DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2019/8

Scientific evaluation of programme area 4

Mineral resources (2011-2018) at the Geological Survey of Denmark and Greenland (GEUS)

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF ENERGY, UTILITIES AND CLIMATE

GEUS

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INTRODUCTION

GEUS Programme Area 4 (Mineral Resources) is divided into three focus areas:

1) Geological mapping and mineral resources of Greenland;
2) Geological mapping and mineral resources of Denmark; and
3) Mineral Intelligence (including the Center for Minerals and Materials (MiMa)).

The programme area includes researchers and staff from Department of Petrology and Economic Geology, Department of Groundwater and Quaternary Mapping, Department of Marine Geology, and Department of Geochemistry.

Act 536 of June 6, 2007 states that "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". GEUS responsibilities within the Mineral Resources programme are described in Act 536 of June 6, 2007 as to provide "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". The evaluation panel found that this includes advice to the Ministry of Energy, Utilities and Climate as well as the Nature Agency and Environmental Protection Agency of the Danish Ministry of Environment regarding on- and offshore raw materials, resource estimates, construction work, wind power plants etc. It also includes advice to the Greenland Ministry of Mineral Resources and Labour concerning strategies, promotion, resource estimates, advice on exploration and exploitation of minerals (and petroleum, though this was outside the scope of this panel's remit).

While the majority of GEUS's funding is derived from the national government of Denmark, it also receives significant funding from several department under the Government of Greenland for activities in Greenland, and, as stipulated 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". The panel was informed this includes private companies, especially those involved in natural resource exploration and production. The types of activity that GEUS may engage in includes: distribution of data and results; sponsored research projects; data acquisition and QC for clients; and consulting.

EVALUATION PROCEDURE

The evaluation panel consisted of the following four individuals:

- **Vera R. M. Van Lancker**, SW2 Workleader, Royal Belgian Institute of Natural Science, Operational Directorate Natural Environment. Research Professor at Ghent University.
- **Alan R. Butcher**, Research Professor, Geological Survey of Finland.
- **Henrik Schiellerup**, Director, Geological Resources and Environment, Geological Survey of Norway.
- **Murray W. Hitzman**, Director, Irish Centre for Research on Applied Geoscience, Professor at University College Dublin.

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

Tuesday, January 22nd 2019

9.15 Introduction to GEUS and the Research Evaluation project,
Presentation of performance contract with the ministry, the involved departments and the sub-programme areas by Managing Director *Flemming Larsen*

10.00 Discussion on the role of the evaluation panel members, on the mission programme, the outcome of the mission, and the time frame for the evaluation (selection of scientists to be interviewed by the panel may be done during the presentations - and no later than Wednesday)

10.20 Highlights of recent and ongoing activities on programme area 4 – Minerals resources. Introduced by Heads of Dept. *Stefan Bernstein and Jørn Bo Jensen*

10.50 Questions

Presentation of main research areas (15 minutes presentation followed by 5 minutes for questions):

11.20 Offshore procedures and geological models as basis for sand and gravel mapping by senior researcher *Niels Nørgaard Pedersen*.

11.40 Marine sand and gravel resources in relation to Marine Spatial Planning (Øresund as example) by senior advisor *Jørgen Overgaard Leth*

12.00 The marine raw material database – Data, work and future by geologist *Nicky Hein Wit*t

12.20 Onshore raw materials by senior advisor *Claus Ditlefsen*

12.40 Questions and discussion

13.00 Lunch at GEUS with the staff presenting in today's session.

14.00 Karrat Zinc and mapping project by senior researcher *Diogo Rosa*

14.20 Tectonic development of East Greenland Basins by senior researcher *Pierpaolo Guarnieri*

14.40 The Greenland REE potential – from inside Earth to global market by chief consultant *Per Kalvig*

15.00 Questions and discussion

15.40 Southeast Greenland Margin, Geology and Mineral Potential Project (SEGMENT) by senior researcher *Kristine Thrane*

16.00 Materials characterization as a tool in urban exploration – example from Municipal Waste Incinerator, Copenhagen by engineer *Rune Clausen*

16.20 MultiMulti-purpose UAV platform for Mineral Exploration EIT-MulseDro by senior researcher *Bjørn Heincke.*

16.40 Bibliometric analysis by senior geologist, scientific coordinator *Lisbeth Flindt Jørgensen*

17.00 Questions and discussion

17.15 Review of the day, plans for the evaluation

Wednesday, January 23rd 2019

9.30 Visions for the future, basic raw materials introduced by Head of Dept. *Jørn Bo Jensen* followed by ultrashort presentations:

- The Danish mapping programme by senior researcher *Peter Roll Jakobsen*
- The Danish system: On- and offshore sand and gravel resources by senior advisor *Steen Lomholt*
- Sediment dynamics in areas with suction and trailing suction dredging marks: example from Disken in the Øresund Strait by senior researcher *Verner Brandbyge Ernstsen*
- The Kriegers Flak case study by Head of Dept. *Jørn Bo Jensen*
- Sediment budget in the shallow near coastal zone. Remote sensing example Zealand North coast by researcher *Matthew Owen*

10.20 Visions for the future, mineral raw materials introduced by Head of Dept. *Stefan Bernstein* followed by ultrashort presentations:

- Mineral mapping by hyperspectral remote sensing, examples from W Greenland by researcher *Sara Salehi*
- Zircon-monazite-titanite dating by senior researcher *Tonny Thomsen*
- Mapping leakages in circular economy, example from scrap metals by chief consultant *Per Kalvig*
- Urban Exploration – Geophysical targeting of Landfill deposits by researcher *Alessandro Sandrin*
- Petrology of fine-grained chalk reservoir rocks by post doc *Stefanie Lode*
- Greenland landslide mapping, recent and past events by researcher *Kristian Svennevig*
- Liverpool Land Basement High, relations to mineralizations and hydrocarbon migration by Head of Dept. *Stefan Bernstein*
- 3D–model Disko–Nuussuaq by senior researcher *Erik Vest Sørensen*
- HighTech AlkCarb (H2020) by post doc *Graham Banks*
- Non-evasive mineral exploration technique EIT-UpDeep by geologist *Simon Thaarup*
- Formation and origin of corundum (ruby and pink sapphire) from the Fiskenæsset complex, Greenland by senior researcher *Nynke Keulen*

12.30 *Lunch at GEUS with the staff members from the morning sessions and the following laboratory visits.*

13.15 Laboratory visit:

- Well Sample Laboratory (Geologist *Henrik Jønsson Granat*)
- SEM Laboratory (Senior researcher *Nynke Keulen*)
- ICP-MS Laboratories (Senior researcher *Tonny Thomsen*)
- 3D Photogeological Laboratory (Senior research *Erik Vest Sørensen*)

15.00 Evaluation panel reflect on the day and decides which staff members to interview Thursday

Thursday, January 24th 2019

9.15 Preparation of draft report and/or interviews with staff members selected by the evaluation panel (continued)

12.00 *Lunch at GEUS*

13.00 Preparation of draft report, preparation of debriefing conclusions.

Friday, January 25th 2019

9.15 Preparation of final draft report.

12.00 *Lunch at GEUS.*

13.00 Debriefing and delivery of final draft report to GEUS.

13.30 End of research evaluation mission.

A summary of the panel's observations and recommendations were presented to Director General Flemming Larsen, Deputy Director General Anne Merete Koefoed, Stefan Bernstein, Jørn Bo Jensen and Lisbeth Flindt Jørgensen on Friday, January 25th 2019. The evaluation panel wishes to extend particular thanks to Special Consultant Lisbeth Flindt Jørgensen who coordinated our visit to Copenhagen, ensured we were well fed and watered, and had access to what was required for the evaluation.

Personal interviews with selected staff

The following staff members were interviewed: Head of Department Stefan Bernstein, Head of Department Jørn Bo Jensen, Chief Consultant Per Kalvig, Post Doc Stephanie Lode, and Senior Researcher Kristine Thrane. Besides the excellent presentations, visits to laboratories, and staff interviews, the evaluation panel was given a memory stick with all pertinent publications for review.

General observations

Programme area 4's publication record, including peer-reviewed publications (average of 25.75 publications per year) is very good and when combined with popular scientific articles and abstracts for conference talks is excellent. The scheme allowing researchers to apply for funding

for writing time is also welcome. Maintaining an influx of graduate students into the programme area should not only contribute new ideas but should generate more publications that can reflect well on the researchers.

The staff we met were excited by their work and enjoyed the working environment. There appears to be a comradery. However, the forced redundancies of several years ago due to budgetary constraints are well remembered. The gender balance is typical of many geological surveys and the balance in the younger population of researchers is near parity. The age profile at GEUS is skewed toward ages near retirement with another bulge in the mid-40s. There is a clear need for more comprehensive succession planning.

GEOLOGICAL MAPPING AND MINERAL RESOURCES OF GREENLAND

Observations

- The basic geological mapping (1:100,000) conducted by GEUS in Greenland appears from the examples provided and from presentations and discussions with GEUS personnel to be of the highest quality. Utilization of non-GEUS personnel in some of these campaigns is especially noteworthy and provides world-class expertise at a very low cost.
- GEUS's photogrammetry program is world-class.
- More value can be derived from the existing GEUS mapping campaigns.
- GEUS has done an excellent job with its mineral assessment workshops.
- Laboratory-based mineralogy and petrology studies are of a very high standard
- The various laboratories at GEUS appear to be operated as isolated entities.
- Some laboratory equipment is clearly showing its age, e.g. the laser equipment
- Publication record is excellent.

<u>Geological Mapping</u>

The basic geological mapping (1:100,000) conducted by GEUS in Greenland appears from the examples provided and from presentations and discussions with GEUS personnel to be of the highest quality. GEUS clearly has mastered logistics in Greenland and is able to mount successful mapping campaigns in very challenging areas and under extreme conditions. The utilization of non-GEUS personnel in some of these campaigns is especially noteworthy and provides world-class expertise at a very low cost. Of special note with the Greenlandic geological mapping is GEUS's photogrammetry programme. This programme is world-class. GEUS researchers should attempt to utilize these newly existing datasets to construct 3D models probably utilizing Leapfrog or a similar platform.

The Panel felt the primary feature of the Greenlandic mapping program that required attention was ensuring that more mapping occurred more quickly. At issue is not the time that it takes to complete a 1:100,000 map sheet (although the Panel believes the time required may be reduced as the photogrammetry program and remote sensing technologies mature), but rather the number of maps that can be completed within the existing budget and with existing personnel. It is recognized that to produce more maps will require additional funding (and staffing).

The Panel believes that GEUS should set itself a stretch goal of trebling (times three) the amount of 1:100,000 scale mapping currently being undertaken. We would hope that GEUS would be able to produce on average one new 1:100,000 sheet every year for the foreseeable future. Accomplishing this will require a new funding stream. We believe funding should be sought from several sources:

- *National funds*: Highlight the national importance in terms of defence, strategic materials, and an understanding of climate change to other Departments within the government to seek additional dedicated funding.

- *European funds*: Work with MPs and others in Brussels to develop a new program for funding geological science in the Arctic highlighting again defence, strategic materials, and an understanding of climate change but in a broader European context.
- *Arctic nations*: Similar arguments to a sub-set of Arctic Council members (Canada, USA).
- *Foundation funding*: Critical elements are certainly present in Greenland and are required to reach the zero-carbon economy of the future. In addition, having an accurate physical and geological mapping base for Greenland is a necessity to properly understand the extreme changes underway there due to climate change.

Prior to seeking new funding, the Greenland programme at GEUS should convene a workshop to consider the importance of geological mapping, and the ancillary data provided by mapping (and see below), of Greenland to multiple stakeholders including the Greenland people and government, other Arctic peoples and countries, the private sector (particularly the high-tech manufacturing and materials sector), the scientific community, and the environmental community. The workshop should be chaired by a noted (non-GEUS) scientist (ideally not a geologist) who does understand the benefits of additional geological data from Greenland. A concise report of the results of this workshop could be used to support additional funding by the groups suggested above.

In addition to more geological maps, there is also an urgent need for additional high-quality geophysical data for Greenland. This should include magnetics, gravity, radiometric, and hyperspectral data. Ideally there should be such geophysical data to accompany every geologic map published. Geophysical surveys should be flown commercially.

The Panel feels strongly that moving forward all geological maps of Greenland produced by GEUS should have legend and map descriptions in Greenlandic, Danish, and English. It is also important that GEUS, in conjunction with MMR in Greenland, develop a decadal strategy for building up Greenlandic geological expertise.

The Panel also believes that more value can be derived from the existing GEUS mapping campaigns. GEUS geoscientists should query other scientists interested in the Arctic or in other scientific disciplines to see what sampling might make sense. For example, suites of soil or tundra samples across a map area could be utilized to undertake a microbiological survey of environments that have rarely been sampled. Soil samples on a widely spaced grid could also be used to initiate a soil geochemical map of Greenland that could serve as a baseline for the future as increased melting and climate change results in different soil development. How much attention is being paid by the existing crews to glaciological and other geomorphic science during these campaigns? Is advantage being taken of the mapping team's location to gather precise meteorological and or marine water and sediment data to increase relevance?

<u>Mineral Resources</u>

Mineral resources research in Greenland depends almost entirely on the production of high-quality, detailed (1:100,000 scale) geological maps. Thus, the mapping (and associated geophysical surveys) are the most important data sets that GEUS can generate for mineral assessment. At this stage in Greenland's development it is not feasible to undertake detailed economic geology research as there are essentially no well-defined ore deposits.

GEUS has done an excellent job with its mineral assessment workshops to educate its own staff and provide the Geology and Ore series documents available in Greenland and elsewhere on different types of mineral commodities. These workshops should be continued with possible topics including dimension stone (a focus in the field in the near future), gemstones (beyond rubies), and high-value minerals such as cryolite (Na_3AlF_6), the mineral that was mined in Greenland at Ivigtut until the deposit was exhausted in 1987.

Geochronology of sediments and crystalline rocks, and trace element geochemistry

GEUS' geochronology facilities are well known within Europe and are clearly a key area of expertise at the Survey. Based on a visit to the SEM and ICP-MS laboratories on 23rd January 2019, as well as the reading of supplied published papers and documents, it is clear the group are undertaking world-class research in the precise age-dating of minerals, trace element analysis, provenance studies, and combinations of all techniques on multi-minerals. The main emphasis during the review period was on U-Th-Pb systematics using laser ablation ICP-MS. Key staff that were introduced to the Panel included the Manager of the laboratories, Tonny Thomsen, and Senior Researcher, Nynke Keulen.

A common problem for many isotope geochronology laboratories worldwide is the ability to maintain equipment and to replace systems as technology advances in this dynamic area. Some equipment at GEUS is clearly showing its age, e.g. the laser equipment. The Panel is in agreement with the researchers at GEUS – as suggested in material provided in the presentations – that a vision of the future needs to be considered so that GEUS can stay cutting edge with the ability to offer the best services for both internal and external customers.

It was also noted that there appears to be a closely integrated operation between the ICP-MS laboratory and allied areas such as the SEM, optical and fluid inclusion laboratories, as well as the EPMA facility at Copenhagen University, which is to be highly commended.

The idea of a vision for the future was presented – of a multi-tasked approach using a combination of a split stream laser ablation ICP-MS, ICP-OES and LIBS – and was noted by the Panel. In our opinion, this should be a high priority for funding in the coming years. It was also noted that there is an urgent need for correlative commercial software that needs to be acquired in order to allow easy and accurate co-location of sampling points across different technology platforms. This will make the integration of mineral, geochemical and isotopic data easier and quicker (thus significantly reducing time required and cost).

It was inferred from the discussions that GEUS has additional in-house analytical facilities and also uses laboratories at Copenhagen University. The Panel noted that even though the analytical laboratories visited were exemplary in generating high-quality data and ICP-MS performance was controlled through round robins and other quality measures, no GEUS-wide quality system seemed to be in place to ensure overall process control and traceability. A closer integration of related laboratories should be considered to ensure more efficient use of capacity and money, as well as better traceability through a comprehensive quality system.

Petrology and mineralogy of igneous rocks and mineral deposits

GEUS has a demonstrable track record of very high-quality research into the petrology and mineralogy of rocks from Greenland during the review period. This has been achieved from well-organized annual field mapping campaigns to Greenland, as well as carefully orchestrated follow-up laboratory work back in Copenhagen and at collaborator's facilities in Denmark. Both fundamental scientific investigations, as well as applied studies (mineral potential), were completed. Special attention was placed on REE-bearing locations and samples (Illĺmauussaq), as well as base and precious metals (NordZinc, Karrat zinc, SEGMENT), and gemstones (rubies), both at GEUS and undertaken with international collaborators (RWTH Aachen, KIT, HZDR, UWA, Durham, Exeter, to name a few). A few studies related to metal concentration and hydrocarbon migration were also completed (example is Liverpool Land Basement High).

Several Greenland Mineral Assessment workshops have also been completed over the period from 2008-2017. Additional work by the team has improved the stratigraphic database by the study of sedimentary basins, along with structural and modelling studies.

A highly welcomed addition to the research area during 2017-2018 has been geohazard mapping – specifically landslide risk assessment and associated risk from debris flows and tsunamis – in response to an incident that took place in NW Greenland in the summer of 2017, which killed 4 people and continues to displace more than 250 people. Funding is currently received directly from the National Bill but opportunities for dedicated funding for a larger program should be exploited.

GEUS's work has resulted in many high quality peer-review publications (Lithos, Economic Geology, Journal of Petrology, EPSL, Geology, Precambrian Research, Chemical Geology, Journal of the Geolological Society London, Mineralium Deposita, American Mineralogist, Tectonophysics, Mineralogical Magazine, Ore Geology Reviews, Geological Magazine, Geochimica et Cosmochimica Acta, to name a few), new geological maps, several GEUS reports, and PhD degrees and conference papers. Most of the work is undertaken within the Department of Petrology and Economic Geology. Consultancy projects for the mining industry also form an important component of activities (with Anglo American, Blue Jay Minerals, First Quantum, to name a few).

Of special mention is the addition of new SEM facilities during the review period, which are state of the art (FEG-SEM with EDS and automated mineralogy, EBSD and CL capabilities). This facility sets GEUS apart from many other research institutions and geological surveys as it allows a comprehensive characterization of geological materials to be carried out.

An area of potential concern, raised both in the presentations and during the one-on-one interviews, is the ability to maintain the level of expertise within the Department given past and upcoming retirements, and the loss of staff due to other factors (including redundancy (2016), and normal staff attrition). The Department of Petrology & Economic Geology is relatively small given their tasks – only 8 senior scientists, 2 chief consultants, 7 researchers, 7 academic staff, plus others. It appears therefore that certain individuals are very important to many areas of research.

Maintaining the high-level of achievement in the future will require a systematic and planned backfilling of all key positions, ideally within a succession planning period and an associated

handover period. This at present is apparently generally not happening, leaving many potential current and future gaps in areas of key expertise at GEUS. Training and mentoring are also areas for future attention – this would include on-going professional development in areas of key competence – such as geochronology, SEM, mineral identification by automated methods, digitization of mineral and petrofabric data – to spread the expertise at GEUS and reduce the dependence on one or two key staff.

Recommendations

- GEUS should set itself a stretch goal of increasing the amount of 1:100,000 scale mapping currently being undertaken by at least three times.
- All geological maps of Greenland produced by GEUS should have legend and map descriptions in Greenlandic, Danish, and English.
- GEUS should ensure the most possible value is derived from the existing GEUS mapping campaigns in regards other scientific aspects (biology, etc.).
- Mineral assessment workshops should be continued.
- A multi-tasked approach using a combination of a split stream laser ablation ICP-MS, ICP-OES and LIBS for the geochemistry laboratory is a high priority for funding in the coming years.
- There is an urgent need for correlative commercial software to allow easy and accurate co-location of sampling points across different technology platforms.
- Additional cross training of personnel as well as systematic and planned backfilling of all key positions, ideally within a succession planning period and an associated handover period, should be a strategic vision.
- GEUS should investigate the potential benefits of a closer integration of staff, quality system, and analytical capabilities in their laboratories, to improve efficiency and process control.

GEOLOGICAL MAPPING AND MINERAL RESOURCES OF DENMARK

Observations

- The terrestrial mapping of Denmark at 1:25,000 scale is still not finished.
- Marine mapping of raw materials is very-well advanced. The team has invested in state-of-the-art equipment and continues doing so.
- 3D mapping/modelling has been proven successful in a number of case studies. Yet, there is no strategy to develop this systematically for land and sea, and integrate data from each.
- High-quality mapping of shallow geology, aggregates and sediments is documented in many case studies and is well respected internationally. Still, only one technician is currently involved, which is limited given the ambitions of the group.
- Mapping has developed to comply with the requirements for mapping of Natura-2000 habitats/shallow coastal habitats and is pivotal to support marine spatial planning. 3D and 4D mapping has started and the necessary skills are in place to develop this further. The mapping is very well positioned to address today's and the future's societal needs.
- The team is well equipped to conduct regional assessments of onshore and offshore aggregate deposits. The cooperation with MiMa and the resulting joint reports are leading examples of good practice.
- The data center is well established but could better reflect the overall GEUS IT expertise.
- Raw data and final products are available to the public.
- Mapping results are not evident in peer reviewed journals.

Geological mapping in Denmark has a long tradition. Different authorities are responsible for the regulation governing extraction on land and offshore. The Danish Regions are the authorities on land and the Danish EPA offshore.

The Marine Geology mapping group clearly benefited from the longer-termed funding scheme from EPA and is expanding in team and projects. The longer-term perspective is essential to strengthen the research potential.

<u>Geological mapping of onshore Denmark (2D-3D)</u>

The terrestrial mapping of Denmark at 1:25,000 scale is still not finished, which is surprising. Mapping of the last 10% of the 2D landscape is planned and should indeed be maximally supported and completed. Map products are available as printed sheets, and as digital products that are free to download (also in ArcGIS). Thematic maps have also been produced based on the digital geological maps. Research spin-off is difficult to evaluate based on the material provided.

Whilst 3D modelling has advanced and proven successful in a number of case studies, there is as yet no strategy to develop 3D modelling systematically for land and sea. However, with expanding infrastructure works and extraction of land and sea aggregate deposits, as well as increasing importance of multi-use spatial planning, more detailed knowledge of the subsurface

is critical. This evolution boosted 3D mapping in The Netherlands and in the UK, and would be expected in Denmark too.

Marine mapping of raw materials (2D-3D-4D)

Marine mapping of raw materials is very-well advanced in Denmark, and the team has invested in state-of-the-art equipment and continues doing so. As such, the team is best placed in Denmark for the mapping of shallow geology, aggregates and sediments. They have proven this in many case studies and the work is well respected internationally. The mapping is developed to comply with the requirements for mapping of Natura-2000 habitats/shallow coastal habitats, and is pivotal to support marine spatial planning. Furthermore, 3D and 4D mapping has started and the necessary skills are in place to develop this further. The mapping is very well positioned to address today's and the future's societal needs.

Needed diversification in marine mapping at GEUS is taking place. Common goals will be required, as well as a good strategy on how to combine the expertise and seek maximum synergies. Acoustic seabed classification probably needs strengthening (e.g., from multibeam backscatter data). Ground-truth validation will be critical and needs careful consideration in terms of planning and targeted accuracy of the mapping. This demands good coordination and support. Only one technician is currently involved, which is limited given the ambitions of the group.

The team is well equipped to conduct regional assessments of aggregate deposits onshore and offshore. The cooperation with MiMa and the resulting joint reports are leading examples of good practice. Common classification standards of onshore and offshore aggregate deposits are another key asset needed. Synergy with MiMa should be continued and deepened to address United Nation's Sustainable Development Goals. Research on more sustainable exploitation of aggregates should be strengthened in light of unprecedented increasing resource demands.

GEUS national data center of raw materials

Internationally, GEUS is renowned for its data management and leads the way in the development of the European Geological Data Infrastructure. Nationally, the databases JUPITER and MARTA have been well established.

Data management is a key component of the marine mapping and should be strengthened, given the diversity of the data involved, and the plethora of derivative products. Traceability of all steps in the mapping process, including mapping and modelling procedures, is becoming increasingly important, e.g. in view of environmental assessments supporting European Directives.

For land-sea resource assessments coordinated databases are critical and maximum coupling of JUPITER and MARTA, but also other databases (e.g. on production or other uses of the subsurface) should be strived towards. Feasibility of conducting material flow analyses within and beyond Denmark should be explored.

Whilst the research is well demonstrated through the mapping, publications of the mapping products, case studies, methodologies, etc. should be better presented in peer-reviewed journals. Mechanisms to facilitate this are in place.

With increasing demand for raw materials, e.g. for new land, construction purposes, and climate-proof coastal protection, there are huge challenges ahead to prioritize areas for extraction. Land-sea resource assessments are needed and collaborative frameworks, e.g. decision support systems, require development to assist in such assessments. These evaluations will need to integrate geological, environmental, and socio-economic data. GEUS's solid geological background should be complemented with ecosystem mapping, including its dynamics (4D component). The team is very-well positioned to support a more ecosystem-based approach. Quality/uncertainty assessments are important and should complement the mapping products.

Whilst establishing a national mapping programme is highly beneficial and required to provide the necessary baseline maps for many management decisions and industrial applications, the panel suggest the GEUS should facilitate more coordinated mapping: e.g., with other mapping bodies in Denmark, including industry, and consultancy firms. Sharing of best practice is critical for upfront standardizing of data in order to better harmonize existing initiatives. Offshore, joint calibration exercises or platforms for calibration for acoustic measurements would largely facilitate this goal and could be coordinated by GEUS.

A strategy is needed on how to better align GEUS's program with the UN Sustainable Development Goals for which a more sustainable exploitation of the environment is key. This demands research on thresholds for exploitation (in size, in depth, and allowable habitat alterations), resource efficiency, and pathways for a circular economy. Simulations of different extraction scenarios, and their impact on the environment and on socio-economics, would facilitate prioritizing areas of research. Strategical alignment could boost transdisciplinary research and the breadth of cooperation with universities.

Recommendations

- Terrestrial mapping of Denmark at 1:25.000 scale should be completed.
- Develop a strategy to maximize the efficiency and accuracy of the multidisciplinary mapping.
- Ensure traceability of all mapping steps in view of environmental assessments supporting European Directives.
- Significantly increase mapping coverage, facilitate more coordinated mapping: e.g. with other mapping bodies in Denmark, including industry, and consultancies.
- Share best practice and jointly calibrate instrumentation.
- Conduct a feasibility study on developing a national land-sea mapping strategy.
- Effective communication on the need for a national raw material strategy. Consider promoting the concept of preserving natural capital for future generations.
- Seek international cooperation on standardized land-sea resource classification.
- Develop decision support systems that enable land-sea resource assessments, and allow integrated analysis of geological, environmental, and socio-economic data in combination with quality/uncertainty parameters.
- Continuously update foresight studies on resource demands and simulate different extraction scenarios starting from geological availability and including the

environmental and socio-economic dimension. Use this to prioritize areas of research (MiMa).

- Align the envisioned national raw material strategy with the United Nations Sustainable Development Goals. International cooperation is recommended.
- Mapping results should be better presented in peer-reviewed journals.

MINERAL INTELLIGENCE

Observations

- MiMa occupies an important societal role in raw materials and industrial strategy development for Denmark and Greenland.
- MiMa has a concentrated set of unique skills which generate essential value chain data and high-value scientific research.
- A major challenge for MiMa moving towards 2020 is to document their relevance and secure permanent funding.
- MiMa has had a strong focus on the geology of rare earth element deposits and the rare earth elements value chain. The relevance and quality of research conducted is outstanding.
- The research and analyses into Danish raw materials is excellent, but not available for an international audience (published only in Danish).
- The research into urban mining and circular economy is currently less mature than the critical raw materials research.

At GEUS, "mineral intelligence" is primarily performed within the Center for Minerals and Materials (MiMa). MiMa's overall task is to build knowledge about issues related to supply and scarcity of raw materials, and to provide solutions for future raw material challenges.

MiMa was formally established at GEUS in 2013 but the initial steps were taken through 2011 and 2012 following the increasing awareness and initiatives connected with criticality of mineral resources across Europe and elsewhere. One of the objectives of MiMa is to analyse whether Danish society and Danish businesses will be affected by a lack of access to mineral resources, and to which extent this could impact the Danish economy. MiMa is also tasked with identifying challenges and opportunities in the reuse of mineral resources.

Currently, MiMa consists of a very diverse group of people from high-school teachers and a PhD student, two geographers, a metallurgist and an environmental civil engineer, to economic geologists. They are supported in an ad hoc manner by regular GEUS personnel. The diversity combined with the GEUS support is a strong asset.

MiMa was initially financed through dedicated funding from the Danish National Bill of 3 million DKK per year for the period 2013 to 2017. In 2017 the funding was extended until 2020. Currently, the MiMa activities require more than dedicated funding and GEUS is adding resources to the centre and its c. 5 person-year spending. A major challenge for MiMa moving towards 2020 is to document their relevance and secure permanent funding.

MiMa has three performance areas:

- Critical Raw Materials assessments
- Global Value Chain analysis
- Urban exploration / Circular Economy

From the inception of MiMa, 12 peer reviewed papers have been published and one is in press. The papers are thematically oriented towards value chain issues, primarily for critical raw

materials, and towards critical raw materials with a strong focus on the geology of REE resources. One paper is on recycling. Most of the MiMa publications (10) have MiMa personnel as first author. In addition, MiMa has produced 12 GEUS reports and publications and almost 40 oral and poster presentations.

Because MiMa was founded during the period 2011-2013, the focus in peer reviewed publications has been biased towards rare earth elements, in line with the European and global attention to the demand-supply situation within the REE industry. MiMa has an important function in which only a few geological surveys have more than general capacity. European institutions with comparable tasks include the German Mineral Resources Agency (DERA) under the German Geological Survey (BGR). The MiMa critical minerals and value chain analyses connects current and future geological resources with down-stream industry and generate required data and information for accurate national and international resource strategies. The work adds relevance to GEUS, and the resources covered by the analyses. MiMa has arranged relevant workshops and seminars, initiated research and has been actively supervising a number of PhD and MSc projects.

MiMa has been highly active in a range of European projects focused on critical raw materials and mineral intelligence data collection and harmonization. Whereas much of this work could have been performed outside MiMa, the wide perspective of MiMa with its composite group of researchers has been an obvious asset in many of the projects. MiMa played a very important role in the supply and demand analyses within the EURARE project, and most of the high-profile publications within MiMa concerns REE. In addition to the papers on market perspectives, two high-profile publications on the geology of the REE deposits in South Greenland have also been produced through MiMa.

Urban exploration and circular economy as research areas for MiMa are exploited through two studies on scrap metal recycling and the identification of leakages in recycling and the circular economy (the metal scrap value chain). The projects are on-going but seem considerably less mature than the MiMa REE projects; the projects are not yet publication ready. A project on geophysical mapping of a land-fill site west of Copenhagen is being planned and aims to start during January/February 2019. The land-fill project is primarily based on a geophysical survey, which is most likely destined to face both technological and interpretative challenges, and it does not appear to depend on MiMa resources. The outcome seems somewhat uncertain and the project would probably better belong to an environmental program and should ideally be supported by the responsible authorities.

The scrap resource value chain obviously lies within the MiMa research approach and a thorough analysis may generate societal benefits in terms of better value assessments prior to export from Denmark. The methodology is likely to be strongly based on the value chain analyses performed by MiMa through several years. The experiences from the REE-based research from geology to market is transferable to other critical mineral resources, such as the energy-critical metals and minerals as well as future critical metals. The collective competence within MiMa, as well as their substantial international network, should give the group an opportunity to predict and analyse the future trends also for battery metals, such as lithium, cobalt, nickel and natural graphite, but also to estimate and analyse the situation for other metals with increasing criticality, such as vanadium.

Resources in Denmark are analysed in three MiMa reports. There are no recorded scientific papers on the subject, but the analyses are very relevant and important to the Danish raw material supply for urban and infrastructure development. Ignoring resource issues concerning the construction materials would come with a high societal cost. The data gathering, analyses and research is clearly within the MiMa competence and should be continued and made widely available. Even if the research is strongly applied, we encourage the MiMa group to use the data for publishable research in the international literature.

Recommendations

- The wide competence of MiMa within REE is both unique and strong and should be upheld with further studies.
- MiMa should continue the research within the secondary resources value chain, applying the experience and methodologies developed since 2013.
- MiMa should develop their research into areas where the experience and collective competence of the MiMa group constitutes an asset in terms of methodology and existing network. This includes a range of commodities of current or future criticality, such as the battery metals and minerals and possibly vanadium or other commodities susceptible to market failure.
- MiMa should uphold its activities on Danish construction raw materials to advocate a balanced supply-demand situation. The work is of high societal importance and will increase the relevance of MiMa for future funding.