amalgamation without knowledge of the impacts to the health of humans and the environment; the project aims to help miners identify substitute methods (such as use of borax) for amalgamation and to employ technologies to clean areas that have been polluted with mercury. In Ghana, two separate project periods (2005-2008 and 2006-2010) focused on leadership training (institutional capacity building) and design of airborne geophysical surveys, respectively. Building upon the small-scale mining theme, the Centre for Sustainable Artisanal and Small-Scale Mining (SASMin) is an interdisciplinary unit for research to help promote and establish sustainable, small-scale mining projects in developing countries; this program is staffed jointly by researchers from GEUS and the University of Copenhagen, and has included work in agrominerals, gold, aggregates, salt, and rubies in, for example, Tanzania, Ghana, China, and India. Work conducted by GEUS staff affiliated with Programme area 4 during the evaluation period have included small-scale mining projects in Mongolia and Kyrgyzstan.

Commercial projects in foreign countries have included titanium resource studies in Cameroon, Brazil, Sri Lanka, India, China, Vietnam, Madagascar, Mozambique, and Zambia. Basic research projects have included detrital zircon studies in West Africa and geochronological studies in Togo and Benin.

In addition to the direct impacts of enhanced capacity, data, and/or knowledge for the partnering countries and commercial clients, documentation of the results of some of these projects have been produced in peer-reviewed journal articles (e.g. *Stendal et al., 2004*; *Stendal et al., 2006*; *Toteu et al., 2006*; *Yongue-Fouateu et al., 2006*) and in GEUS reports (e.g. *Tychsen, 2010/133*; *Appel, 2005/4*; *Appel et al., 2004/11*). The reader is also asked to review the articles by Bernstein and co-authors in the previous section on laboratory development; these publications were the result of work conducted in SW India in support of titanium resource development.

These international activities typically engage about 10% of the actual manpower of Programme area 4 staff in a given year, translating to approximately 1-3 man-years of time over the last 10 years. Fifty percent of the projects have been supported and initiated by GEUS; the other half has been those for which GEUS has applied for the financial support to undertake. Sponsors for the projects have included the European Development Fund, the Nordic Development Fund, the World Bank, UNDP, DANIDA, Geocenter Denmark, various foreign embassies, and GEUS' own funding and various research funds.

Evaluation

The international work conducted to date by GEUS staff affiliated with Programme area 4 has been compelling in terms of the impacts for people in the recipient country—including the general public (women and children in Uganda), mine workers, researchers, and host governments. Results from commercial projects have also been successful in terms of the continual support of international projects by particular clients over the course of years, and the fact that some peer-reviewed journal articles have also been produced. Based on the information shared with the panel and the articles we were able to review, the international research conducted appears to be of high quality.

In addition to the anticipated outcome of building capacity in other nations, additional returns for this development work for GEUS include enhancing the existing expertise of GEUS researchers, developing new core expertise, and generating sources of external income.

Recommendations

Although the participation of GEUS staff in Programme area 4 in international projects has been consistent over the course of the past 7 years, the panel saw opportunities to become more engaged in a number of opportunities being offered specifically by the European Union in raw materials research, and by the World Bank. The panel recommends that a concerted effort should be taken by Programme area 4 to continue and expand international work, by actively seeking new sponsors and collaboration partners. Some specific areas of focus for contacts with the EU are outlined in the section of this report on “Mineral assessments.” This kind of work, though requiring significant oversight in allocation of staff time and other resources, has enormous potential benefits such as building research networks and the reputation and profile of GEUS, serving as a key contribution to professional development, and increasing the level of knowledge that can be brought back to projects in Denmark and Greenland.

Communication/outreach

Overview

Although the evaluation panel did not have the opportunity to examine in detail the various forms and content of Programme area 4's communications and outreach mechanisms, we noted specific communications-related issues that arose during the course of the evaluation in individual sections of this report regarding the Programme's website, communication and collaboration with clients, and profiling activities with specific kinds of impacts. Regarding the GEUS website, for example, the panel found some degree of variation among the styles and level of information presented from Department to Department ("Afdelinger" on www.geus.dk). The Department for Petrology and Economic Geology has an attractive and informative main page that is designed to encourage the viewer to explore further in the website. Descriptions of the laboratories also informative and encourage potential clients or collaborators to seek engagement. The Department of Marine Geology and Glaciology web page also has informative arrangement that encourages interaction by the viewer. Other Department web pages are somewhat more static in their presentations.

Although a web presence is only one form of communication with GEUS' domestic and international audiences, the panel thinks that communications are going to be a critical tool for the Programme's success in the coming years and makes some recommendations to build upon positive developments, for example, with the Department of Petrology and Economic Geology website.

The evaluation panel considers that GEUS is far too modest on communicating and quantifying its importance for society.

Recommendations

- Impacts of GEUS research: The Programme should develop good and balanced set measuring tools or metrics for its research activities that is not limited to peer-reviewed publications. These metrics could include, for example, post-delivery dissemination plans following delivery of the product, an active plan to demonstrate and communicate project relevance to appropriate audiences, etc.
- The Programme should identify and develop strategy for specific target audiences: Primary audiences are likely to be (1) Ministry; (2) Greenland Bureau of Mineral Resources and Petroleum; (3) other government authorities in Denmark and Greenland. Secondary audiences, dependent upon the activities, may include the private sector and the general public. The expectations and needs of the audiences should be identified and appropriate communications mechanisms and formats discussed.
- The Programme should develop a more through-going communications strategy for ongoing research and research/objectives in development. Some short, one-page summaries of these communications points can be developed, if not already available, for discussions with potential sponsors and collaborators.
- Build upon the very informative web page for the Department of Petrology and Economic Geology, continuing to provide new information in a variety of formats for different audiences.

- Formalize one or more advisory panels (for example one for Greenland and one for Denmark activities) for Programme area 4 who should meet regularly with GEUS directors and departmental heads to provide feedback on programme activities. Such panels might include a balance of representative stakeholders from the private sector, from academia, and from government both within Denmark and Greenland and abroad. The panel could be asked to provide objective comments and guidance on tactics to balance basic and applied scientific research projects, suggestions to identify and build relationships with new, potential external collaborators and project sponsors, and communications and outreach strategies to reach relevant stakeholder groups.
- Quantify and communicate how important GEUS is for society.